

GeoPlanet: Earth and Planetary Sciences

Subhasish Dey

Fluvial Hydrodynamics

Hydrodynamic and Sediment Transport
Phenomena



Springer

Subhasish Dey

Fluvial Hydrodynamics

Hydrodynamic and Sediment
Transport Phenomena

Subhasish Dey
Department of Civil Engineering
Indian Institute of Technology
Kharagpur
India

The GeoPlanet: Earth and Planetary Sciences Book Series is in part a continuation of Monographic Volumes of Publications of the Institute of Geophysics, Polish Academy of Sciences, the journal published since 1962 (<http://pub.igf.edu.pl/index.php>).

ISSN 2190-5193 ISSN 2190-5207 (electronic)
ISBN 978-3-642-19061-2 ISBN 978-3-642-19062-9 (eBook)
DOI 10.1007/978-3-642-19062-9
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014939385

© Springer-Verlag Berlin Heidelberg 2014

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law. The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

GeoPlanet: Earth and Planetary Sciences

Editor-in-Chief

Paweł Rowiński

Series editors

Marek Banaszkiewicz, Warsaw, Poland

Janusz Pempkowiak, Sopot, Poland

Marek Lewandowski, Warsaw, Poland

Marek Sarna, Warsaw, Poland

For further volumes:

<http://www.springer.com/series/8821>

Series Editors

Geophysics	Paweł Rowiński <i>Editor-in-Chief</i> Institute of Geophysics Polish Academy of Sciences ul. Ks. Janusza 64 01-452 Warszawa, Poland p.rowinski@igf.edu.pl
Space Sciences	Marek Banaszkiewicz Space Research Centre Polish Academy of Sciences ul. Bartycka 18A 00-716 Warszawa, Poland
Oceanology	Janusz Pempkowiak Institute of Oceanology Polish Academy of Sciences Powstańców Warszawy 55 81-712 Sopot, Poland
Geology	Marek Lewandowski Institute of Geological Sciences Polish Academy of Sciences ul. Twarda 51/55 00-818 Warszawa, Poland
Astronomy	Marek Sarna Nicolaus Copernicus Astronomical Centre Polish Academy of Sciences ul. Bartycka 18 00-716 Warszawa, Poland sarna@camk.edu.pl

Managing Editor

Anna Dziembowska

Institute of Geophysics, Polish Academy of Sciences

Advisory Board

Robert Anczkiewicz

Research Centre in Kraków
Institute of Geological Sciences
Kraków, Poland

Aleksander Brzeziński

Space Research Centre
Polish Academy of Sciences
Warszawa, Poland

Javier Cuadros

Department of Mineralogy
Natural History Museum
London, UK

Jerzy Dera

Institute of Oceanology
Polish Academy of Sciences
Sopot, Poland

Evgeni Fedorovich

School of Meteorology
University of Oklahoma
Norman, USA

Wolfgang Franke

Geologisch-Paläontologisches Institut
Johann Wolfgang Goethe-Universität
Frankfurt/Main, Germany

Bertrand Fritz

Ecole et Observatoire des
Sciences de la Terre,
Laboratoire d'Hydrologie
et de Géochimie de Strasbourg
Université de Strasbourg et CNRS
Strasbourg, France

Truls Johannessen

Geophysical Institute
University of Bergen
Bergen, Norway

Michael A. Kaminski

Department of Earth Sciences
University College London
London, UK

Andrzej Kijko

Aon Benfield
Natural Hazards Research Centre
University of Pretoria
Pretoria, South Africa

Francois Leblanc

Laboratoire Atmospheres, Milieux
Observations Spatiales, CNRS/IPSL
Paris, France

Kon-Kee Liu

Institute of Hydrological
and Oceanic Sciences
National Central University Jhongli
Jhongli, Taiwan

