SECOND EDITION

HYDRODYNAMICS AND WATER QUALITY

Modeling Rivers, Lakes, and Estuaries

ZHEN-GANG JI

with website

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Hydrodynamics and Water Quality

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Hydrodynamics and
Water Quality

In memory of Dr. John M. Hamrick for his important contributions to the modeling of surface waters.

Preface to the Second Edition

The first edition of this book was successful and well received by the environmental and water resources community. It is extremely gratifying to see that both the English edition and the Chinese edition have become an essential reference for practicing engineers, scientists, and water resource managers, as well as an excellent text for advanced undergraduate and graduate students in engineering and environmental sciences.

As mentioned by Singh (2009) while reviewing the first edition: "On the whole, the topics are well organized, the prose is easy to read and understand, the style is lucid, and there is a wealth of information reflecting the knowledge and experience of the author. The book will also be useful to practicing water and environmental engineers." The same strategy and style have been continued and strengthened in the second edition.

Multidisciplinary modeling has increased dramatically in the past decade, so is the need for an intergraded coverage of these disciplines. The increase in computer power, involving the use of parallel computing, has made it possible to run comprehensive hydrodynamic and water quality models time and cost effectively. The objective of this book is to present an integrated coverage of hydrodynamics, sediment processes, toxic fate and transport, and water quality and eutrophication in surface waters, including rivers, lakes, estuaries, coastal waters, and wetlands.

This book is about processes and modeling these processes. It is not about models. Detailed discussions on models are referred to their manuals and reports and are minimized in this book. The theories, processes, and modeling of these processes presented in this book are generally applicable to numerical models, not just a particular model. This book illustrates the principles, basic processes, mathematical descriptions, and practical applications associated with surface waters. Instead of trying to give detailed coverage of every aspect of surface water processes and their mathematical descriptions, this book focuses on solving practical problems in surface waters.

In the 8 years since the first edition was published, I have received numerous comments from readers on the book and suggestions on how it could be improved. I have also built up a large amount of new materials based on my own experience in research and teaching. With the aid of all this information, I have made the changes and additions in the second edition. All chapters have been revised and updated with works published in the recent years. Compared with the first edition, the second edition has contents increased by more than 40%, including more than 120 new/updated figures and nearly 450 new references. More specifically, the second edition adds the following:

1) A new chapter on wetlands. This chapter focuses on shallow water processes in wetlands and the simulation of these processes with surface water models.
2) A new chapter on risk analysis. This chapter is devoted to two essential and interrelated topics: extreme value theory and environmental risk analysis.
3) A new section on the impact of wind waves on sediment transport.
4) A new section on the mathematical representation and multi-year modeling of submerged aquatic vegetation.
5) A new section on the long-term variation and simulation of pollutants in a lake.
6) A new section on the water quality modeling of a shallow estuary.
7) A new appendix on the EFDC_Explorer, which is a Windows-based graphic user interface (GUI) for pre and postprocessing of the Environmental Fluid Dynamics Code (EFDC).
8) A new website for the book (www.wiley.com/go/ji/hydrodymanics_water_quality). It includes sample applications that are discussed extensively in this book, including their source codes, executable codes, input files, output files, and some results in animations. These applications illustrate the modeling of a channel, a river, an estuary, and a lake, respectively. The website also contains model manuals, reports, technical notes, and utility programs.

I would like to thank all those who showed a steady, extraordinary interest in this book. They gave me the motivation, courage, and opportunity to undertake the challenge of a new edition. The book has also benefited from my teaching at the Catholic University of America and inputs from my students. Jianping Li and his team translated the first edition into Chinese and gave insightful comments on how to improve the book. Working with the Wiley staff was once again a pleasure. I thank, in particular, my editors, Bob Esposito and Vishnu Narayanan.

September 2016
Fairfax, Virginia

Zhen-Gang Ji

Reference

Singh, V.P. (2009) Review of hydrodynamics and water quality: modeling rivers, lakes, and estuaries by Zhen-Gang Ji: Wiley Interscience, John Wiley & Sons, Inc., 111 Rivers Street, Hoboken, NJ 07030; 2008; 676 pp. ISBN: 978-0-470-13543-3. *Journal of Hydrologic Engineering*, **14** (8), 892–893.

Foreword to the First Edition

The management of surface water resources is essential for human and ecosystem health and social and economic growth and development. Water resources professionals use a wide range of technical management tools firmly based on the physical, biological, mathematical, and social sciences. This work addresses the fundamental physical and biological processes in surface water systems that provide the basis for both deeper understanding and management decision making. The complexity of the natural surface water environment combined with the ever-increasing capabilities of computers to simulate the temporal evolution of systems represented by differential equations has made hydrodynamic and water quality models essential tools for both science and management. Although the present work discusses modeling and presents case studies involving model applications, the author has appropriately chosen to emphasize processes and their commonality and differences between different surface waterbody types.

