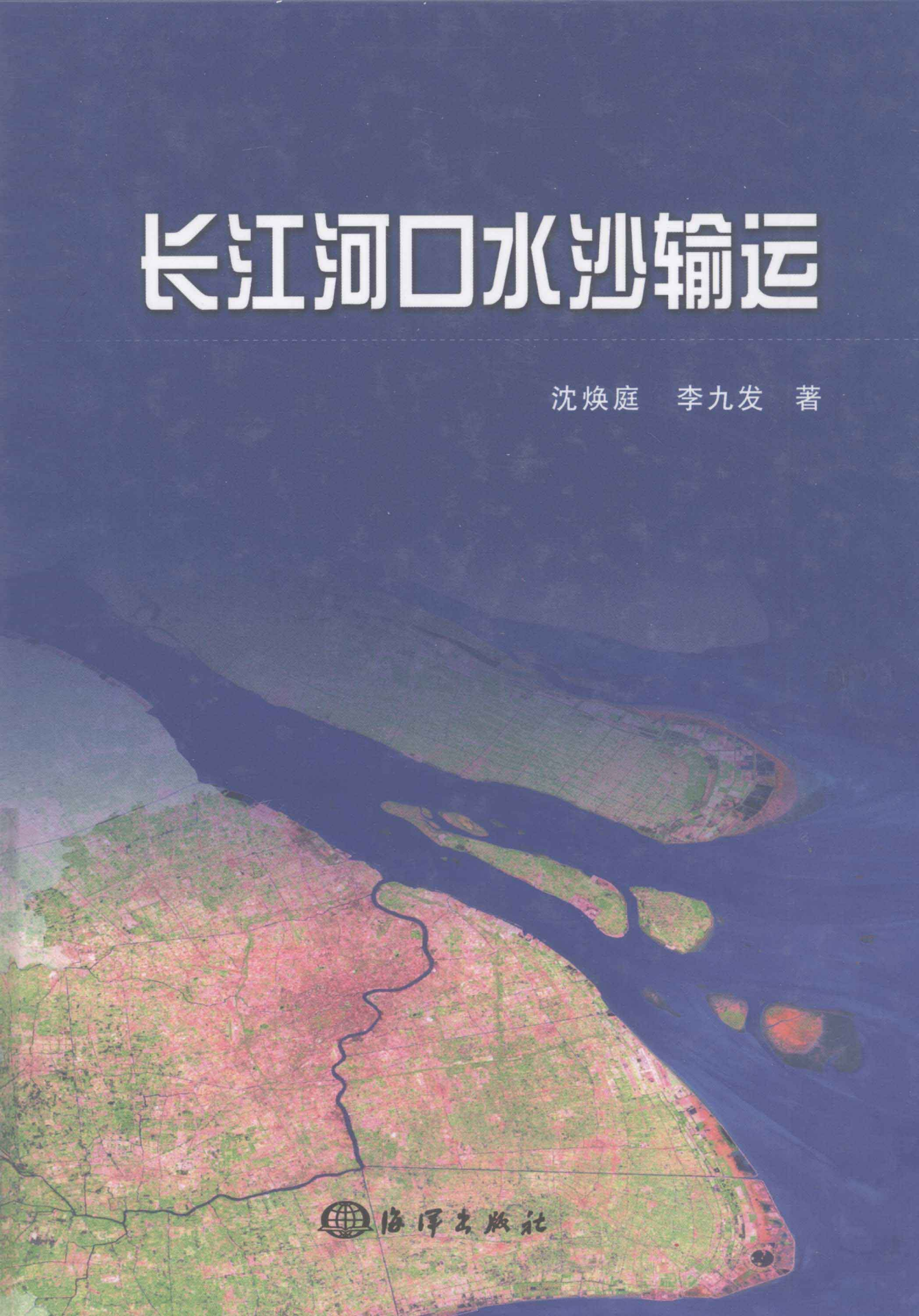
# 长江河口水沙输运

沈焕庭　李九发　著



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## 内容简介

本书系作者多年来对长江河口水沙输运及其对河槽演变影响研究的系统总结。全书共分6章。主要内容为:河口区不同区段的水沙通量,潮汐潮流、余流余环流及其对悬沙输运与对河槽演变的影响,悬沙输运特性和机制,滩与槽、长江口与杭州湾之间的水沙交换,涨潮槽和最大浑浊带的水沙输运,底沙输运。

