NATO Science Series
IV. Earth and Environmental Sciences

ISBN 1-4020-4910-2

springer.com

ISBN 1-4020-4910-2

H. Vereecken
A. Binley
G. Cassiani
A. Revil
K. Titov

Applied Hydrogeophysics

IV/71

Applied Hydrogeophysics

Edited by

Harry Vereecken, Andrew Binley, Giorgio Cassiani,
André Revil and Konstantin Titov

NATO Science Series

IV. Earth and Environmental Sciences – Vol. 71

Applied Hydrogeophysics

NATO Science Series

A Series presenting the results of scientific meetings supported under the NATO Science Programme.

The Series is published by IOS Press, Amsterdam, and Springer in conjunction with the NATO Public Diplomacy Division

Sub-Series

I. Life and Behavioural Sciences	IOS Press
II. Mathematics, Physics and Chemistry	Springer
III. Computer and Systems Science	IOS Press
IV. Earth and Environmental Sciences	Springer

The NATO Science Series continues the series of books published formerly as the NATO ASI Series.

The NATO Science Programme offers support for collaboration in civil science between scientists of countries of the Euro-Atlantic Partnership Council. The types of scientific meeting generally supported are “Advanced Study Institutes” and “Advanced Research Workshops”, and the NATO Science Series collects together the results of these meetings. The meetings are co-organized bij scientists from NATO countries and scientists from NATO’s Partner countries – countries of the CIS and Central and Eastern Europe.

Advanced Study Institutes are high-level tutorial courses offering in-depth study of latest advances in a field.
Advanced Research Workshops are expert meetings aimed at critical assessment of a field, and identification of directions for future action.

As a consequence of the restructuring of the NATO Science Programme in 1999, the NATO Science Series was re-organised to the four sub-series noted above. Please consult the following web sites for information on previous volumes published in the Series.

http://www.nato.int/science
http://www.springer.com
http://www.iospress.nl

Series IV: Earth and Environmental Sciences – Vol. 71

Applied Hydrogeophysics

edited by

Harry Vereecken
Forschungszentrum Julich GmbH,
Germany

Andrew Binley
Lancaster University, UK

Giorgio Cassiani
Università di Milano Bicocca, Italy

Andre Revil
Université Aix-Marseille, Aix-en-Provence, France

and

Konstantin Titov
State University of St. Petersburg, Russia

Springer

Published in cooperation with NATO Public Diplomacy Division

Proceedings of the NATO Advanced Research Workshop on
Soils and Groundwater Contamination: Improved Risk Assessment
St. Petersburg, Russia
25-29 July 2004

A C.I.P. Catalogue record for this book is available from the Library of Congress.

ISBN-10 1-4020-4911-0 (PB)
ISBN-13 978-1-4020-4911-8 (PB)
ISBN-10 1-4020-4910-2 (HB)
ISBN-13 978-1-4020-4910-1 (HB)
ISBN-10 1-4020-4912-9 (e-book)
ISBN-13 978-1-4020-4912-5 (e-book)

Published by Springer,
P.O. Box 17, 3300 AA Dordrecht, The Netherlands.

www.springer.com

Printed on acid-free paper

CONTENTS

Acknowledgements **vii**

List of Contributors **ix**

1. **Applied Hydrogeophysics** **1**
   Harry Vereecken, Andrew Binley, Giorgio Cassiani,
   André Revil, and Konstantin Titov

2. **Hydrogeophysical Parameter Estimation Approaches for Field Scale Characterization** **9**
   Niklas Linde, Jinsong Chen, Michael B. Kowalsky,
   and Susan Hubbard

3. **A Successive Linear Estimator for Electrical Resistivity Tomography** **45**
   Tian-Chyi J. Yeh, Junfeng Zhu, Andreas Englert,
   Amado Guzman, and Steve Flaherty

4. **Unsaturated Zone Processes** **75**
   Giorgio Cassiani, Andrew Binley, and Ty P.A. Ferré

5. **Solute Transport Processes** **117**
   Andreas Kemna, Andrew Binley, Frederick Day-Lewis,
   Andreas Englert, Bülent Tezkan, Jan Vanderborght,
   Harry Vereecken, and Peter Winship

6. **Biogeophysics: The Effects of Microbial Processes on Geophysical Properties of the Shallow Subsurface** **161**
   Estella A. Atekwana, D. Dale Werkema, and Eliot A. Atekwana

7. **Cold Regions Hydrogeophysics: Physical Characterization and Monitoring** **195**
   Helen K. French, Andrew Binley, Ivan Kharkhordin,
   Bernd Kulessa, and Sergey S. Krylov

