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Preface

God always forgives, man sometimes, nature never

Pope Francis

This book brings together systems theory and environmental science, by recasting environmental problems into a common system-theoretic methodology. In this way, simple models can be developed and new insights can be gained, which could not have been achieved otherwise. System theory is inherently a 'reductionist' discipline and its integration with the naturally 'holistic' environmental science at first was not easy. The first pioneering attempts at translating ecological principles into mathematical laws (Maynard Smith, 1974; Rinaldi et al., 1979) were met with a somewhat supercilious reaction by ecologists, who resented the intrusion of mathematicians (let alone engineers!) into their turf, and looked down on the attempt at translating ecological concepts into mathematical relations. Over the years, ego clashes have gradually receded and now mathematical modelling has become a well-established branch of ecology, in which this book is naturally set.

This book is about developing dynamical models of environmental processes, using a wide variety of mathematical methods. The first four chapters introduce the analytical tools for investigating environmental models and data. The emphasis is evenly balanced between the mechanistic and the data-driven approaches, assessing the merits and liabilities of both. Theory is introduced in its most accessible form and is applied to test cases based on first-hand data and experiences. While Chapters 1 and 2 deal with the basic concepts of modelling and identification, Chapter 3 deals with data processing, rarely considered in the environmental analysis, by introducing numerical techniques to improve the quality of the data and to extract the information they carry, in the context of model building and verification. Chapter 4 introduces the basic concepts of fuzzy logic and applies them to the modelling of environmental systems. Chapters 5 through 7 apply these methodologies to specific aspects of environmental modelling: population dynamics, flow systems, and environmental microbiology. The last chapter (Chapter 8) combines the notions of the previous chapters into the analysis of several aquatic ecosystems' case studies.

I am quite aware of the limitations of this book, because it reflects my own research experience, and therefore it is strongly oriented towards the aquatic environment, while it completely disregards other equally important subjects such as air pollution, groundwater, or solid waste, simply because I never worked in those areas.

Far from being a 'theory' book, its approach is eminently practical, in that every methodological aspect gives rise to a MATLAB® code. Nevertheless, this is not a recipe cookbook, but it takes the reader through a logical sequence from the basic steps of model building and data analysis to implementing these concepts into working computer codes, and then into assessing their results. Who should read this book? Certainly anyone who is looking for an introduction of the mathematical approach to ecology, or anyone who wants to take a fresh look at known problems from a differing viewpoint. This book may represent a first encounter with mathematical modelling before going on to more advanced books in the specific field of interest.

I have set up a quiver full of arrows. Then it is up to the archer to call the shots. As Figure 1 shows, this book spins a web of relations among system theory and environmental issues, moving from the predominantly methodological first four chapters to the more applicative subsequent part, where specific environmental problems are addressed. Clockwise from the top of Figure 1, Chapter 1 summarizes the basic concepts of system theory for both linear and nonlinear models, while Chapter 2 is devoted to model identification. Chapter 3 considers the data acquired from the field, how their quality can be improved and the embedded information extracted. Chapter 4 describes the fuzzy approach to modelling and data analysis, showing that fuzzy models in many cases have an advantage over their mechanistic counterparts, and how the fuzzy approach can be profitably used for