本书可供水文、泥沙、水利、港口航道、水资源、环境、地理、海洋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。

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# Water and Sediment Transport in the Changjiang Estuary

**Shen Huanting  Li Jiufa**

China Ocean Press
Beijing, 2011

# 前　言

大尺度河流物质输运问题已引起人们越来越多的关注。很多国际项目，如IGBP（国际地圈－生物圈计划）的三个核心计划：BAHC（水文循环中的生物问题）、LOICZ（海岸带陆海相互作用）和PAGES（古全球变化研究）都将河流输送作用作为核心研究工作的一部分。美国陆地边缘生态研究（LMER）和长期生态研究（LTER）已经对陆－水相互作用及其中的各种过程进行全面、长期的定时研究，研究范围一直到海岸带。

长江是我国第一大河，它源于青藏高原，经巴蜀“天府之国”，中渡两湖“鱼米之乡”，下达河口“金三角洲”，形成得天独厚的“黄金水道”，对全国经济的发展起着至关重要的作用。长江水丰沙富，据大通站资料（1950—2006年）统计，入河口区的多年平均流量为28 518 $m^3 \cdot s^{-1}$，年径流量达8 978 $\times 10^8$ $m^3$，在世界大河中仅次于南美的亚马孙河与刚果的扎伊尔河，居第三位；多年平均输沙量达4.1 $\times 10^8$ t，在世界上次于恒河－布拉马普特拉河、黄河和亚马孙河，居第四位。长江巨量水沙下泄及其时空变异不仅影响河口区的河床演变、盐水入侵和生态环境，而且对邻近海域甚至太平洋的温盐特征、流场和沉积过程等也有重要影响。对长江河口水沙输运的研究具有重要的理论意义和实用价值，长期以来一直受到科技界和管理部门的高度关注。

笔者于1957年在华东师范大学地理系毕业留校任教，1960—1962年在山东海洋学院（现中国海洋大学）和中国科学院青岛海洋研究所进修物理海洋学，1962—1965年为华东师范大学海洋水文气象专业讲授《海洋潮汐学》和《海岸动力地貌学》，1969年开始涉足河口研究领域，将地理学与海洋学结合致力于河口海岸研究。根据当时生产建设的需要、自己的知识背景以及陈吉余先生“动力、地貌、沉积相结合”的学术思想，该时期的研究重点是河口动力及其对地貌、沉积的影响。

20世纪70年代初,国家发出“三年改变港口面貌”的号召,作为我国最大港口——上海港咽喉的长江河口通海航道,首期目标是通航水深从6 m增深到7 m,使万吨级海轮可全天候进出,2万吨级海轮能乘潮进出上海港。笔者有幸参加了这一工程的可行性研究工作,根据工程需要,对长江河口的径流、潮汐、潮流、盐淡水混合、余流、余环流及其对泥沙输运及河槽演变的影响进行了较为全面系统的开拓性综合研究,提出了一系列具有创新性的见解,不仅为7 m通海航道的选槽、定线、疏浚、泥土处理和维护等提供了必要的动力依据,也在一定程度上阐明了长江河口发育、演变的动力机理,深化了对长江河口发育规律的认识,为深水航道建设和综合治理规划的制订提供了依据。尔后又结合三峡工程、南水北调、长江口深水航道等重大工程以及JGOFS、LOICZ等一些国际前沿的研究项目对长江河口水沙输运做持续研究,取得的研究成果已被有关工程设计和编制长江综合治理规划时采用,并在此基础上撰写了多篇论文在国内外发表并被广为引用。

合作者李九发教授于1973年在华东师范大学地理系毕业留校任教,1978—1980年先后赴武汉水利电力学院(现武汉大学)和清华大学水利系进修泥沙运动力学,师从国际著名泥沙专家钱宁教授,他将地理学与泥沙运动力学相结合,长期从事河口悬沙、浮泥和底沙运动及河口演变研究,取得了一系列颇有价值的研究成果,已在国内外合作发表论文100余篇。