8. **Hydrogeophysical Applications in Coastal Aquifers** **233**
Mark Goldman and Uri Kafri

9. **Applications of the Self-Potential Method to Hydrological Problems** **255**
André Revil, Konstantin Titov, Claude Doussan, and Vincenzo Lapenna

10. **Engineered Barriers for Pollutant Containment and Remediation** **293**
Lee Slater and Andrew Binley

11. **Geoelectrical Characterisation of Covered Landfill Sites: A Process-Oriented Model and Investigative Approach** **319**
Maxwell Meju

12. **Chernobyl-Born Radionuclides: Groundwater Protectability with Respect to Preferential Flow Zones** **341**
Vyacheslav M. Shestopalov, Yuriy F. Rudenko, Alexander S. Bohuslavsky, and Volodymir N. Bublias

Index **377**

ACKNOWLEDGEMENTS

The book "Applied Hydrogeophysics" presents the outcome of a successful NATO Advanced Research Workshop which was held in St. Petersburg, 25–29 July, 2004 and entitled "Soils and groundwater contamination: Improved risk assessment." We thank NATO for supporting and funding this workshop.

We are grateful to all reviewers who helped to increase the quality of the scientific information contained in this book: Alberto Bellin, Fred Day-Lewis, Claudio Gallo, Alberto Godio, Sander Huisman, Ivan Kharkhordin, Sebastien Lambot, Maxwell Meju, Véronique Naudet, Jirka Simunek, Heiner Stoffregen, Andreas Weller and Paul Wilkinson.

We particularly thank Gaby Pillert for the administrative and technical support in preparing the workshop but especially for her support in organisation and preparation of this book and for maintaining good contact with all authors.

Andrew Binley
Giorgio Cassiani
André Revil
Konstantin Titov
Harry Vereecken
Editors

LIST OF CONTRIBUTORS

Atekwana Estella
Dep. of Geological Sciences and Enineering
University of Missouri-Rolla
125 McNutt Hall
65409Rolla, Missouri
MO, USA

Atekwana Eliot
University of Missouri-Rolla
Dep. of Geological Sciences and Engineering
125 McNutt Hall
65409 Rolla, Missouri
MO, USA

Binley Andrew
Lancaster University
Dep. of Environmental Science
Bailrigg
LA1 4YQ Lancaster
UK

Bohuslavsky Alexander
National Academy of Sciences of Ukraine
Radioenvironmental Center
O.Gonchar Str.
1054 Kyiv
Ukraine

Bublias Volodymir
National Academy of Sciences of Ukraine
Radioenvironmental Center
O.Gonchar Str.
1054 Kyiv
Ukraine

Cassiani Giorgio
Università di Milano
Dipartimento di Scienze Geologiche e Geotecnologiche
Piazza della Scienza 4
20126 Biocca
Italy

Chen Jingsong
Earth Science Division
Lawrence Berkeley National Laboratory
1 Cyclotron Rd.
MS 90-1116 Berkeley
CA, USA

Day-Lewis Frederick
U.S. Geological Survey
Office of Ground Water, Branch of Geophysics
11 Sherman Place, Unit 5015,
Storrs
CT, USA

Doussan Claude
INRA
Unité Climat Sol Environnement
Domaine St Paul, Site Agroparc,
84914 Avignon Cedex 9
France

Englert Andreas
Forschungszentrum Jülich GmbH
Agrosphere (ICG-IV)
52425 Jülich
Germany

Ferré Ty P.A.
Dep. of Hydrology and Water Resources
The University of Arizona
1133 E. James E. Roger Way
85721Tuscon
Arizona, USA

French Helen
Norwegian Institute for Agicultural and Environmental Research
Soil, Water and Environment Division
Frederik A. Dahlsv. 20
1432 As
Norway

Flaherty Steve
ARCADIS
3777 E. Broadway Blvd. Suite 100
85716 Tuscon
Arizona, USA

Goldman Mark
The Geophysical Institute of Israel
PO Box 182. Industrial Zone North
71100 Lod
Israel

Guzman Amado
ARCADIS
3777 E. Broadway Blvd. Suite 100
85716 Tuscon
Arizona, USA

Hubbard Susan
Earth Science Division
Lawrence Berkeley National Laboratory
1 Cyclotron Rd., MS 90-1116
Berkeley
CA, USA

Kafri Uri
Geological Survey of Israel
PO Box 182. Industrial Zone North
95501 Jerusalem
Israel

Kemna Andreas
Forschungszentrum Jülich GmbH
Agrosphere (ICG-IV)
52425 Jülich
Germany

