Flow Through Heterogeneous Geologic Media

This textbook integrates classic principles of flow through porous media with recently developed stochastic analyses to provide new insight on subsurface hydrology. Importantly, each of the authors has extensive experience in both academia and the world of applied groundwater hydrology. The book not only presents theories but also emphasizes their underlying assumptions, their limitations, and the potential pitfalls that may occur as a result of blind application of the theories as "cookie-cutter" solutions. The book has been developed for advanced-level courses on groundwater fluid flow, hydraulics, and hydrogeology, in either civil/environmental engineering or geoscience departments. It is also a valuable reference text for researchers and professionals in civil/environmental engineering, geology, soil science, environmental science, and petroleum and mining engineering.

TIAN-CHYI "JIM" YEH is a professor in the Department of Hydrology and Water Resources at the University of Arizona; a joint professor in the Department of Resources Engineering at the National Cheng Kung University, Taiwan, Republic of China; and an adjunct professor in the Department of Earth and Environmental Sciences at the University of Waterloo. He also holds an Overseas-Renowned Professorship from the Chinese Department of Education at Jilin University, China. Dr. Yeh has more than 30 years of experience in stochastic/numerical analysis and laboratory/field investigations, as applied to heterogeneity effects on flow and solute transport in the saturated and unsaturated geologic media. He pioneered stochastic analysis of the effects of spatial variability on flow in unsaturated geologic media; he discovered and developed the theory of moisture-dependent anisotropy for unsaturated hydraulic conductivity, which has significantly advanced our understanding, characterization, and prediction of unsaturated and saturated zone processes. Dr. Yeh also was the first to explore the conditional simulations and inverse modeling of flow and transport processes in variably saturated geologic media. He developed a stochastic successive linear estimation technique as an innovation that overcomes difficulties of the traditional inverse modeling technique. This innovation has led to his pioneering development of a new generation of aquifer characterization method (hydraulic tomography) and stochastic fusion methods to image the subsurface heterogeneity. Success of the stochastic fusion method further brings about his vision of exploiting naturally occurring stimuli (storm, earthquake, river stage, lightning, etc.) as energy sources for basin-scale subsurface tomographic surveys. He believes this new concept is the future of hydrologic sciences and other disciplines of environmental sciences and engineering.

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Preface and Acknowledgments

Unlike traditional groundwater hydrology textbooks, this book integrates classical principles of flow through porous media with recently developed stochastic analysis to provide new insight into subsurface hydrology. It is not a collection of "cookbook" recipes for solving groundwater flow problems as are many currently available textbooks. On the contrary, it examines classical principles of groundwater flow in geologic media in a stochastic framework; it explains their limitations to real-world problems and provides improved solutions and a better understanding of the underlying principles.

We believe that there is a lack of understanding of scale issues related to observations, theories, and processes, as well as uncertainty in hydrogeologic science. Likewise, there is a fundamental knowledge gap between the stochastic groundwater theory and its applications to applied, real-world problems. As a result, this book is designed to illustrate to readers what different laws and conceptual models tell us in relation to our observation scales, why we should care about stochastic theories, and why we need to consider using stochastic subsurface hydrology principles for real-world problems.

Specifically, this book starts in Chapter 1, with a discussion the fundamental fluid mechanic concepts, built upon the control volume (CV) at a scale that is larger than many molecules, but still smaller than a pore in porous media. By expanding the CV to scales larger than many pores, we then discuss in Chapters 2 and 3 Darcy's law under variably saturated conditions, and we define hydraulic properties for flow through porous media at laboratory scales, using the fluid mechanics principles. New concepts of spatial REV (representative elementary volume) and ensemble REV are introduced. Because of the average nature of the CV, spatial REV, and ensemble REV concepts, the importance of scale consistency among our interests, observations, hydraulic properties, and Darcy's law is then emphasized.

In order to quantify multiscale spatial variability of the laboratory-scale hydraulic properties in a field, stochastic processes or random field concepts are presented in

Chapter 4. These concepts facilitate a quantitative method to describe spatially varying hydraulic properties of a field in terms of their spatial statistics (i.e., the most likely value, their standard deviation, as well as their spatial fabrics – sizes of layers or stratifications). In Chapter 5, different conceptual models are discussed for characterizing and modeling a heterogeneous porous medium, including equivalent homogeneous, geologic, and highly parameterized heterogeneous conceptual models, satisfying different scales of our interests. The governing flow equations based on the heterogeneous conceptual model are also presented thereafter. Afterward, the conventional effective properties (e.g., hydraulic conductivity anisotropy and tensor) and mathematical models for the equivalent homogeneous conceptual model are presented in Chapter 6. At the end of Chapter 6, we discuss the prediction resolution of different conceptual models in relation to CV, REV, and our observation scale.

Chapters 7 and 8 examine traditional analyses of aquifer tests for confined, leaky, and unconfined aquifers, and boundary effects, which are built upon the equivalent homogeneous conceptual models. While more realistic numerical models for three-dimensional variably saturated flow through heterogeneous geologic media may replace these analyses, the two chapters aim to illustrate the ingenuity of past scientists in overcoming limitations of their tools (analytical solutions) to estimate aquifer properties and to understand their influence on large-scale flow and transport behaviors of an aquifer in a very conceptual sense. These chapters also expose scale issues and nonrepresentative characteristics of the estimated properties associated with applications of the conventional aquifer analysis methods to real-world heterogeneous aquifers.

Lastly, Chapter 9 introduces stochastic modeling approaches including the unconditional approach and the conditional stochastic approach to derive the best unbiased estimates of aquifer properties, which can yield unbiased predictions of flow and head fields at different resolutions and levels of uncertainty. At the end, a new approach to conduct and interpret pumping tests (joint interpretation of sequential pumping tests, or *hydraulic tomography*) is discussed. This new approach allows us to maximize the utility of existing well facilities so as to reduce uncertainty associated with our estimates of properties and predictions of flows.

The first author, Tian-Chyi Jim Yeh, would like to take this opportunity to express his deepest appreciation for sacrifices made by his beloved wife, Mei-Lin Yeh, for the past four decades, since the author started pursuing his science career in the United States of America. Undoubtedly, without Mei-Lin's endurance, support, and encouragement, the thoughts and philosophy of this book would not have evolved and materialized. In every sense, she is the real inspiration behind the book. Supports for Yeh from the Chinese Department of Education as an Overseas-Renowned Professor at Jilin University, China, as well as the NSF EAR grant 1014594 and the Strategic Environmental Research and Development Program (SERDP) under grant ER-1365

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