在对长江河口水沙输运的研究过程中,我们主要做了如下工作:一是亲自策划和参加了数十次现场水文泥沙观测,在长江河口内外水域度过了很多个日日夜夜,其中多次观测,参加了从制订观测计划—准备仪器—摇绞车取样观测—仪器检修—资料整理、计算分析,一直到编写研究报告的全过程,获得了大量亲自取得的第一手资料;二是多次上“涨潮一片汪洋、落潮一片沙滩”的潮间带浅滩观测浅滩水流、微地貌和沉积特征,九段沙、中央沙、扁担沙、瑞丰沙、青草沙和南汇边滩、崇明东滩等都留下了我们的足迹;三是到崇明、长兴、横沙、佘山、鸡骨礁等岛屿和测量船、渔船、挖泥船,访问长期生活和工作在长江口、对长

江口的水文泥沙特性和河床演变有丰富感性认识的船员、海塘工人、航道工人、渔民和部队官兵，从他们那里学到了很多书本上学不到的知识；四是参加可行性研究的有许多资深的老专家，如华东水利学院（现河海大学）原院长严恺教授、华东师范大学河口海岸研究所所长陈吉余教授、上海航道局原总工程师黄维敬、上海港务局原总工程师丁承显、南京水利科学研究院河港室主任黄胜教授、河海大学呼延如琳教授等，以及多位著名的国际合作研究者。在合作研究过程中向他们学习到很多知识和经验，得益匪浅；五是坚持科研为生产建设服务，研究的主要问题都是工程建设中急需解决的问题，后来发表的论文大都是工程实施后在原生产报告的基础上进一步研究写成的；六是重视学科之间的交叉渗透，努力探索动力与地貌、沉积相结合的途径，产生新的学科生长点。以上这些工作也从一个侧面反映了本书的特色。

回顾本人数十年的河口研究生涯，大致可分为四个阶段：第一阶段是从20世纪60年代末致力于河口研究开始，主要研究长江河口的水动力及其对泥沙输运与河床演变的影响，将动力过程研究与地貌、沉积过程研究相结合，代表作为《长江河口动力过程和地貌演变》（上海科学技术出版社，1988）中的多篇论文；第二阶段是从70年代末开始，结合流域重大工程建设，开展南水北调、三峡工程对长江河口生态与环境影响的研究，重点研究对河口盐水入侵的影响，代表作为《三峡工程与河口生态环境》（科学出版社，1994）、《长江河口盐水入侵》（海洋出版社，2003）；第三阶段是从80年代后期开始，在研究过程中逐渐感悟到，河口的泥沙有很多是一些属于非牛顿体的细颗粒泥沙，仅研究物理过程其运动机理是无法搞清楚的，必须同时研究化学、生物过程对它的影响。另外，河口的环境问题已日显突出，其中很多是化学、生物方面的问题，作为河口研究工作者也应给予高度关注。故从此时开始，我除研究物理过程外，还与有关单位合作进行化学、生物过程研究，并将三者相结合，切入点是研究河口最大浑浊带的形成机制与时空变化规律，代表作为《长江河口最大浑浊带》（海洋出版社，2001）；第四阶段是从90年代开始，为了追踪河口国际前沿研究和为全球变化研究做贡

献，结合 IGBP 中的两个核心计划（JGOFS——全球海洋通量联合研究、LOICZ——海岸带陆海相互作用）开展长江河口物质通量和陆海相互作用研究，代表作为《长江河口物质通量》（海洋出版社，2001）和《长江河口陆海相互作用界面》（海洋出版社，2009）。

本专著是笔者等多年来（主要是第一阶段）在有关研究成果的基础上进行系统综合、梳理、修改和补充完成的，全书共分6章。第1章为长江河口水沙通量，自陆向海主要探讨长江中下游的水沙通量、入河口区的水沙通量、河口段内南、北港的水沙通量和口外海滨的悬沙通量及其变化。第2章为长江河口水动力及其对河槽演变的影响，主要探讨长江河口的潮汐、潮流、余流、余环流及其对悬沙输运与河槽演变的影响。第3章为长江河口悬沙输运与滩槽水沙交换，主要探讨长江河口悬沙输运特性、盐淡水混合对悬沙输运的影响、南槽北槽悬沙输运机制、南汇边滩及邻近海域的悬沙输运、滩槽水沙交换、长江口与杭州湾泥沙交换以及口外海滨的悬沙分布及扩散特征。第4章为长江河口涨潮槽的水沙输运，主要探讨长江河口涨潮槽的形成与演变、水沙输运的特征与规律，并与落潮槽进行对比。第5章为长江河口最大浑浊带水沙输运，主要探讨长江河口最大浑浊带的时空变化及其影响因子、水沙输运机制、河口形状对浑浊带形成的影响以及浮泥的形成机理及变化过程。第6章为长江河口底沙输运，主要探讨长江河口底沙的颗粒组成、沙波运动以及水下沙洲的推移。