This book is organized as follows: An introductory chapter precedes four chapters on fundamental hydrodynamic and water quality processes, followed by two chapters that discuss modeling in the context of regulatory programs and model credibility and performance. The book concludes with three chapters on rivers, lakes, and coastal waterbodies. The overarching emphasis of the presentation is the interaction of hydrodynamic and water quality or physical and biogeochemical processes. Chapter 2 presents the fundamentals of surface water hydrodynamics in the context of the three-dimensional (3D), Reynolds-averaged, hydrostatic, or primitive equations of motions, as well as related dimensionally reduced formulations including the shallow-water and St Venant equations. The understanding of and ability to predict surface water hydrodynamics is important in its own right, addressing topics including riverine floods, water supply reservoir operations, coastal surges, and estuarine salinity intrusion. It readily follows that the physical transport and fate of dissolved and suspended materials is governed by hydrodynamic advection and turbulent diffusion. The term "water quality" is used in two general contexts in this book as well as in current professional practice. The most general context includes the presence and behavior of dissolved and suspended materials in amounts undesirable for human and ecosystem health, as well as agricultural and industrial use. The more limited historical context, often referred to as "conventional water quality," addresses pathogenic organisms and dissolved oxygen dynamics including eutrophication and aquatic carbon, nitrogen, and phosphorous cycles.

The remaining three process-oriented chapters address three broad water quality categories: sediment transport, toxic contaminants, and eutrophication. Sediment transport, which is also important in water supply and navigation, has important water quality implications related to water clarity, habitat suitability, and its ability to transport adsorbed materials. The chapter on toxic contaminants provides an overview of the transport and fate of heavy metals and hydrophobic organic compounds, both of which adsorb to inorganic and organic sediments. The final process chapter presents the traditional water quality or water column eutrophication process formulations, as well as the associated remineralization or diagenesis of settled organic material. The presentation of process formulations in these four chapters is complemented by the inclusion of illustrative results from actual studies.

Many scientific and engineering studies of surface water systems are in response to regulatory requirements directed at protecting human and aquatic ecosystem health. In the United States, the major regulatory programs include the National Point Discharge Elimination System (NPDES), total maximum daily load (TMDL), and Superfund Remedial Investigation/Feasibility Study (RI/FS). Chapter 6 provides an overview of the role of hydrodynamic and water quality modeling in TMDL development, which leads to the following chapter on model performance evaluation.

The use of models for decision making requires the establishment of the model's scientific credibility using accepted quantitative methods, which are outlined in Chapter 7. The book concludes by focusing on specific aspects of three major groups of surface water systems: streams and rivers, lakes and reservoirs, and estuaries and coastal regions. Many of the example case studies are based on the author's professional experience. These case studies, as well as those integrated into earlier chapters, provide excellent guidance in the organization and execution of hydrodynamic and water quality studies.

In *Hydrodynamics and Water Quality*, Dr Ji has produced a work that should be an essential reference for practicing engineers, scientists, and water resource managers, as well as a text for advanced undergraduates and graduate students in engineering and environmental sciences. The author has brought extensive professional experience and insight to the field, and it has been my pleasure to have worked and collaborated with him over the past decade.

Tetra Tech, Inc. *John M. Hamrick*
Fairfax, VA

Preface to the First Edition

The objective of this book is to present an integrated coverage of hydrodynamics, sediment processes, toxic fate and transport, and water quality and eutrophication in surface waters, including rivers, lakes, estuaries, and coastal waters. The book is intended to serve as a reference book for graduate students and practicing professionals with interest in surface water processes and modeling. Mathematical modeling of surface waters has made great progress in past decades and has become a powerful tool for environmental and water resources management. There are growing needs for integrated, scientifically sound approaches that identify surface water problems and simulate these waterbodies numerically.

This book illustrates principles, basic processes, mathematical descriptions, and practical applications associated with surface waters. Instead of trying to give detailed coverage of every aspect of hydrodynamics, sediment transport, toxics, and eutrophication processes, this book focuses on solving practical problems in rivers, lakes, estuaries, and coastal waters. After Chapter 1 (Introduction), each of the next five chapters (2–6) is devoted to one basic and important topic: hydrodynamics, sediment transport, pathogens and toxics, water quality and eutrophication, and external sources and total daily maximum load (TMDL), respectively. Chapter 7 provides general discussions on mathematical modeling and statistical analysis. Based on the theories and processes presented in Chapters 2–7, rivers, lakes, and estuaries and coastal waters are discussed in Chapters 8, 9, and 10, respectively. Each chapter (after Chapter 1) is organized as follows: it begins with an introduction of basic concepts, proceeds to discussions of physical, chemical, and/or biological processes and their mathematical representations, and concludes with case studies. Organizing the book in this application-oriented approach allows readers to easily locate information that is needed for their studies and to focus on the relevant chapters/sections.

