长江河口盐水入侵

沈焕庭 茅志昌 朱建荣 著

海洋出版社

长江河口盐水入侵

沈焕庭　茅志昌　朱建荣　著

海洋出版社

2003年·北京

内 容 简 介

本专著系作者20多年来对长江河口盐水入侵及其对重大工程响应研究的系统总结。全书共分8章。主要内容为：绪论，影响长江河口盐水入侵的因素，长江河口盐淡水混合类型及时空变化，口外海滨高盐水特征及盐度的时空变化，河口段盐水入侵的来源及盐度的时空变化，南水北调，三峡水库等重大工程对河口盐水入侵影响预测，长江河口盐水入侵预测的统计模型和数值模型。

本书可供水资源、水利、环境、地理、港口航道等学科的科技工作者、大专院校师生及政府有关部门的工作人员阅读参考。

图书在版编目(CIP)数据

长江河口盐水入侵/沈焕庭等著. —北京：海洋出版社，2003.10

ISBN 7-5027-5974-3

Ⅰ.长… Ⅱ.沈… Ⅲ.长江—河口—盐水入侵—研究 Ⅳ.TV882.2

中国版本图书馆CIP数据核字(2003)第088992号

责任编辑：陈茂廷

责任印制：刘志恒

海洋出版社 出版发行

http://www.oceanpress.com.cn

(100081 北京市海淀区大慧寺路8号)

北京海洋印刷厂印刷 新华书店发行所经销

2003年10月第1版 2003年10月北京第1次印刷

开本：787×1092 1/16 印张：12.75

字数：301千字 印数：1～1000册

定价：40.00元

海洋版图书印、装错误可随时退换

序

径流带来的淡水通过河口向海扩散，高盐的海水向河口入侵，由此产生的盐淡水混合是河口特有的自然现象，也是河口区的本质属性。它对河口的物理、生物地球化学过程以及淡水资源的开发利用有深刻影响，是河口研究中关键的科学问题之一，对它进行研究具有重要的理论和实践意义。

长江河口的径流量大，在丰水期冲淡水向海扩展很远，有时可及济州岛海域，但长江河口的潮流也很强，盐水入侵河口在枯水期也很严重，有时可上溯到南北支分汊口以上水域。盐水入侵对长江河口的环流、最大混浊带和拦门沙等的形成与变化有深刻影响，对上海、江苏的工农业、生活用水以及水产、渔业等也至关重要。特别是近年来，随着我国经济的快速发展，三峡工程、南水北调、河口深水航道等多项重大工程都已在开工建设，这些工程的实施必将对河口环境特别是盐水入侵产生影响。因此，研究长江河口盐水入侵规律及其对重大工程的响应，不仅是深入研究长江河口过程的必需，也将为重大工程建设与河口淡水资源的开发利用提供科学依据。

由沈焕庭教授负责的课题组，自20世纪70年代以来，结合南水北调、三峡工程等重大工程建设，对长江河口的盐水入侵规律及其对工程的响应进行了较全面系统的研究，至今已持续20多年，取得了一系列具有开拓性和创新性的研究成果，其中有的已被有关部门采用，有的以论文形式在国内外发表，本书是对这些基础研究和应用研究成果的系统总结。

纵观全书内容，其研究成果具有两个鲜明特色：(1)国外对河口

盐水入侵也做过很多研究工作，但研究的内容主要集中在盐淡水混合的机制、类型以及盐水楔活动规律等方面，有关工程兴建对盐水入侵的影响研究甚少。而此项研究，除较全面、系统地研究了长江河口盐水入侵的来源及盐度扩展的时空变化规律外，还对南水北调、三峡工程等重大工程对河口盐水入侵可能产生的影响进行了预测，为有关工程的建设提供了重要科学依据；(2)在研究过程中进行了大量的现场观测，积累了丰富的第一手资料，为本项目原创性研究打下了坚实基础。为了从不同侧面更准确地预测盐水入侵及其对工程的响应，在计算方法上进行了很多探索，选用了多种行之有效的数学方法，建立了5个统计模型和2个数值模型，多模型相互补充和印证，取得了较为满意的结果，为进一步开展盐水入侵研究打下了基础和拓展了思路。

