COASTAL HYDROGEOLOGY

Water resources are of enormous societal and ecological importance. In coastal areas, they are under ever greater pressure due to population growth, more affluent lifestyles, food production and the growing tourism industry. Changes to the coastal landscape, through urbanisation and land reclamation, and by natural processes such as climate change and sea level rise, modify the interaction between seawater and groundwater and put water resources at risk. This comprehensive volume covers both theory and practice of coastal hydrogeology. It discusses hydrochemistry; submarine groundwater discharge; groundwater management; palaeo-hydrology; land reclamation; climate change and sea level rise; and mathematical models of variable-density flow. With its up-to-date coverage and numerous case studies that illustrate practical implications, it is perfect for students, practitioners, managers and researchers who wish to develop an in-depth understanding of topics relevant to sustainably managing coastal groundwater resources.

JIMMY JIAO is a professor of hydrogeology in the Department of Earth Sciences at the University of Hong Kong and has more than 20 years of teaching and research experience in various topics in coastal hydrogeology. He was the 2011 recipient of the John Hem Excellence in Science and Engineering Award from the National Groundwater Association. Dr Jiao is a Fellow of the Geological Society of London, the Geological Society of America and the American Society of Civil Engineers. He has provided consultancy services to industry and government organisations regarding various coastal groundwater issues. Dr Jiao was an Associate Editor (2004–2008) and Editor (2008–2015) of the *Hydrogeology Journal* and Associate Editor (2002–2008) for *Groundwater*.

VINCENT POST has nearly 20 years of professional experience in coastal hydrogeology. He completed his PhD on groundwater salinisation in the Netherlands and has worked on projects in coastal zones around the world, including Portugal, Kiribati and Australia. His expertise spans a broad range of topics, which include numerical modelling, hydrochemistry, measurement techniques and freshwater resource management. Dr Post has published extensively on coastal groundwater flow and chemical processes. He was an Editor of the *Hydrogeology Journal* (from 2010 to 2015) and is an Associate Editor for the *Journal of Hydrology*. He is also actively involved in the organisation of the Salt Water Intrusion Meeting series that saw its fiftieth anniversary in 2018.

"This book presents a systematic and comprehensive approach to understanding coastal groundwater and gives readers a balanced examination of almost all important facets of coastal hydrogeology, ranging from palaeo groundwater issues in the recent geological past to future behaviour of coastal aquifers in response to climate change and sea level rise. Numerous international case studies from coastal aquifers cultivate reader understanding of the occurrence, movement and hydrochemistry of coastal groundwater in a variety of geologic settings. I am delighted to have this excellent book on my shelf and believe it will become a classic. I have no hesitation in recommending it as a "must use" book to all those who work in any aspect of groundwater in the coastal environment."

John Cherry, University of Guelph

"The reader of Jiao and Post's book will find excellent chapters from the principles of hydrology and hydrodynamics to highly practical issues of coastal hydrogeology, complementary to the genetic knowledge of aquifers. The book provides the knowledge and background necessary for all researchers, engineers and practitioners dealing with coastal issues, including groundwater resources, land use, environmental values and ecological services."

Emilio Custodio, Polytechnic University of Catalonia, Barcelona

"At last – a readable and comprehensive compilation of the principles, analytical solutions and literature relevant to coastal groundwater. Jiao and Post have done an incredible job of summarising and discussing the diverse and voluminous literature on coastal hydrogeology in a highly readable book. Basic principles such as equivalent freshwater head and Darcy's law in variable density flow are clearly explained and illustrated. Topics covered range from salt water intrusion, submarine groundwater discharge, tidal dynamics and geochemistry to land reclamation, sea level change and relict (palaeo) salt water in coastal aquifers, with interesting historical insights included throughout. A final chapter pulls together many of the concepts in a discussion of coastal aquifer management and seawater intrusion control. This book is essential for anyone interested in groundwater in coastal areas."

Mary P. Anderson, University of Wisconsin-Madison

"Coastal groundwater presents unique challenges to hydrogeologists, both in its vulnerable position squeezed between land and sea and in the physical and chemical complexities created by variations in density, sources of contamination and characteristic coastal forcings. As pressures on coastal water resources rise with increasing demand, changes in climate and sea-level rise, careful management of coastal groundwater is a greater priority than ever. This book is a timely contribution that provides both a broad overview and a thorough dive into fundamental and emerging topics in the field. With a mix of theory and application, this will be a valuable resource for researchers, practitioners and managers looking to address the coastal water challenges of the coming decades."