Most of the theories and technical approaches presented in the book have been implemented in mathematical models and applied to solve practical problems. Throughout the book, case studies are presented to demonstrate (1) how the basic theories and technical approaches are implemented into models, and (2) how these models are applied to solving practical environmental/water resources problems. These examples and cases studies are based on either simplified analytical solutions or my professional practice.

A memorable quote from the James Bond movie *From Russia with Love* is that "training is useful, but there is no substitute for experience," which is directly applicable to the modeling of rivers, lakes, and estuaries. Experience is a key element of modeling and is also one of the primary reasons why modeling is often called an "art." The case studies described in detail throughout the book exemplify this premise. A slightly modified version of this quote also perfectly describes the relationship between modeling and field sampling: *modeling is useful, but there is no substitute for field sampling*. Law ordains that a person is innocent until proven guilty. A numerical model (and its results), in my opinion, is guilty until proven innocent by data. This highlights the importance of calibrating models against measured data.

This book is about processes and modeling these processes. It is not about models. Detailed discussions on models are referred to their manuals and reports and are minimized in this book. The theories, processes, and modeling of these processes presented in this book are generally applicable to numerical models, not just a particular model. It is my intention to make the book unique in three ways:

1. This book will cover state-of-the-art hydrodynamics, sediment transport, toxics fate and transport, and water quality in surface waters in one comprehensive text. In the past 10 years, environmental engineering, water resources engineering, and computer engineering have changed dramatically, especially with respect to progress in mathematical models and computer technology. Comprehensive mathematical models are now routinely used in solving practical engineering problems. This book provides essential and updated information.

2. Instead of trying to cover every detail of hydrodynamics, sediment transport, toxics, and water quality, this book will focus on how to solve practical problems in surface waters. Basic theories and technical approaches are presented, so that mathematical models can be understood and applied to simulate processes in surface waters. From the book, readers will not only understand basic principles but also learn how to use the models/tools to solve their problems in professional practice. Information is presented only on a need-to-know basis. For example, tides, salinity, and open boundary conditions are not discussed until Chapter 10, where estuaries and coastal waters are covered, since these topics are more likely to be relevant in the modeling of estuaries rather than of rivers or lakes.
3. A modeling package on a CD, including electronic files of numerical models, case studies, and model results, is attached to the book. Relevant user manuals and technical reports are also available. This becomes helpful when a reader plans to use the models and tools described in the book to solve practical problems in surface waters. The input files of the case studies described in the book can also serve as templates for new studies.

June 15, 2007
Fairfax, Virginia

Acknowledgments for the First Edition

Many people have contributed to this book over the years that it has taken to write. My former and present colleagues provided great support and encouragement in my professional career and while I was drafting the manuscript, including Robert LaBelle, James Kendall, and Walter Johnson of Minerals Management Service; James Pagenkopf and Leslie Shoemaker of Tetra Tech; Alan Blumberg of HydroQual; and George Mellor of Princeton University. Professor Cesar Mendoza, my former advisor at Columbia University, helped me in revising the manuscript. Professor Ji-Ping Chao of National Marine Environmental Forecast Center, China, guided me through my early years of scientific research.

I would like to thank the colleagues and friends who took time from their work to review the chapters of this book. Their comments and advice added to the usefulness of the book. I would like to acknowledge their thoughtful reviews of the manuscript and discussions over the years with them. I am most grateful to Yi Chao (Jet Propulsion Laboratory), Sayedul Choudhury (George Mason University), Tal Ezer (Old Dominion University), Weixing Guo (Schlumberger Water Services), Earl Hayter (US Environmental Protection Agency), Michio Kumagai (Lake Biwa Environmental Research Institute, Japan), Chunyan Li (Louisiana State University), Cesar Mendoza (University of Missouri-Rolla), Leo Oey (Princeton University), Kyeong Park (University of South Alabama), Jian Shen (Virginia Institute of Marine Science), Andy Stoddard (Dynamic Solutions), Dong-Ping Wang (State University of New York at Stony Brook), Tim Wool (US Environmental Protection Agency), Yan Xue (National Oceanic and Atmospheric Administration), Zhaoqing Yang (Battelle Marine Sciences Laboratory), Kirk Ziegler (Quantitative Environmental Analysis), and Rui Zou (Tetra Tech).