冲淡水向海扩散与外海高盐水向河口入侵是一个问题的两个方面。1997年朱建荣教授与沈焕庭教授出版的《长江冲淡水扩展机制》专著，曾将长江冲淡水向外海扩展研究向前推进了一大步。现在由沈焕庭教授负责的课题组，又对20多年来取得的研究成果加以总结，出版《长江河口盐水入侵》专著，把长江河口盐淡水相互作用研究推上了一个新的台阶，是对河口研究的新贡献。值此，我很高兴将这本富原创性的书推荐给大家，相信本书的出版将会进一步推动河口盐水入侵的研究和河口学的发展。

2003年9月

于国家海洋局第二海洋研究所

前　言

河口是盐水与淡水的交汇地带，河口出现的多种物理、化学、生物过程，如河口环流、细颗粒泥沙絮凝沉降、最大浑浊带等都与盐水入侵密切相关，因此，研究河口盐水入侵对全面深入了解河口过程具有重要的理论意义。

河口也是人口密集、经济发达地区，随着工农业生产的迅猛发展和人口的急剧增长，对淡水的需求无论在数量上还是质量上均提出了更高的要求。根据国际国内给水标准，饮用水的氯化物含量一般不能超过250 mg/L，工业用水和农业灌溉用水对氯化物含量也有一定要求。严重的盐水入侵，将影响人民的身体健康和工农业生产。上海的用水现在主要取自黄浦江，但无论从水质或水量上看，均不能满足日益增长的需要。自宝钢水库和陈行水库建成后，长江河口作为上海的第二水源已日益被人们所关注，充分利用长江河口的淡水资源已势在必行。但长江河口在枯水时常发生盐水入侵现象，有时还非常严重，使水质不能满足要求。现在南水北调、三峡水库、河口深水航道等一批大型工程也正在建设，这些工程对长江河口盐水入侵是否会产生影响，若有影响，其影响程度如何等，这些众所关注的问题也需要作科学预测。另外，盐水入侵河口对水产、渔业等也有明显影响。可见，研究长江河口的盐水入侵也具有重要的实际意义。

由本人负责的课题组，根据我国国民经济建设的需求，从20世纪70年代末开始，就对长江河口的盐水入侵规律进行研究，先后承担与此相关的主要研究项目有：中国科学院主持的“南水北调（东线）对生态环境影响研究”中的对长江口盐水入侵影响预测（1978～1979）；“七五”攻关项目“长江三峡工程对生态环境的影响及对策研究”中的对长江河口盐水入侵的影响（1984～1990）；上海市重大项目“长江——上海城市供水第二水源规划方案研究”中的长江河口盐水入侵（1986～1991）；高等学校博士学科点专项科研基金“长江河口径流与盐度

及其相互关系的谱分析"(1993～1995);国家自然科学基金"长江河口盐水入侵规律研究"(1994～1996);上海市建委重点项目"青草沙水库预可行性研究"中的青草沙水源地盐水入侵规律研究(1994～1996);1998 年国家高技术应用部门发展项目"三峡工程对长江口及邻近海域的环境和生态系统的影响"中的对盐水入侵的影响(1999～2000);国家环保局下达的"南水北调对长江口盐水入侵影响"(2000～2001);2001 年度上海市决策咨询研究重大课题"三峡工程与南水北调工程对长江口水环境影响问题研究"(2001);上海市环境保护科学技术发展基金科研项目"上海水源地环境分析与战略选择研究"(2002～2003)等。