Teresa Madeyska

Research Centre in Warsaw
Institute of Geological Sciences
Warszawa, Poland

Stanisław Massel

Institute of Oceanology
Polish Academy of Sciences
Sopot, Polska

Antonio Meloni

Istituto Nazionale di Geofisica
Rome, Italy

Evangelos Papathanassiou

Hellenic Centre for Marine Research
Anavissos, Greece

Kaja Pietsch

AGH University of Science and
Technology
Kraków, Poland

Dušan Plašienka

Prírodovedecká fakulta, UK
Univerzita Komenského
Bratislava, Slovakia

Barbara Popielawska

Space Research Centre
Polish Academy of Sciences
Warszawa, Poland

Tilman Spohn

Deutsches Zentrum für Luftund
Raumfahrt in der Helmholtz
Gemeinschaft
Institut für Planetenforschung
Berlin, Germany

Krzysztof Stasiewicz

Swedish Institute of Space Physics
Uppsala, Sweden

Roman Teisseyre

Earth's Interior Dynamics Lab
Institute of Geophysics
Polish Academy of Sciences
Warszawa, Poland

Jacek Tronczynski

Laboratory of Biogeochemistry
of Organic Contaminants
IFREMER DCN_BE
Nantes, France

Steve Wallis

School of the Built Environment
Heriot-Watt University
Riccarton, Edinburgh
Scotland, UK

Wacław M. Zuberek

Department of Applied Geology
University of Silesia
Sosnowiec, Poland

*To my wife, Swastika, and children, Sibasish
and Sagarika, for their unconditional love,
patience and continued support*

Foreword I

Various problems from the broad field of research on sediment transport, such as local scouring, sedimentation in reservoirs, erosion due to floods, dam breaching flows, aggradations, and degradations of riverbed are of fundamental importance for river engineers, geophysicists, decision makers, and environmentalists. At the same time, these problems are still far from being solved and constitute the basic issue for scientists dealing with environmental hydraulics. Even at microscale level, we realize that sediment particles respond to hydraulic forces such as shear and lift, whose effects are in turn related to basic hydrodynamic flow properties, particle size, shape, and density. Sediment transport can, in principle, be thought of as moving water exerting both lift and drag on sediment particles at rest and/or in motion. Although this concept is relatively simple numerous other, very often nonlinear, processes occur and quantitative modeling of sediment transport turns out to be extremely difficult. This is the result of the complexity of the physical processes that govern the particle transport in water bodies, manifold of important scales, meaningful uncertainties related to input data, knowledge gaps, and numerical difficulties.

This book brings together emerging perspectives from fluid mechanics, sediment transport theory, civil engineering, and mathematical modeling. Reflecting on the book's theoretical and empirical focus, the audience is two-fold: students and scholars working within the university tradition, and environmental scholars and engineers interested in solving real life problems. Together, this mix forms a creative synthesis for both sets of readers.

Although the problems of sediment transport have been studied for more than two centuries, there are not many up-to date reference books presenting the actual state of the art in the field. In view of this lack of readily available, clearly presented information, this volume fills an important void. Its analyses and discussions of also individual aspects provide the kind of basis that any student and specialist in the field would like to have in approaching this subject. It is thus a most welcome contribution to the growing body of literature on hydraulics, focusing exclusively on what is clearly the key area of concern.

Subhasish Dey has been a pioneer in the field of applied hydrodynamics, turbulence, and sediment transport. His journey in the world of science and engineering took him from the University of North Bengal through a number of stops at the Universität Stuttgart, Technische Universität Darmstadt, University of Iowa,

Technical University of Denmark, Adelaide University, University of Bradford, Chinese Academy of Science, Tsinghua University, University of Hong Kong, Università di Pisa, Università della Calabria, Politecnico di Milano, University of Florence, University of Oulu, Instituto Superior Tecnico Lisbon, National Taiwan University, National Chung Hsing University, National Cheng Kung University, Nanyang Technological University, Laboratoire Central des Ponts et Chaussées, and other academia, where he offered a course on sediment transport and/or stayed as a visiting professor, to his present home at the Indian Institute of Technology Kharagpur where he is the professor and head of the Department of Civil Engineering. This journey has given him a unique perspective on the thrilling field of sediment transport. I could personally experience his extraordinary passion and devotion to science having *Sub* (as I call him in short) as invited speaker during two international schools of hydraulics (2010 and 2012) that I had the privilege to chair. The contacts and the friendship struck up that time have brought fruit at enormous speed and we can now enjoy this fantastic tome.