Holly Michael, University of Delaware

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The highest goodness is like water. Water benefits all things and does not compete. It stays in the lowly places which others despise. Therefore it is near The Eternal.

Laozi (1368–1644)

It will not be a case of a check returned with 'No Funds' written across it, but a case of drawing undrinkable water from our faucets.
It behooves us, then, to keep our expenditure within our income, to draw no more water from the artesian system than nature puts into it.

Palmer (1927)

Contents

Foreword

Most of the global population now lives in coastal areas that include megacities such as Los Angeles, New York, Tokyo, Jakarta, Shenzhen, Hong Kong, Shanghai, Singapore and many more. Important groundwater-related problems occur nearly everywhere around the globe, and coastal areas are no exception. The increasing concentration of human settlements in coastal regions, associated with expanding agricultural, industrial and urbanisation activities, places great stress on the water resources, resulting in seawater intrusion and related degradation of water quality. Human activities along coasts, such as land reclamation, and natural factors, such as sea level rise driven by climate change, also modify the natural coastal groundwater flow system and the interaction between seawater and groundwater. The pressure on coastal groundwater can only become more severe.

As a result of investigations of theoretical and practical problems related to coastal groundwater, much new knowledge has been gathered, and advanced technologies have been developed for coastal groundwater investigations. Coastal hydrogeology is an emerging science encompassing the theory and practice of groundwater in the context of issues such as variable-density flow, tidal fluctuations, mixing between freshwater and seawater, submarine groundwater discharge, land reclamation and climate change.

This book *Coastal Hydrogeology* is needed as an assemblage of these advancements for informing local communities, the technical professions and the water supply industry, as well as government regulators and policy makers. The book is a timely response to the academic developments and is much needed for students, engineers, scientists, environmentalists and coastal managers.

Coastal hydrogeology has not been extensively covered in previous textbooks or monographies. Commonly, coverage has been focused mostly on seawater intrusion. This first book focused entirely on coastal hydrogeology is a welcome contribution to groundwater science. It has been prepared by two hydrogeologists who have been working for more than 20 years exclusively and extensively on coastal groundwater environments in the Asia-Pacific and Europe. Both authors have served as editors of the *Hydrogeology Journal* and so are well aware of hydrogeological problems in coastal areas around the world. Many groundwater problems and issues that occur inland also exist in coastal areas, where they

take on different shades of complexity commensurate with the highly dynamic physical and chemical interactions between seawater and groundwater and the vulnerability of coastal areas to sea level rise driven by global warming.

Most of the chapters in this book are based primarily on the authors' own research, but they show awareness of what is important in the literature. Between the two, the authors read literature in five languages. This book covers new topics that have emerged over the past two decades but were omitted from or covered only lightly in other books. Chapters contributing most to the uniqueness of this book include Chapter 4, 'Groundwater Tidal Dynamics'; Chapter 7, 'Submarine Groundwater Discharge'; Chapter 8, 'Coastal Palaeo-Hydrogeology'; Chapter 9, 'Impact of Land Reclamation on Coastal Groundwater Systems'; Chapter 10, 'Sea Level Change and Coastal Aquifers'; and Chapter 11, 'Tide-Induced Airflow in Unsaturated Zones'.

This book also covers classic topics related to coastal aquifers, such as seawater intrusion, hydrogeochemistry and aquifer management with most recent research findings and insights from the authors and other researchers. Both authors have an interest in the history of hydrogeology, and so a number of chapters have notes to position scientific advances within the historical context, which makes for even more interesting reading.

As the expanding field of coastal hydrogeology attracts more students, researchers, coastal engineers and water resources administrators, all will benefit from this book. With the subject of coastal hydrogeology becoming more relevant, interactions between coastal hydrologists and other professionals, such as marine scientists, environmental engineers and water managers, will expand. There will be more demand for training in coastal hydrogeology by consulting organisations, state and federal regulatory agencies, and industrial firms. I believe that teachers, students, researchers and practitioners concerned with coastal water issues will find this book to be informative, instructive, useful and timely.

John Cherry
Director, University Consortium
Adjunct Professor, University of Guelph
Distinguished Professor Emeritus, University of Waterloo
13 November 2018

Preface

We live in a time that is unprecedented in our planet's 4.5 billion year history as humans are transforming the natural environment everywhere on Earth. While the number of people continues to grow, so does their impact on the landscape as well as the rate at which changes are occurring. Among the most affected areas are coastal zones, not only because these are among the most densely populated parts of the world but also because they are among the first to bear the brunt of climate change and sea level rise.