科学进步来自集体智慧，本书是集体研究的结晶。参加本项研究的还有：潘定安、朱慧芳、徐海根、胡辉、郭成涛、茅志昌、时伟荣、金元欢、吴加学、吴华林、刘新成、杨清书、王永红、沈健、万新宁、谷国传、李身铎、刘高峰、应铭、陈小华、张琛、傅德健等。本项目研究得到交通部上海航道局等生产单位、国家自然科学基金委（如 No:50939003,40071013,50579021,50179012,40576042 等）的资助，还得到华东师范大学河口海岸科学研究院和国内外兄弟院所同仁们的支持和帮助。王佩琴参加绘图和打字排版工作。出版时得到河口海岸学国家重点实验室学术著作出版基金的资助，在此一并深表谢忱。

本书综合了从20世纪70年代至今不同时段的研究成果，时间跨度大，有些统计数字和表现方式存在一些差异，为了尊重原研究成果的真实性，本书未作全部统一的修订。科学研究是接力赛跑，河口水沙输运是河口河床演变的基础，水动力是泥沙等物质运动的驱动力，泥沙是水动力与河床演变的纽带，河床演变是结果，此结果又反作用于水动力和泥沙运动，这是一个开放的、非常复杂的巨系统，尤其是细颗粒泥沙，人们对它的认识还只是冰山一角，还有很多现象与问题有待去发现和探索。近10多年来，长江流域众多大型拦河大坝、南水北调和河口航道整治及土地圈围工程建设，必将对河口水沙输运过程带来新的巨大的影响，更有待我们去做深入研究。

本书学科跨度较大，加上条件和水平有限，书中不当和错误之处在所难免，敬请批评指正。

**沈焕庭**

2010年冬于纽约长岛

# Foreword

Recently, large scale fluvial mass transport has become an important issue. Fluvial mass transport is one of the core themes of the three core projects of the International Geosphere – Biosphere Programme (IGBP), viz. Land-Ocean Interactions in the Coastal Zone (LOICZ), Biospheric Aspects of the Hydrological Cycle (BAHC), and Past Global Changes (PAGES). The programmes of Land Margin Ecosystems Research (LMER) and International Long Term Ecological Research (ILTER) projects have carried out long and systematic investigations on the Land – Ocean Interactions and the many processes that are involved.

The Changjiang River is the biggest river in China, flowing from the glaciers on the Tibetan Plateau in Qinghai eastward across the southwest, central and eastern regions of China before discharging into the East China Sea through the Changjiang River Delta, viz. "golden delta". The Changjiang River is the most significant waterway flowing from west to east in the central region of China, and plays a key role in to the exponential growth of the Chinese economy. The annual mean freshwater discharge into the estuary is 28 518 $m^3 \cdot s^{-1}$ and the annual runoff is 897.8 billion $m^3$ (based on observations at Datong gauge station from 1950 to 2006). It is the third biggest river in the world, in terms of discharge, next to Amazon River and Congo River. The annual mean sediment discharge of the Changjiang is about 0.41 billion tones, which is the fourth largest in the world, next to Ganges River, Huanghe River and Amazon River. The large amount of freshwater and sediment input to the estuary and its temporal and spatial variation not only greatly affects the river bed evolution salt intrusion and ecology of the estuary, but also influences the temperature and salinity distributions, flow fields and sedimentation processes of the adjacent sea, and even the Pacific Ocean. Consequently, the study of the both water and sediment transport of the Changjiang River has significant theoretical and practical implications, attracting attention from various members of the scientific community and regulation administration.