Kharkhordin Ivan
Inst. of Environmental Geosciences
St. Petersburg Division
14-th Line, 29
199178 St. Petersburg
Russia

Kowalsky Michael
Earth Science Division
Lawrence Berkeley National Laboratory
1 Cyclotron Rd., MS 90-1116
Berkeley
CA, USA

Krylov Sergey
Dep. of Earth Physics, Inst. of Physics
St. Petersburg University
Ulyanovskaya 1, Petershof
198904 St. Petersburg
Russia

Kulessa Bernd
University of Wales Swansea
School of the Environment and Society
Singleton Park
SA2 8pp Swansea
Wales, UK

Lapenna Vincenzo
Institute of Methodology for Environment Analysis (IMAA-CNR)
Potenza I 85050
Italy

Linde Niklas
Dep. of Earth Sciences/Geophysics
Uppsala University
Villav. 16
75236 Uppsala
Sweden

Meju Maxwell
Dep. of Environmental Science
Lancaster University
Bailrigg
LA1 4YQ Lancaster
UK

Revil André
CNRS-CEREGE, Dept. Geophysics
BP 80
13545 Aix-en-Provence, Cedex 4
France

Rudenko Yuriy
National Academy of Sciences of Ukraine
Radioenvironmental Center
O.Gonchar Str.
1054 Kyiv
Ukraine

Shestopalov Vyacheslav
Radioenvironmental Center
National Academy of Sciences of Ukraine
O.Gonchar Str.
1054 Kyiv
Ukraine

Slater Lee
Dep. of Earth & Environmental Sciences
Rutgers University
101 Warren Street
7102 Newark
NJ

Tezkan Bülent
Inst. of Geophysics and Meteorology
Cologne University
Albertus-Magnus-Platz
50923 Köln
Germany

Titov Konstantin
Russian Institute of Exploration Geophysics
20 Fayansovaya St.
193019 St. Petersburg
Russia

Vanderborght Jan
Forschungszentrum Jülich GmbH
Agrosphere (ICG-IV)
52425 Jülich
Germany

Vereecken Harry
Forschungszentrum Jülich GmbH
Agrosphere (ICG-IV)
52425 Jülich
Germany

Werkema Dale
U.S. EPA, ORD, NERL, ESD, CMB
944 E. Harmon Ave
89119 Las Vegas
Nevada, USA

Winship Peter
Lancaster University
Dep. of Environmental Science
Bailrigg
LA1 4YQ Lancaster
UK

Yeh Tian-Chyi J.
Dep. of Hydrology and Water Resources
The University of Arizona
1133 E. James E. Roger Way
85721Tuscon
Arizona, USA

Zhu Junfeng
The University of Arizona
Dep. of Hydrology and Water Resources
1133 E. James E. Roger Way
85721 Tuscon
Arizona, USA

1. APPLIED HYDROGEOPHYSICS

Harry Vereecken, Andrew Binley, Giorgio Cassiani, Andre Revil, and Konstantin Titov

1.1. Introduction

Soils and groundwater are important natural resources that sustain life on Earth. In the last century, the enormous expansion of industrial and agricultural activities has led to an increased environmental pressure on these systems. Soils and groundwater are extremely important because they yield much of our water resources and sustain food production for humanity. Agricultural activities consume nearly 80% of the fresh water used throughout the world, and the majority of this water is used for irrigation. In many countries aquifers are used as the major source of water for this purpose. Irrigation of cropland has greatly increased food production, but has also had some drawbacks due to the amount of water drawn from aquifers. Some of the major problems related with irrigation are excessive leaching of nutrients and pesticides, depletion of aquifers, ground subsidence, and soil salinization.

The vadose zone, being the subsurface environment between soil surface and groundwater, also serves as the repository for municipal, industrial and government waste. In Europe, more than 1.5 million sites are estimated to be potentially contaminated (EEA, 2000). These sites consist of military, industrial and waste disposal sites that are either abandoned or still under operation. The total number of identified sites that have been explicitly identified is about 21,000. The estimated total clean-up costs are at least in the order of 100 billion Euros.

As safe and effective use of the subsurface environment is a major challenge facing our society, there is a great need to improve our understanding of the shallow subsurface and the groundwater systems. As the subsurface is impossible to 'observe' directly, methods are needed to reveal its physical and hydrological properties, in addition to the hydrochemical characteristics of fluids stored and flowing through it. Traditional borehole-based sampling is often limited because of the localized knowledge often derived from such measurements and the disturbance induced to samples. As in the oil and mining industry, geophysical methods may offer a means of addressing this problem, by providing a spatially extensive, non-invasive means of investigating the subsurface. In the past, applications of geophysical methods in

H. Vereecken et al. (eds.), Applied Hydrogeophysics, 1–8.

groundwater and vadose zone hydrology have mainly focused on mapping geological structures (e.g. clay/sand layers, bedrock valleys, etc), delineation of aquifer boundaries, mapping of fracture zones, etc. In summary, the focus has been for a long time on the "geometrical" characterization of the subsurface. For such purposes standard methods are presently available and well-documented in the literature.