通过上述项目研究,对长江河口的盐水入侵进行了大量的现场观测,积累了较丰富的资料,并在此基础上用相合非参数回归、分段线性模型、频谱分析、马尔科夫模型和线性动态模型、人工神经网络模型和二维、三维数值模型等多种方法进行计算和分析,较系统地揭示了长江河口不同汊道盐水入侵的来源、盐淡水混合类型和盐度的时空变化规律,并对三峡工程、南水北调等重大工程对长江口盐水入侵可能产生的影响进行了预测,为有关工程的规划设计提供了重要的科学依据。如:在上世纪 70 年代东线南水北调规划时,有关部门曾提出不会对河口盐水入侵产生影响,通过由本人负责的课题组研究,认为会加重对河口的盐水入侵,并率先提出"控制流量"概念,此研究成果很快被有关部门接受和采纳;上世纪 80 年代承担三峡工程对长江口环境影响研究时,提出三峡工程对长江口盐水入侵有利有弊,利在枯水期流量增加使盐度峰值削减,弊在 10 月流量减少使河口盐水入侵时间提前,总受咸天数增加。此结论被送交全国人大的《长江三峡水利枢纽环境影响报告书》采纳;宝山钢铁厂受由本人负责的课题组提出的长江河口盐水入侵规律的启发,放弃了原先的淀山湖取水方案,经有关单位进一步研究,成功地在长江口边滩上建造了"避咸蓄淡"水库,既节约了巨额投资,又为上海和沿海地区利用河口淡水资源提供了新途径;上世纪 90 年代由本人负责的课题组参与"长江——上海第二水源规划研究",根据长江河口盐水入侵规律提出了近、远期取水方案,为解决浦东开发和整个上海用水提

供了重要依据;本世纪初在接受上海市和国家环保局有关研究任务时,为了既能支持南水北调,又能不加重甚至可减轻长江口的盐水入侵,在多年对长江口盐水入侵规律研究的基础上,提出了综合治理北支削减甚至杜绝北支盐水倒灌南支等对策,受到有关领导和部门的重视,现正在组织进一步论证。

从20世纪70年代末至今的20多年中,由本人负责的课题组对长江河口盐水入侵的研究,几乎没有中断过,取得的研究成果,大部分已被或正在被有关部门或单位采用,部分研究成果也已在国内外有关学术刊物上发表,本书是对上述这些应用研究和基础研究成果的系统总结。如所周知,国外对河口盐水入侵的研究约始于20世纪50年代,研究的内容大都集中在盐淡水混合和盐水楔的活动规律方面,对大型工程对盐水入侵的影响研究甚少。而我们不仅对长江口盐水入侵的来源、盐淡水混合类型以及盐度的时空变化规律进行了较为全面、深入的研究,还对重大工程对盐水入侵的影响以及减轻盐水入侵的对策进行了较为深入的研究,取得的研究成果既有理论意义,又有实用价值。为了更全面地掌握长江河口盐水入侵规律,书中也引用了有关作者的部分研究成果。

全书共分8章:第1章,绪论,主要论述长江河口区的范围及其分段、氯度与盐度的定义及其换算关系、盐水入侵对河口环流、细颗粒泥沙絮凝和对工农业和生活用水的影响,以及国内外河口盐水入侵研究的进展;第2章,影响长江河口盐水入侵的因素,主要阐述径流、潮汐、潮流、口外流系、海平面变化和河口河势演变的特性及其对盐水入侵的影响;第3章,长江河口盐淡水混合类型,主要阐述河口盐淡水混合类型的划分、长江河口各汊道的盐淡水混合类型、盐淡水混合的时空变化及对悬沙沉降和输移的影响;第4章,长江河口口外海滨盐度的时空变化,主要阐述外海高盐水入侵的特征、来源,盐度的空间变化和盐度锋;第5章,河口段盐水入侵的时空变化,主要阐述河口段盐度的周日、半月、季节、年际等时间变化和纵向、横向、垂向等空间变化,以及北支盐水倒灌南支的机理、形式、途径,倒灌盐水对南支和南北港水质的影响;第6章,重大工程对长江口盐水入侵影响预测,主要阐述南水北调和三峡工程对长江河口盐水入侵的影