The author has worked at the East China Normal University since graduation from the Department of Geography in 1957. Between 1960 and 1962, he specialized in the study of the physical oceanography in Shandong Ocean College. After that, he was a lecturer in the ocean hydrology and meteorology between 1962—1965, giving lectures on "ocean tides" and "coastal morphodynamics". Since 1969, he has focused his career on the study of estuaries by combining the fields of geography and oceanography. This research focused on the hydrodynamics of estuaries and its interaction with morphology and sedimentation in the primary stage.

In the 1970s, the Chinese government paid special attention to improving ports and waterways. The author was involved in the feasibility study on the project to improve the navigability of the waterway to the Shanghai Harbour. The objective of this project was to deepen the waterway

from 6 m to 7 m, making it possible for ships in the 10 thousand ton class to navigate to this harbour during both low and high tides and for ships in the 20 thousand ton class to navigate to the harbour during high tide. In this feasibility study, the characteristics of the runoff, tides, mixing of freshwater and saline water, residual currents, residual circulation and their effects on the sediment transport and channel evolution were investigated systematically. Consequently, a series of important new results were obtained, which not only served as the fundamental hydrodynamic basis for the project, but also partly illustrated the dynamical mechanisms of the evolution of the Changjiang River Estuary. Thereafter, the water and sediment transport of the Changjiang River Estuary was investigated in the following projects: the construction of the Three Gorge Dam Water Diversion Project, the deep waterway regulation project and several international research projects, e. g. JGOFS and LOICZ. The research results have been widely used as instructions of the regulation and management of the Changjiang River Estuary. Many articles were published, and were acknowledged with numerous citations.

The co-author, Prof. Li Jiufa, works in East China Normal University since graduation from the Department of Geography of this university in 1973. He specialized in the study of sediment dynamics in Wuhan University of Hydraulic and Electric Engineering (now Wuhan University) and Tsinghua University in the period of 1978—1980, and worked with the world famous expert on sediment dynamics, Qian Ning. He now studies suspended sediment transport, bedload transport, fluid mud and evolution of estuaries by combining geography and sediment transport mechanics, working together with the author. Numerous valuable results were achieved, and more than 100 articles have been published.

The present work is the integration of six research aspects. Firstly, tens of field observations of flow and sediment characteristics were conducted in the estuary. We were responsible for the planning process, preparing instruments, taking samples, analysing the data and writing the necessary reports. Secondly, field work on flow structure, micro-morphology and sedimentation processes were also arranged over several observation periods in the Jiuduansha Shoal, the Zhongyangsha Shoal, the Biandansha Shoal, the Ruifeng Shoal, the Qingcao Shoal, the Nanhui Shoal and the Chongming East Shoal. Thirdly, we consulted many locals who provided useful knowledge on the characteristics of the flow and sediment in the estuary, as well as the evolution of the estuary. These included those who either work on the ships or live on the island of the estuary, e. g. the Chongming Island, the Changxing Island, the Hengsha Island, the Sheshan Island, and the Jigujiao Island. Fourthly, vast knowledge was gained from the co-workers, viz. prof. Yan Kai, prof. Chen Jiyu, ir. Huang Wei-jing, ir. Ding Chengxian, prof. Huang Sheng and prof. Huyan Rulin. Fifthly, all the main research questions were the problems of most importance which needed urgent solutions, and the articles published were written by improving the relevant reports. Sixthly, special importance was attached to the integration of different disciplines, seeking a way to integrate the hydrodynamics with morphology and sedimentation.

The research career of the author can be divided into four periods. The first period is from late 1960s when I started my research on estuary, focusing on the hydrodynamics and its impact