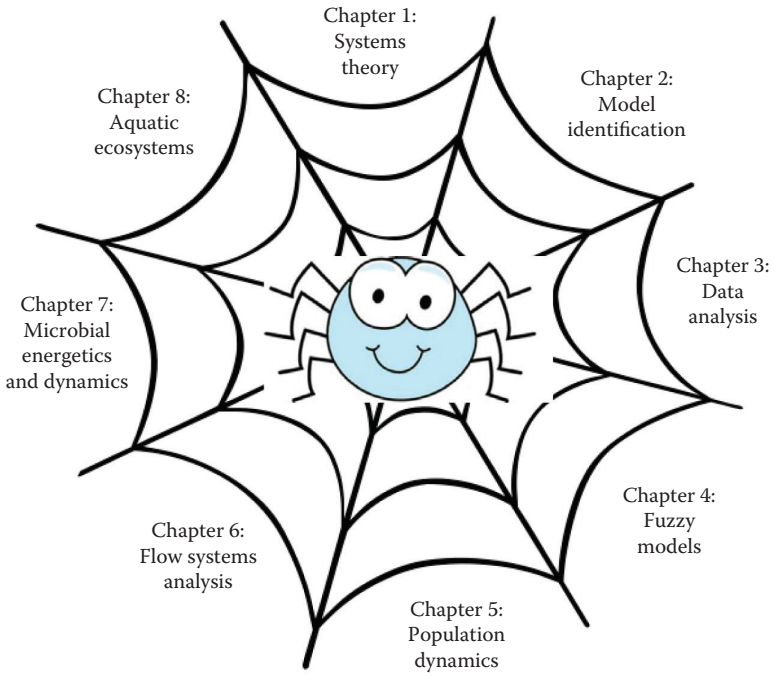

FIGURE 1 This book spins a web of relations (clockwise from the top) among system theory and environmental issues, moving from the predominantly methodological first four chapters to the more applicative subsequent chapters where specific environmental problems are addressed.

data analysis and diagnosis. While the first four chapters illustrate the methodological aspects of environmental systems analysis, the subsequent chapters apply them to specific environmental problems. Chapters 5 deals with population dynamics, from single species to food webs, with an emphasis on investigating the conditions for species conservation, or on explaining unexpected behaviours like the catastrophic forest defoliation caused by the spruce budworm. Chapter 6 deals with flow modelling. Far from competing with hydraulic modelling, it considers some simple flow schemes, which provide the first level for aquatic ecosystem modelling. Chapter 7 introduces the basic concepts of environmental microbiology, both in the natural and man-made environment. I strived to show the similarities and the differences of microbial processes in either setting, without getting too much involved in the analysis of wastewater treatment systems, given the many excellent textbooks available in this area (Bastin and Dochain, 1990; Orhon and Artan, 1994; Olsson and Newell, 1999; Dochain and Vanrolleghem, 2001; Gujer, 2008). The final Chapter 8 is a wrap-up chapter, in which I discuss several case studies drawn from my own experience.

It has been said that any scientific book is partly autobiographical, and this one is no exception. In fact, being near the end of my academic career, I felt the need to gather the lecture material that I have amassed in over 30 years of environment analysis teaching. Educating has been an exciting experience all along, because I was fortunate enough to teach students with differing backgrounds and brilliant minds, ranging from automation to environmental engineering, which resulted in a fruitful cross-fertilization. Class projects frequently became master theses, and sometimes produced journal papers, with the students' involvement as co-authors. These mixed classes reflected my own mixed background, which blended my early electronic engineering training with the subsequent commitment to environmental issues. I felt that I owed this book to generations of students, who have now become accomplished professionals, and from whom I still receive a constant flow of affection and gratitude. Now, when we meet at professional gatherings or just over a pizza, they

love to reminisce over their student days and how much we enjoyed working together and learning together. This book is my token of gratitude for the endless affection and inspiration I have been receiving from them all.

All the material in this book has been intensively student-tested and the companion software has been honed through many critical reviews by cohorts of students. I have found that MATLAB is an ideal teaching, and learning, tool in that it provides a platform that makes the implementation of mathematical ideas into executable code very quickly. Unlike other more formal programming languages, such as Fortran or C/C++, which require setting up complex structures, in MATLAB the user can immediately translate the problem at hand into an executable code and get the results in no time. Many segments of the MATLAB code (referred to as *scripts*) are included in the boxes along the book to demonstrate the programming structure, while the complete software collection can be downloaded from the book web page in the CRC Press website and copied in the local hard disk. It is strongly suggested to maintain the original folder structure, with a master directory named `ESA _ Matlab`, in which each chapter folder contains the pertinent codes for that chapter, plus a 'tools' folder, which gathers all the utility functions common to all chapters. No installation is necessary, but once MATLAB is started, the master folder and its subfolders must be added on top of the MATLAB path. This software organization makes the path definition vital to retrieve the called functions. The exercises for each chapter have self-explanatory names and are referenced in the figure captions. Of course, this book should not be considered as a MATLAB primer, many of which are freely available in the web. So a certain basic MATLAB literacy is a prerequisite.

A brief clarification regarding an important mathematical notation. Throughout the book the imaginary unit is indicated by j, so that $j \times j = -1$. There was an old joke circulating in the past saying how you could tell a mathematician from and engineer. When asked about the imaginary unit, the mathematician would say $i \times i = -1$, while the engineer would claim that $j \times j = -1$, and this book goes for the latter, though MATLAB uses i. Additional material is available from the CRC Press Web site: http://www.crcpress.com/product/isbn/9781498706353.