响;第7章,长江河口盐水入侵预测模型,主要阐述多元回归与相合非参数回归、分段线性模型、频谱分析、马尔科夫模型和线性动态模型、人工神经网络等五种盐水入侵预测模型;第8章,长江河口盐水入侵的数值模拟,主要阐述设想河口环流和盐水入侵的数值试验、北支盐水倒灌的二维数值模拟以及长江河口流场的三维数值模拟。本书第1,2,3,4,6,7章由沈焕庭执笔,第5章由茅志昌执笔,第8章由朱建荣、肖成猷执笔,全书由沈焕庭构思、编写大纲、统稿和定稿。

本书是由本人负责的盐水入侵课题组全体成员多年悉心研究的结晶。除本人外主要成员还有:华东师范大学河口海岸国家重点实验室、河口海岸研究所的茅志昌教授、朱建荣教授、肖成猷副教授、王晓春博士、杨清书博士和胡松硕士;上海市自来水公司的徐彭令高级工程师;华东师范大学数学系的袁震东教授、周纪芗教授、陈树中教授和潘仁良副教授。在本课题研究和本书撰写过程中,曾得到我室、所陈吉余院士、潘定安教授、胡方西教授、李九发教授、胡辉教授、吴加学博士等的关心和帮助,得到原上海市公用事业管理局芮友仁、程济生、俞季兴等领导的大力支持,王佩琴同志为本书精心绘制图件,海洋出版社盖广生社长、陈茂廷等编辑为本书的出版工作付出了辛勤的劳动。出版时还得到上海市"重中之重"学科建设和"211"工程学科建设项目的资助。特别应指出的是中国科学院苏纪兰院士还为本书作序,在此一并表示衷心感谢!

最后应指出的是,河口盐水入侵是一个极为复杂的问题,而长江河口是一个三级分汊、四口入海的大河口,其盐水入侵更为复杂。本书仅是阶段性的研究成果,诸多问题还有待作深入研究。由于经费、条件和水平等多种因素,书中不足甚至错误之处在所难免,有关这方面的研究我们仍在继续进行之中,恳请读者不吝赐教。

沈焕庭

2003年酷暑于华东师范大学丽娃河畔

河口海岸国家重点实验室、河口海岸研究所

Foreword

An estuary is the confluent zone of salt-and fresh-water masses, where saltwater intrusion occurs frequently. Many important estuarine processes are closely connected with the saltwater intrusion, such as estuarine circulation, flocculation settling, maximum turbidity. So the understanding of saltwater intrusion has an important implication for various phenomenon in the estuarine environment.

The region near the estuary is usually densely populated and highly developed. With the rapidly increasing population and economy, more substantive and cleanly freshwaters are required. The main freshwater supply in Shanghai is presently from the Huangpu River, which has not satisfied the ever increasing requirements. After the construction of Baogang and Chengxing Reservoirs, the Changjiang Estuary has become another important freshwater source of Shanghai. So fully exploited freshwater resource in the estuary becomes imperative under the situation. The saltwater intrusion, however, occurs frequently in the dry season, and makes the water quality not meet the requirements of people's usages. Now lots of huge projects are under way in the Changjiang River, such as the South-to-North Water Transfer Project, the Three-Gorge Project, the Deepwater Waterway Regulation project. What and how these projects produce influences on the saltwater intrusion are not yet fully clear. The saltwater intrusion also influences the aquaculture and fisheries near the river mouth.

