GRAVITATIONAL SYSTEMS OF GROUNDWATER FLOW

Theory, Evaluation, Utilization

Groundwater of meteoric origin permeates the upper parts of the Earth's crust in spatially organized flow systems down to several kilometres. Since the discovery of the flow-system concept in the 1960s, hydrogeology's basic paradigm has shifted from confined flow in aquifers to cross-formational flow in drainage basins. Consequently, groundwater has been recognised as a fundamental geologic agent, generating and modifying natural processes and phenomena of scientific, practical and economic interest.

This book is the first to present an extensive and illustrated overview of the history, principles, study methods, practical applications and natural effects of gravity-driven groundwater flow. Its user-friendly presentation requires no advanced background in mathematics, with the necessary mathematics being explained in full, and the physical meaning of the equations emphasized. The author highlights significant inter-relationships between the broad range of seemingly disparate processes and systems, demonstrating how these can be traced to a common root cause involving gravity-driven groundwater flow. Examples are used to illustrate practical applications in areas as diverse as hydrogeology, land-use planning, environment protection, wetland ecology, agriculture, forestry, geotechnical engineering, nuclear-waste disposal, mineral and petroleum exploration, and geothermal heat flow.

Written by one of the founding fathers of modern hydrogeology, and including an extensive glossary to aid students and researchers from a variety of disciplines, this book is a key reference for researchers, consultants and advanced students of hydrogeology and reservoir engineering.

JÓZSEF TÓTH began his study of geophysics in Hungary in the early 1950s, but moved to the university of Utrecht in the Netherlands in 1956 following the Hungarian revolution. He later emigrated to Canada, where he joined the Alberta Research Council in 1960. He shifted the paradigm of strata-bound groundwater flow in drainage basins to cross-formational water movement by two ground-breaking papers in 1962 and 1963 before defending his PhD thesis in Utrecht in 1965, and has contributed fundamental concepts and observations to the role of groundwater as a geologic agent. He joined the University of Alberta in Canada as a sessional instructor in 1966 and as a full-time faculty member in 1980. He currently holds the positions of Professor Emeritus at the University of Alberta, and Titular Professor at the Eötvös Loránd University in Budapest, Hungary.

Professor Tóth has received many awards for his work in hydrogeology, including: the first O. E. Meinzer Award from the Geological Society of America in 1965; the 1999 President's Award from the International Association of Hydrogeologists (IAH); the 2002 Prix R. N. Farvolden Award from the Hydrogeology Division of the Canadian Geotechnical Society; the 2003 M. King Hubbert Science Award of the National Ground Water Association (NGWA) of the USA; and the 2004 C.V. Theis Award of the American Institute of Hydrology.

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To my wife Erzsike, who has patiently endured the many lonely days,
weeks and months that I have devoted to my hobby

Contents

Preface

This monograph is intended to present a personal perception of the birth, evolution and consequences of a single geological concept: the gravitational systems of groundwater flow. The concept seems to have been instrumental in redefining the scope of a single-issue water-supply problem into the many-faceted earth science sub-discipline of modern hydrogeology. It has shifted the paradigm of aquifer-bound groundwater flow to cross-formational water movement in hydraulically continuous drainage basins.

This view was corroborated recently by approximately twenty-five papers presented at the Annual Meeting of the Geological Society of America, Denver, October 28–31, 2007, in the two sessions of Topic 34, 'Regional Groundwater Flow: . . .' The papers demonstrated a still lively interest in the topic 45 years after the first publication of the concept (Tóth, 1962a, 1962b), a still broadening scope of research, and an increasing variety of practical applications, as exemplified by Glaser and Siegel (2007), Gleeson and Manning (2007), Mádl-Szőnyi, (2007), Otto (2007), Rudolf and Ferguson (2007) and Winter (2007).

My perception has evolved from my own research, practical experience and literature studies in hydrogeology over 47 years (Tóth, 2002, 2005, 2007). It is presented here as a distilled summary of the relevant parts of my earlier publications, lectures and courses. I hope to summarize the results and the consequences of that work in the form of a consistent, coherent and all-round story. Illustrative case studies and case histories have been taken from my field and theoretical work as well as from published literature.

The subject matter is the basinal-scale systems of gravity-driven natural groundwater flow. It is recognized, however, that the term 'basinal scale' is relative and the question is addressed explicitly (Section 3.1.3). Conceptually, the discussion is focused on three main aspects of the topic: (i) the mathematically formulated theory of the formation, evolution and controlling factors of gravity-driven flow

systems; (ii) the methods of and approaches to the practical evaluation and portrayal of those flow systems; (iii) the hydrological, hydrogeochemical, geothermal, geotechnical, mineralogical, pedological, botanical and ecological factors, i.e. the natural consequences and manifestations of flow systems.

Since the publications of Domenico (1972) and Freeze and Cherry (1979), most monographs and textbooks on hydrogeology discuss certain aspects of gravitational flow systems of regional scales. In the present treatise I try to give a comprehensive overview of all the principal aspects of the topic.

Hydrogeology is not treated generally at the introductory level in the book. Only basic concepts directly relevant to the subject matter are defined and explained explicitly. Nevertheless, I have noticed over the years that some concepts and parameters, particularly those that are novel or not generally discussed in basic texts, are notoriously difficult for some students to grasp. In order, therefore, to ensure a thorough understanding of the intended subject I found it necessary to go into almost elementary detail of the elucidation of such questions. In these explanations I place the emphasis on the physical content rather than on mathematical pedantry. In general, owing chiefly to the rapidly increasing popularity of hydrogeology both in academia and practice, a growing number of professionals from a wide variety of disciplines probably already possess the required basic knowledge in hydrogeology to be interested in the book. I would thus expect the primary readership to be graduate students, researchers and consultants in the various disciplines mentioned above. However, undergraduate students in hydrogeology, land-use planners and administrators in water and natural resources may also have an interest in some aspects of the topics presented.

A piece of work like this can never be considered to be the product of one single individual. This book is no exception. I would, therefore, like to acknowledge the contribution of the many friends, colleagues and coworkers who have broadened my knowledge, questioned, tested, or complemented my ideas, or warned of possible dead-ends through extended collaboration, chance discussions, private and published debates and many other means. There are too many such people to name them individually. Nevertheless, I cannot leave unmentioned my former Graduate Students at the University of Alberta, Edmonton, Canada, an ever challenging and rewarding group. I am sure you, my friends, will recognize your contributions sprinkled all over the following pages. I must also express my gratitude, while retaining responsibility for the contents, to Dr O. Batelaan and Dr Zijl for kindly reviewing and advising on the sections developed from their papers, Dr E. Eberhardt and Dr G. D. Lazear, for providing me with the originals of some diagrams from their papers that I discuss, and Dr D. Hansen who, without knowing me personally, spontaneously offered to have the derivations in Appendices A and B typed from my then forty year old hand written script. Last, but by no means least, I am indebted

to the Department of Physical and Applied Geology, Eötvös Loránd University, Budapest, Hungary, for giving me a comfortable and warm working environment for writing this book.

As a participant in this small but personally rewarding part of scientific history it has given me a life-long pleasure to be part of the process.

József Tóth
Budapest, 2008