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Acknowledgements

Research is a constant swing from frustration to elation and back, and so is scientific book writing. Far from being a solitary activity, I am indebted to a vast number of people with whom I shared elation and to whom I am grateful for pulling me out of frustration. My first thanks goes to my wife Patrizia, a devoted and reliable life companion, for the loving empathy and constant encouragement, apart from discussing some mathematical aspects of the book, as a math teacher. My daughters Ilaria and Chiara provided an equally enthusiastic backing. Ilaria, an agricultural microbiologist, is also to be thanked for revising Chapter 7. Apart from the family circle, I am deeply grateful to several people for their vital contribution both as accomplished professional and as very close friends. Two very special persons stand out, without whom this endeavour could not have been accomplished: Irma S. Britton, CRC Press senior editor, and Professor Emeritus William D. Lakin, University of Vermont, Burlington, VT. Irma has been a dream editor, the one that any author would love to encounter. From her and her staff, I received endless support and encouragement. Her ability to answer my queries and smooth my workflow has been invaluable. Bill Lakin, a friend of long standing and an excellent mathematician, carefully reviewed the whole manuscript and provided valuable comments regarding both the English and the mathematical aspects. His support has been vital. I am also grateful to Dr. Alessandro Spagni, ENEA Bologna and University of Padua, co-author of many papers and careful reviewer of Chapter 7. A special thanks goes to Dr. Luca Palmeri, University of Padua, for being the first instigator of this book. Upon his suggestion, I was invited by CRC Press to write a brief account of his book (Palmeri et al., 2014) and then I was asked whether I had a book proposal of my own. I said yes, CRC Press liked my proposal, and this is how it all started. Another precious instigator of this book has been Dr. Michela Mulas, Aalto University, Finland, who in 2012 invited me to teach a short course entitled 'Environmental Data Modeling and Analysis'. The material I prepared for that course later became the kernel of this book and her enthusiastic support for the initiative always spurred me throughout my toil. Much of the material presented in this book is the result of research carried out with my assistant Elisabetta Giusti, PhD. Her invaluable input, her curiosity, and her hard-nosed determination supported me in many ways during our decade-long fellowship rich in scientific advances, frank discussions, forthright personal interaction. I am also deeply indebted to Professor Antony Jakeman, Australian National University and Editor-in-Chief, *Environmental Modelling and Software* (EMS), for his loyal friendship, optimistic wisdom and constant encouragement over our long friendship. He asked me to join the EMS editorial board in 2004 and that job has been a constant source of reward, satisfaction and personal growth. I am also deeply grateful to Michelle Herbert, IWA Journals Editorial Co-ordinator, who sympathetically modulated my *Water Science & Technology* editorial work flow while I was busy with the book, and quickly provided the permission to reproduce several figures from my WST papers. I am also indebted to Design Science (www.dessci.com), particularly Bob Mathews and Derrick Fimon, for helping me getting the most out of MathType 6.9 for Windows, a superb math editor, which I used extensively to write the many equations appearing in the book. My PhD students Emanuele El Basri and Giacomo Barni are to be thanked for their helpful assistance and the revision of the MATLAB codes. I am also thankful to www.brainyquotes.com for providing me with a vast source of inspiring citations, some of which I used as chapter openers.

In further hindsight, I am grateful to my late parents, who taught me to love and respect Nature from my early days, and to the medical staff who helped me in my battle against cancer, particularly Professor Moretti, who took away the worst part of me, and Professor Amadori, who guided me through the painful path of chemotherapy with a strong hand, unabashed optimism, and a captivating smile. Teaching during these 'medical' months was not easy, and I am grateful to my family and to my students, who supported and encouraged me through that dire moments. I owe them all this new

lease of life, which made the book possible. In that time I experienced first-hand Winston Churchill's quotation 'Success is not final, failure is not fatal: it is the courage to continue that counts'.

Scientific research is a never-ending struggle to further our knowledge, but there are times when we must pause and take stock of our progress. I hope that you will enjoy reading this book, as much as I did in writing it, and after turning the last page, lean back—as I have done after writing the last line—and take time to stand and stare.