Since the end of 1970s, a series of research projects supervised by the author have been conducted to deal with the saltwater intrusion in the Changjiang Estuary. Major projects related include: the impact of the South-to-North Water Transfer Project (eastern route) on the saltwater intrusion in the Changjiang Estuary (1978 ~ 1979), the impact of the Three-Gorge Project on ecologies and environments and the countermeasures (1984 ~ 1990), the programming study of the Changjiang River as the second freshwater source for the Shanghai water supply (1986 ~ 1991), the runoff and salinity variation in the Changjiang Estuary and their relationship based on spectral analysis (1993 ~ 1995), the evolution of the saltwater intrusion in the Changjiang Estuary (1994 ~ 1996), the preliminary feasibility of the Qingchaosha Reservoir (1994 ~ 1996), the impact of Three-Gorge Project on the environment and ecosystem in the Changjiang Estuary and adjacent waters (1999 ~ 2000), the impact of the South-to-North Water Transfer project on the saltwater

intrusion in the Changjiang Estuary (2000～2001), the impact of the Three-Gorge project and the South-to-North Water Transfer project on the water environments in the Changjiang Estuary (2001), the environmental analysis and strategic selection of the water sources in Shanghai (2002～2003), etc.

In the above projects, lots of field measurements have been conducted, and various approaches such as harmonic non-parameter regression, subsection linear model, spectral analysis, Markov model and linear dynamic model, artificial neural network, two/three－dimension numerical models, have been used to systematically study the sources of saltwater masses, salt-and fresh-water mixing types and temporal and spatial variability of salinity. The underlying impact of huge projects (i.e., the Three-Gorge Project, the South-to-North Water Transfer Project, etc.) on the saltwater intrusion has been predicted, which provided important scientific supports for the plan and design of the engineering construction. For example, when the plan of the South-to-North Water Transfer Project (eastern route) was made in the 1970s, it was once put forward that the project would not change the degree of saltwater intrusion. But our studies showed that the project would surely aggravate the saltwater intrusion according to a new concept of controlled discharge, as was later accepted by the policymaker. When the study of the impact of the Three-Gorge Project on the environments in the Changjiang Estuary was implemented in the 1980s, the viewpoint was raised that both advantage and disadvantage consist in the influences of the project on saltwater intrusion. On the advantageous side, increasing discharge in the dry season will flat the salinity peak, whereas on the disadvantageous side, the decreasing discharge in October will make the occurrence of the saltwater intrusion ahead of the normal condition and prolong the whole duration affected by the saltwater masses. The above research results have become a part of an important report submitted to the Nationwide People Delegation Plenary Meeting for discussion, entitled by a report on the environmental assessment of the Three-Gorge Hydraulic Engineering. According to our study of the evolution of the saltwater intrusion in the Changjiang Estuary, an original schedule of water supply from the Dianshan Lake to the Baoshan Steel Factory was discarded and was replaced by a reservoir characterized by escaping salt waters and storing fresh waters, which was relocated at the beach of the Changjiang Estuary. The successfully building of the reservoir saved lots of investments and searched a new measure to exploit estuarine freshwater resources in Shanghai and other coastal regions. A short- and long-term water supply schedule was raised in the 1990s in the Plan of the Changjiang Estuary as the Second Water Source, based on the evolution laws of the saltwater intrusion in the estuarine zone. This scheme provided impor-

tant scientific support for solving the water supply problem in the Pudong New Zone and even the whole Shanghai. In order to mitigate, or even stop the negative impact of the saltwater masses from the North Branch on the South Branch, a comprehensive regulation countermeasure in the North Branch was brought forward in the early century.

During the past over 20 years since the end of 1970s, the systematic studies of the saltwater intrusion in the Changjiang Estuary have continually been conducted. Most of the research results have been accepted or adopted by the government departments, part of which was published in various academic journals. In order to comprehensively understand the saltwater intrusion and its application in freshwater exploit, all the above research results have summarized in this book. In the meanwhile, some results published by the other scientists are also cited in this book.