Recently, increased attention has been given to the use of geophysical methods to derive parameters and state variables characterizing especially surface near groundwater systems and soils (Vereecken et al., 2002, 2004; Rubin and Hubbard, 2005). This approach has also similarities with the experience of the oil industry, having as an objective the "petrophysical" characterization of the subsurface. Research in this direction is mainly driven by the fact that geophysical methods allow continuous mapping in space and time of geophysical properties which can be transferred to parameters or variables characterizing the aquifer system (e.g. water content, porosity, flow velocity). Classical approaches like drilling and coring have shown their limitations in capturing this spatial and temporal variability. Characterizing spatial and temporal variability of aquifers is, however, a key factor determining e.g. success of water management strategies or predicting pollution risks to water supply systems.

Hydrogeophysical methods and approaches are presented in the recent book *Hydrogeophysics* edited by Yoram Rubin and Susan Hubbard (2005). That book is the first to deal explicitly with geophysical methods for hydrological and hydrogeological processes. It addresses in depth the fundamentals of hydrogeological characterization as well as the fundamentals of geophysical characterization. A series of case studies and emerging technologies in the field of hydrogeophysics are also presented.

In *Applied Hydrogeophysics* we follow up on the material presented in *Hydrogeophysics* but focus on the applications of hydrogeophysical methods to the understanding of hydrological processes and environmental problems dealing with the flow of water and the transport of contaminants. This book, unlike its predecessor, is therefore organized mainly in hydrological process-driven chapters, rather than in methodological chapters. We feel that this structure is suitable particularly to the understanding of the end user and the professionals that want to make use of the new hydrogeophysical techniques for their specific field of application. In addition, this structure gives a more pronounced practical touch to the book. Hence the title *Applied Hydrogeophysics*.

The book is the outcome of a successful NATO Advanced Research Workshop held in St. Petersburg, 25–29 July, 2004 entitled "Soils and groundwater contamination: Improved risk assessment based on integrated hydrogeological and geophysical methods." The objectives of the meeting were to critically evaluate the state of the art in hydrogeophysics for the assessment of risks related to soil/groundwater contamination, to promote the interaction between soil scientists, hydrologists, hydrogeologists and geophysicists from all over the world; and to identify goals for future research. Specific attention was given to the applications of hydrogeophysical methods and techniques to problems arising in the use and management of soil and groundwater systems.

In the following we present a brief summary of the context and content of the various chapters.

1.2. Brief Overview

The book is organised in 12 chapters. The chapter of Linde et al. (Chapter 2) discusses the choices that must be made in estimating hydrogeophyiscal parameters. The authors identify three different methods presently available in the literature: direct mapping, integration methods and joint inversion methods. Direct mapping refers to the transformation of a geophysical model into hydrogeological model. A typical example is the estimation of water content data using ground penetrating radar. In integration methods the geophysical inversion is performed independently from the hydrogeological data and it includes the well-known methods such as cokriging and Bayesian estimation. The joint inversion methods aim to simultaneously invert geophysical and hydrogeophysical data. In their chapter, Linde et al. present the state of the art cases for each of these three methods.

The chapter by Yeh et al. on the hydrogeophysical use of sequential successive linear estimator (SSLE) and electrical resistivity tomography (ERT) introduces the SSLE as a promising alternative procedure for the inversion of ERT measurements. The SSLE is a geostatistically based cokriging-like approach. However, unlike the classical cokriging, the SSLE is able to tackle the nonlinear relationship between electrical potentials and the electrical conductivity. After a description of the SSLE, several synthetic case studies and a field application using the SSLE are given. The examples show the ability of the SSLE to condition the inverse procedure by a priori knowledge about the structure of the electrical conductivity as well as independent point measurements of the electrical conductivity in the subsurface. As expected, the conditioning of the inverse procedure reduces the ill-posedness of the inverse problem and therefore enhances the quality of the inversion results. Furthermore the SSLE features a quantification of the estimate of the electrical conductivity that is essential for decision making based on inversion results.

The chapter by Cassiani and others on unsaturated zone processes presents the basic concepts of non-invasive determination and monitoring of the