What is this life if, full of care,
We have no time to stand and stare.
No time to stand beneath the boughs
And stare as long as sheep or cows.
No time to see, when woods we pass,
Where squirrels hide their nuts in grass.
No time to see, in broad daylight,
Streams full of stars, like skies at night.
No time to turn at Beauty's glance,
And watch her feet, how they can dance.
No time to wait till her mouth can
Enrich that smile her eyes began.
A poor life this if, full of care,
We have no time to stand and stare.

W. H. Davies
Leisure, *1911*

Florence,
July 30, 2015.

Author

Stefano Marsili-Libelli was born and educated in Florence, Italy. He received a *cum laude* MS degree in electronic engineering from the University of Pisa in 1973. Later in the same year, he joined the University of Florence on a post-graduate grant and has served in the Faculty of Engineering ever since, first as a technical assistant, then as an associate professor (since 1983), and finally as a full professor of environmental system modelling since 2000.

He has always been active in promoting the system theory approach to the study of environmental systems, both at a faculty level and in a broader context, teaching seminars and courses on environmental modelling and control at the University of Gent (Belgium), University of Leuven (Belgium), Institute of Hydroinformatics (IHE, Delft, the Netherlands), Institute of Environmental Biotechnology, TU Delft (the Netherlands), University of Glamorgan (Wales, UK), Aalto University (Finland) and University and Polytechnic of Valencia (Spain).

He spent study periods at the Institute of Hydrology, Wallingford (UK); International Institute of Applied Systems Analysis (IIASA), Laxenburg (Austria); University of Glamorgan (Wales, UK).

He established Erasmus bilateral links with the University of Gent (Belgium), University of Delft (the Netherlands) and University of Amsterdam (the Netherlands).

Apart from being a founding member of the environmental engineering curriculum at the University of Florence, and serving as the director of the Laboratory of Environmental Process Control, he joined several PhD faculties, among which the PhD curriculum in hydrodynamics and environmental modelling (Consortium among the Universities of Padua, Florence, Genoa and Trento) and the PhD curriculum of sanitary engineering (University of Rome 2). He is presently serving as a faculty member of the international PhD curriculum in civil and environmental engineering (University of Braunschweig, University of Florence, University of Pisa and University of Perugia).

Dr. Marsili-Libelli's teaching responsibilities have always been in the modelling and control of the environmental systems, particularly aquatic environment, both natural and man-made, developing models describing the ecology of lagoons and rivers, as well as new models of microbial kinetics to be applied in the control of wastewater treatment systems.

Other research interests include the modelling of the environment using the fuzzy sets approach and the identification of environmental models, for which he proposed new ad hoc optimization methods for parameter estimation and validation. Modelling applications range from the rivers and lagoon to subsurface constructed wetlands, anaerobic digesters, aerobic wastewater treatment processes and agricultural systems.

He is presently serving as an associate editor for the ISI international journals *Environmental Modelling & Software* (Elsevier) and *Water Science & Technology* (IWA Publishing).

He is member of the following scientific societies:

- International Environmental Modelling & Software society (iEMSs)
- International Society of Ecological Modelling (ISEM)
- International Water Association (IWA)
- Italian Society for Automation (ANIPLA)

Over the years, Dr. Marsili-Libelli has received the following awards:

- The paper Checchi N., Giusti E., Marsili-Libelli S. (2007). PEAS: A toolbox to assess the accuracy of estimated parameters in environmental models. *Environmental Modelling & Software* **22**: 899–913, was awarded the Best Paper Award 2007 by the *Int. J. Environmental Modelling & Software.*

- *Biennial Medal* awarded by the International Environmental Modelling & Software society (iEMSs) in 2008.
- Nomination to *iEMSs Fellow* in 2008.
- *Best paper award* granted by AssoAutomazione (Italian association for automation) in the area of Technological Innovation in the Water Sector, biennial Forum for remote control of public utilities, Rome, October 2009.
- Nominated *Reviewer of the year* 2010 by the Editorial Board of the *Int. J. Environmental Modelling & Software*.
- *Best paper award* granted by AssoAutomazione (Italian association for automation) in the area of Competition and Sustainability in the Public Utilities, biennial Forum for remote control of public utilities, Bologna, November 2013.