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Abbreviations

ADCP	acoustic Doppler current profiler
AOCR	dissolved oxygen/carbon ratio
Bbbl	billion barrels
bbl	barrels
BC	boundary condition
BOEM	Bureau of Ocean Energy Management
BRI	Blackstone River Initiative
BS	boundary segment
CBOD	carbonaceous biochemical oxygen demand
CDOG	Clarkson Deepwater Oil & Gas
CDF	cumulative distribution function
CERP	Comprehensive Everglades Restoration Program
cfs	cubic feet per second
Chl *a*	chlorophyll *a*
cms	cubic meters per second
C.L.	confidence limit
COD	chemical oxygen demand
CSOD	carbonaceous sediment oxygen demand
CWA	Federal Clean Water Act
1D, 2D, 3D	one-, two-, three-dimensional
DA	drainage area
DIN	dissolved inorganic nitrogen
DDT	dichlorodiphenyltrichloroethane
DIP	dissolved inorganic phosphorus
DM	dissolved matter
DMR	discharge monitoring reports
DO	dissolved oxygen
DOC	dissolved organic carbon
DON	dissolved organic nitrogen
DOP	dissolved organic phosphorus
DWH	Deepwater Horizon oil spill
ECMWF	European Center for Medium Range Weather Forecasting
E. coli	*Escherichia coli*
ECOM	Estuarine, Coastal, and Ocean Model
EFDC	Environmental Fluid Dynamics Code
EIS	environmental impact statement
EOF	empirical orthogonal function
EPA	US Environmental Protection Agency
ERA	environmental resource area
ET	evapotranspiration
EVT	extreme value theory
FDEP	Florida Department of Environmental Protection
Fcb	fecal coliform bacteria
FFT	fast Fourier transform
FPIP	fraction of predated phosphorous produced as inorganic phosphorus
GEV	generalized extreme value
GLS	grouped land segment
GOM	Gulf of Mexico
GPD	generalized Pareto distribution
GUI	graphic user interface
GPC	Game and Parks Commission
HSPF	Hydrologic Simulation Program-FORTRAN
iid	independently and identically distributed
IPCC	Intergovernmental Panel on Climate Change
IRL	Indian River Lagoon
LA	local allocations
LHS	left-hand side
LOEM	Lake Okeechobee Environmental Model
LNG	liquefied natural gas
LPOC	labile particulate organic carbon
LPON	labile particulate organic nitrogen
LPOP	labile particulate organic phosphorus
LS	land segment
MAE	mean absolute error
Mbbl	thousand barrels
ME	mean error
ML	maximum likelihood
MMbbl	million barrels
MOS	margin of safety
MPN	most probable number
MRRE	mean relative RMS error
MSL	mean sea level
N	nitrogen
NBOD	nitrogenous biochemical oxygen demand
NDEQ	Nebraska Department of Environmental Quality
NH_4	ammonia nitrogen
Nit	nitrification rate

NO_3	nitrate nitrogen
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
OBC	open boundary conditions
OCS	Outer Continental Shelf
ON	organic nitrogen
OP	organic phosphorus
OSCAR	oil spill contingency and response
OSRA	oil spill risk analysis
P	phosphorus
PAH	polycyclic aromatic hydrocarbons
PBAPS	Peach Bottom Atomic Power Station
PC	personal computer; principal component
PCB	polychlorinated biphenyls
PCS	Permit Compliance System
PDF	probability density function
pH	power of hydrogen
PM	particulate matter
PO_4p	particulate phosphate
PO_4d	dissolved phosphate
PO_4t	total phosphorus
POM	Princeton Ocean Model
PON	particulate organic nitrogen
POT	peaks-over-threshold
PP	probability–probability
ppb	parts per billion
ppt	parts per thousand
PROFS	Princeton Regional Ocean Forecast System
QQ	quantile–quantile
RAE	relative absolute error
RHS	right-hand side
RMS	root-mean-square
RMSE	RMS error
ROMS	Regional Ocean Modeling System
RPD	rooted plant shoot detritus
RPE	rooted plant epiphyte
RPOC	refractory particulate organic carbon
RPON	refractory particulate organic nitrogen
RPOP	refractory particulate organic phosphorus
RPR	rooted plant root
RPS	rooted plant shoot
RRE	relative RMS error
SA	available silica; surface area
SAV	submerged aquatic vegetation
SFWMD	South Florida Water Management District
SG	specific gravity
SLE	St. Lucie Estuary
SMB	Sverdrup, Munk, and Bretschneider
SRP	soluble reactive phosphorus
SSC	suspended sediment concentration
SU	particulate biogenic silica
SWAN	Simulation WAve Nearshore
T	transpiration
TAM	total active metal
TDS	total dissolved solids
TKN	total Kjeldahl nitrogen
TMDL	total maximum daily load
TOC	total organic chemicals
TP	total phosphorus
TS	transpiration stream
TSS	total suspended solids
UBWPAD	Upper Blackstone Water Pollution Abatement District
USACE	US Army Corps of Engineers
USGS	US Geological Survey
WLA	waste load allocations