The book is composed of eight chapters. Chapter One is an introductory section. It deals with the scope and subsections in the Changjiang Estuary, definition and conversion of chlorinity and salinity, impact of the saltwater intrusion on water usage and estuarine processes, and the state of the art on saltwater intrusion in estuarine environments. Chapter Two is about the factors on the saltwater intrusion in the Changjiang Estuary. Runoff, tides and tidal currents, offshore current system, sea level change, estuarine evolution and its impact on the saltwater intrusion are discussed in this chapter. Chapter Three concentrates on the mixing in the Changjiang Estuary. It includes classification of mixing in the estuarine waters, mixing types in each sub-channel in the Changjiang Estuary, temporal and spatial variability and its impact on suspended sediment settling and transport. Chapter Four focuses on the spatial and temporal variability of salinity off the Changjiang River mouth. Characteristics and sources of high-salinity water masses, spatial distribution of salinity and salt fronts are discussed. Chapter Five is dealt with spatial and temporal variability of saltwater intrusion at the Changjiang estuarine zone. Temporal variability is examined over daily, fortnightly, seasonal and interannual scales, respectively and spatial variability in longitudinal, lateral and vertical dimension, respectively. In the next section follows the mechanism, modes and pathways of saltwater back-intrusion from the North Branch, and its impact on the water quality in the South Branch and the South and North Channels. Chapter Six is dealt with the impact of huge hydraulic engineerings on the saltwater intrusion in the Changjiang Estuary including the South-to-North Water Transfer Project and the Three-Gorge Project. Chapter Seven details various mathematical models of the saltwater intrusion in the Changjiang Estuary, including multi-regressive analysis and harmonic non-parameter regression, subsection linear model, spectral analysis,

Markov model and linear dynamic model, artificial neural network. Chapter Eight shows the numerical model on the saltwater intrusion in the Changjiang Estuary.

The Chapters 1, 2, 3, 4, 6, 7 are written by Shen Huanting , Chapter 5 by Mao Zichang , and Chapter 8 by Zhu Jianrong and Xiao Chengyou . The design, outline compilation, manuscript finalization are done by Shen Huanting. The book can eventually come out, owing to multi-years of studies of the saltwater intrusion in the Changjiang Estuary by the group of the author. Main members on this issue include: Professor Mao Zichang, Professor Zhu Jianrong, Associate Professor Xiao Chengyou, Dr. Wang Xiaochun, Dr. Yang Qingshu, and Hu Song of State Key Laboratory of Estuarine and Coastal Research, Institute of Estuarine and Coastal Science, East China Normal University; Xu Pengling, Senior Engineer of Shanghai Water Supply Corp.; Professors Yuan Zhendong, Zhou Jixiang, Chen Shuzhong and Associate Professor Pan Renliang of the Mathematics Department of East China Normal University. I am grateful for the assistance and support to the following colleague: Professors Chen Jiyu (an academician of Chinese Academy of Engineering), Pan Ding'an, Hu Fangxi, Li Jiufa, Hu Hui of State Key Laboratory of Estuarine and Coastal Research, Institute of Estuarine and Coastal Science, East China Normal University, and Dr. Wu Jiaxue of the School of Ocean and Earth Science, Tongji University. I am in debt to Rui Youren, Cheng Jisheng, Yu Jixing of the former leaders of the Shanghai Public Utility Administration. Mrs Wang Peiqing drew the figures in the book. I am also thankful to Gai Guangsheng, Proprieter of China Ocean Press (COP) and Chen Maoting, Editor-in-General of COP. The book publication is jointly funded by the Key Subject Construction of Shanghai and Subject Construction of the 211 Project. Special thanks to Professor Su Jilan, an academician of Chinese Academy of Science, for writing a preface of the book.

It should be pointed out herein that the saltwater intrusion in the estuaries is a complex problem, especially for the Changjiang Estuary with three-order branching and four outlets to the East China Sea. The problems raised in the book are partly solved and need to be further studied. The author should be responsible for mistakes or errors in the book and any response will be greatly appreciated.

Shen Huanting
Summer 2003
At the Liwa riverside
State Key Laboratory of Estuarine and Coastal Research
East China Normal University
Shanghai, 200062, P. R. China

目　　次