on the sediment transport and the evolution of the river bed, and several articles in the book *Dynamic processes and morphological evolution in the Changjiang Estuary* (Shanghai Science & Technology Press, Shanghai, 1988) are the representative work. In the second period, which started from late 1970s, the research was about the effects of the large-scale hydraulic engineering projects (water diversion project and Three Gorges Dam) on the ecology and the environment of the estuary. The books *Three Gorges Dam and the ecology and the environment of the estuary* (Science Press, Beijing, 1994) and *Salt intrusion in the Changjiang Estuary* (China Ocean Press, Beijing, 2003) are the representative work of this period. In the third period, which started from late 1980s, we recognized that the sediment in the estuary is mainly the fine sediment which is non-Newton mass. The mechanisms of sediment transport cannot be well understood only by investigating its physical process, and the chemical and biological processes should be included. The problem on the estuarine environment, mainly related to chemical and biological processes, became more and more severe, hence became important in the estuarine research. Hereafter, the chemical and biological processes was combined with physical process in my research. The mechanisms of formation of the estuarine turbidity maximum and the characteristics of its spatial and temporal variation were investigated, and the book *Turbidity maximum in the Changjiang Estuary* (China Ocean Press, Beijing, 2001) was published. The fourth period is from late 1990s, when the research was related to the two core research projects of the IGBP, which are JGOFS and LOICZ. The research work done in this period focused on the mass flux and land-ocean interaction, with publications of *Mass flux in the Changjiang Estuary* (China Ocean Press, Beijing, 2001) and *Interface of the land – ocean interaction in the Changjiang Estuary* (China Ocean Press, Beijing, 2009).

This book is the integration and synthesis of the related research results. The book consists of six chapters. The first chapter presents the water and sediment flux of the Changjiang Estuary. It introduces the water and sediment flux of the middle and lower reaches of the Changjiang River, and the water and sediment flux to the estuary and to the North Channel, the South Channel and nearshore area of the estuary. The second chapter focuses on the hydrodynamics in the Changjiang Estuary and its impact on the channel evolution, investigating the characteristics of the tides, residual currents, residual circulations and their effects on the sediment transport and channel evolution. The third chapter is devoted to suspended sediment transport and water and sediment exchange among shoals and channels. This includes characteristics of suspended sediment transport, mixing of fresh water and salty water and its impact on the suspended sediment transport. It also discusses mechanisms of suspended sediment transport in the North Passage and the South Passage, suspended sediment transport in the Nanhui Shoal and the sediment exchange between the Changjiang Estuary and the Hangzhou Bay as well as nearshore suspended sediment distribution and diffusion. The fourth chapter concentrates on the formation and evolution of the flood channels and the characteristics of water and sediment transport in flood channels. The fifth chapter investigates the water and sediment transport in the Turbidity Maximum of the Changjiang Estuary, including temporal and spatial variation of the Turbidity Maximum and its determining factor, mech-

anisms of water and sediment transport in the Turbidity Maximum, the effect of the geometry of the estuary on the formation of the Turbidity Maximum and the formation and the variation of the fluid mud. The sixth chapter studies bed load transport, consisting of grain size distribution of the bed load and migration of sand waves and subtidal sand bars.

It is necessary to point out that this book belongs to the project collective. The other main members involved are Pan Dingan, Zhu Huifang, Xu Haigen, Hu Hui, Guo Chengtao, Mao Zhichang, Shi Weirong, Jin Yuanhuan, Wu Jiaxue, Wu Hualin, Liu Xincheng, Yang Qingshu, Wang Yonghong, Shen Jian, Wan Xinning, Gu Guochuan, Li Shenduo, Ying Ming, Chen Xiaohua, Zhang Chen, Fu Dejian among others. We would like to thank the colleagues in the State Key Laboratory of Estuarine and Coastal Research and numerous international collaborators who have provided help. The help of Wang Peiqin for making figures and typing the manuscript is gratefully acknowledged. Special thanks to Amy F. Waterhouse, who helped in writing this Foreword. Support for this research was provided by CCCC Shanghai Dredging Co., Ltd and several NSFC Grants (No: 50939003, 40071013,50579021, 50179012, 40576042). We gratefully acknowledge support from publication foundation of the State Key Laboratory of Estuarine and Coastal Research, East China Normal University.

As the book is a synthesis of the research results since the 1970s, the results may have been presented in different manners. To keep the original results authentic, these results have not been modified when preparing this book. The water motion, water and sediment transport and river-bed evolution interact with each other, which result in an open and complicated system. In this system, water motion is the driving force of the mass transport as sediment transport; sediment is the bridge between the water motion and the river-bed evolution; and the river-bed evolution is the forced result in the system. There are still many open problems that need to be investigated, especially with the effects of human interventions, such as dam constructions, waterway regulations in the estuary and exploiting shoals.

Limited by time and due to the interdisciplinary span of this work, errors and defects are sure to exist. We would be greatly appreciated your comments and criticisms if errors are indeed found.

**Shen Huanting**

Winter of 2010

At Long Island, New York, the U. S. A.

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