Scientists and engineers working in the field of hydrodynamics, sediment transport, and related areas owe *Subhasish Dey* a debt of gratitude for producing this excellent volume. It will help young people entering the field and will serve as a valuable reference work for more experienced scientists. I believe that the field of sediment research will progress more quickly and vigorously as a result of the publication of this excellent book. This volume will also enormously enrich the Springer book series: *GeoPlanet: Earth and Planetary Sciences*.

Warsaw, March 2014

Pawel M. Rowinski

Foreword II

The traditional Fluvial Hydraulics has significantly transformed over recent decades moving from a largely empirical discipline towards a qualitatively new level of mathematically and physically rigorous methodologies of modern fluid mechanics. This step change has become possible due to the progress in modeling and experimental capabilities that led to significant advances in the understanding of the key processes involved in fluvial dynamics. The turbulence structure among them is particularly important as it is a fundamental driver of the interactions between turbulent flow and its erodible boundaries. As a reflection of these changes, the title of the discipline has changed from Fluvial Hydraulics to *Fluvial Hydrodynamics* and this book is an excellent highlight of this important transition.

Over the years, the author of this book has been among key players in the modernization of fluvial hydraulics by contributing on many fronts, from fundamental issues of open-channel flow turbulence to particle entrainment and transport. This personal involvement in the subject makes this book particularly interesting and stimulating.

The book joins a great family of recent texts on this topic, such as W. Graf and M. Altinakar (1998), A. Raudkivi (1998), G. Parker (2004), M. H. Garcia (1996, 2008), J. C. Winterwerp and W. G. M. van Kesteren (2004), A. Gyr and K. Hoyer (2007), E. Partheniades (2009), and A. J. Mehta (2013). Each of these books is unique and provides their own specific perspective on the subject. *Subhasish Dey's* book continues this tradition and the author should be highly commended for his outstanding effort. I have no doubt that this book will help in training a new generation of civil and hydraulic engineers and will inspire new discoveries in hydraulic research.

Aberdeen, March 2014

Vladimir Nikora

Foreword III

This book, *Fluvial Hydrodynamics*, by *Subhasish Dey* is based on his teaching, laboratory research, and extensive field experience for more than 30 years. His practical knowledge along with a strong scientific background has enabled him to come up at this stage. This spirit impregnates to write this excellent book that contains a wealth of theoretical as well as applied material justifying a comprehensive treatise on hydrodynamics of sediment transport. I strongly believe that the book would be a standard textbook all over the world not only for postgraduate and research level students, but also for field engineers as a practical guide and supplementary engineering handbook.

Knoxville, March 2014

Thanos Papanicolaou

Foreword IV

The book *Fluvial Hydrodynamics* that comprehensibly addresses the issues of sediment transport by turbulent flow differs from most texts in this field. It deals with every aspect of hydrodynamics related to sediment transport and is important in the context of sediment research and practice.

The author *Subhasish Dey* is not only an excellent researcher and at the forefront of current understanding of sediment transport, but also reviewed a broad spectrum of scientific literature to bring to the audience of this text an excellent volume that is up-to-date in all respects.

Beijing, March 2014

Zhao-Yin Wang

Foreword V

...I thought and still so believe that a book of this title will be of great value to the upcoming generations. As is evident from the most detailed list of contents, the book covers all possible problems, which future engineers will be confronted in their professional career, but equally in research. The exercises, a special feature in the text, presented in the book will be very useful.

Lausanne, November 2013

Walter H. Graf

Preface

*I come from haunts of coot and hern,
I make a sudden sally
And sparkle out among the fern,
To bicker down a valley.*

*By thirty hills I hurry down,
Or slip between the ridges,
By twenty thorpes, a little town,
And half a hundred bridges.*

*Till last by Philip's farm I flow
To join the brimming river,
For men may come and men may go,
But I go on forever.*

...