This book brings together the available science about the subsurface part of the hydrological cycle in coastal zones. Coastal aquifers have unique issues compared to other aquifers. A particular problem is that of water supply, as subsurface water resources near the sea are more susceptible to salinisation than those in inland regions. Water levels are influenced by tides, which, as this book will show, can have important engineering implications. Moreover, the simultaneous occurrence of fresh- and saltwater in coastal aquifers leads to complex flow dynamics, as well as water quality changes. Only with comprehensive, science-based understanding of these processes can water and natural resources in coastal areas be managed sustainably.

The book's title, *Coastal Hydrogeology*, is also the name of the scientific specialisation that deals with aquifer systems that are under the influence of the sea, and where variable-density flow and tidal effects influence groundwater flow patterns. This specialist area of hydrogeology became established at the start of the twentieth century and has come of age since. It is a dynamic research field, as new discoveries are being made that shape our understanding of the functioning of coastal groundwater systems. A prominent example is the topic of subsurface discharge pathways to the oceans, which has seen a leap in research activity over the past two decades since it became apparent that large quantities of land-derived nutrients and other chemical substances can be delivered to the marine environment via groundwater. This growing interest is part of a broader appreciation of the importance of the connection between onshore and offshore aquifer systems more generally, which has remained understudied to date due to a scarcity of observational data.

Societal change also provides an impetus for coastal hydrogeology research. As coastal cities are expanding, more and more land is being reclaimed, giving rise to a suite of specific groundwater problems. Also, a growing proportion of the rising water demand is nowadays being met by desalination, often using groundwater as the source. The economic value of brackish and saline groundwater, previously considered uninteresting as a resource, is thus

increasing. These developments require new and better knowledge of the consequences for coastal groundwater resources and the corollary effects of human activities on ecosystems.

One reason for writing this book was to provide the state of the art of the theory and practice in coastal hydrogeology. Another motivation for writing the book was to cover all the important aspects of coastal hydrogeology. The book's focus is therefore not restricted to seawater intrusion research; it also aims to complement other works by including subjects like land reclamation effects, tidal airflow, palaeo-hydrology and offshore groundwater reserves. No book to date has covered these topics extensively within the context of coastal groundwater research, yet they are important, as they have direct relevance to coastal zone management.

This book is aimed at students, academics, engineers and managers who wish to develop an in-depth understanding of various topics relevant to sustainably managing coastal groundwater resources. It discusses a wide variety of topics, including mathematical models, hydrochemistry, submarine groundwater discharge, coastal aquifer management, palaeo-hydrology, land reclamation and of course climate change and sea level rise. It is assumed that the reader has a basic knowledge of groundwater hydrology and is familiar with the elementary principles of geology, mathematics, physics and chemistry. Its intended use for students is therefore mainly at the graduate level. The book is also a resource for researchers and engineers working on groundwater-related issues in coastal areas. It serves as an access point to the scientific literature, as it provides ample references to other works to help the reader find additional information.

The research in the field of coastal hydrogeology is evolving quickly, and a problem we faced as authors was the vast number of journal articles and other scientific publications that exist. Nowadays, there are so many that it has become impossible to read all of them. Although this necessitated making a selection and, inevitably, leaving out even some good papers, we hope we have done justice to all those who have made important contributions to the science and practice of coastal hydrogeology. We are sorry if you miss your work in this book.

Numerous people have provided valuable contributions to this book. We would first of all like to thank our international colleagues who have reviewed one or more chapters of the book: Maike Gröschke, Yoseph Yechieli, Jacobus Groen, Romain Chesnaux, Maria Pool, Georg Houben, Gu Oude Essink, Willard Moore, Hailong Li and Xingxing Kuang. Their reviews have led to substantial improvements. We are very grateful to Xin Luo and Yi Liu, who drew most of the figures, which has considerably increased the clarity of the scientific message. We would like to acknowledge Jaouher Kerrou, Philippe Renard, Holly Michael, Xuan Yu, Pieter Stuyfzand, Ya Wang, Haipeng Guo, Elad Levanon and Antonio Bosch, who provided data or helped us reproduce figures from their work, as well as Atsushi Kawachi for locating the hard-to-find papers by Nomitsu et al. (1927) and Toyohara (1935). We are grateful to Zoë Pruce and Matt Lloyd at Cambridge University Press for their support during this long project.

It seems that no scientific textbook can be written without the authors sacrificing precious time together with family and friends. We are forever indebted to Tong Chen, Bilin Jiao, Bikun Jiao and Francis Boogaerdt for their understanding, support and, above all, patience.

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