The Brook, Alfred Lord Tennyson (1809–1892)

Flow in a river that goes on forever is one of the most evident manifestations of gravity. The river and its characteristics must be studied, must be understood. The book, *Fluvial Hydrodynamics*, goes in this direction written by an *unknown* hydraulician.

The state of the art in fluvial hydrodynamics can be examined only through a careful exploration of the theoretical development and applied engineering technology. This book is primarily focused, since most up-to-date primary research findings in this field are presented, on the research aspects that involve a comprehensive understanding of the mechanics and physics of sediment transport by turbulent flow. It begins with the fundamentals of hydrodynamic principles applicable to open-channel flow followed by turbulence characteristics related to sediment motion. Then, the sediment dynamics are described from a classical perspective by applying the mean bed shear approach, and additionally, incorporating a statistical description of the role of turbulence. The book also describes the local scour problems at hydraulic structures and scale models. It is thus intended primarily as a course textbook at the graduate/research level and also as a guide for field engineers, keeping up with modern scientific developments. Therefore, as a simple prerequisite, the readers should have a basic background knowledge in

hydraulics/fluid mechanics and an understanding of fundamentals of calculus, probability, statistics and physics.

In the field of civil engineering, where engineers typically learn about rivers in courses called open channel hydraulics and sediment transport, sound knowledge of fluvial hydrodynamics is important because it determines the aggradations and degradations of the river systems, life span of hydraulic structures and river protection works, etc. Thus, it is not surprising that this subject is of interest to a wide circle of professions that include hydraulicians, hydrologists, geologists, sedimentologists, geographers, civil engineers, environmental engineers, and so on.

I understand from the discussions with and comments from colleagues and students over the years during delivering lectures on an international short course on *turbulent flows, sediment transport and scour* offered to different universities around the world and on the regular graduate courses on *hydraulics of sediment transport* and *turbulent fluid flows* at my Institute (Indian Institute of Technology, Kharagpur) that the phenomena concerning the dynamics of sediment particles under a turbulent flow invite many open questions. My primary attempt is therefore to address the fundamental aspects of fluvial hydrodynamics from the viewpoint of micro-mechanical interaction of sediment particles with turbulent flow.

I am of the opinion that it could be possible to build a sound understanding of fluvial hydrodynamics on the typical foundation of fluid mechanics, basic calculus, probability, statistics and physics. Introducing new aspects found in the research of turbulent flow, this book updates the theories of sediment transport. It is therefore my hope that this book would close the gap between the micro-mechanics of sediment transport and the stochastic characteristics of turbulent flow. It differs from the traditional treatments of open channel hydraulics and sediment transport in its greater emphasis on the basic physics of turbulent flow in terms of quantitative analytical information.

A course based on this book would be appropriate for graduate and research students in hydraulic engineering and earth sciences curricula and would be expected to be taught by a teacher with an active interest in this field. Under these circumstances, instructors would assign students in exploring questions that arise and in discussing papers from the journals, and to involve them in laboratory experiments and/or field studies. Therefore, I have also included exercises that can be used to explore the problems of practical importance involving complex hydrodynamic phenomena in the context of sediment dynamics. I would be greatly rewarded if this book proves to be of any assistance in improving existing scarcity of textbooks on sediment transport by turbulent flow.

I express my deep sense of indebtedness to *Pawel Rowinski*, Institute of Geophysics, Polish Academy of Sciences, Warsaw, Poland, who proposed and inspired me to write this book in his capacity as the Editor-in-Chief of the Springer book series: *Geoplanet: Earth and Planetary Sciences*. He was an endless source of help and encouragement. I heartily thank *Oscar Castro-Organ*, University of Cordoba, Spain for reviewing the manuscript at various stages in its development. I also thank *Walter Hans Graf*, Laboratoire de Recherches Hydrauliques, École Polytechnique Fédérale, Lausanne, Switzerland for his suggestions at the final stage of