

Stochastic Methods for Flow in Porous Media, Coping with Uncertainties



DONGXIAO ZHANG

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Flow of water in sub-surface geologic environments takes place through an array of interconnected pore spaces, the spatial distribution of which eludes us. The presence of complex variations in water pathways and geologic characteristics produces large spatio-temporal fluctuations in the values of the variables describing water flow and/or transport of contaminants. The situation is accentuated by the small number of measurements that are usually available in groundwater studies, the dependence of parameter values onto instruments' resolution, measurement and interpretation errors during sampling procedures, and model uncertainties in the description of a hydrologic system.

Traditionally, analyses of groundwater problems relied on solution of partial differential equations that required precise definition of parameters, water sources or sinks, and conditions at the boundaries of the hydrogeologic system. However, and in addition to the hydrogeologic parameters' variation, one typically has to estimate water inputs or outputs to aquifers from agricultural activities, leakage from lagoons, lakes, or other sources of surficial water in an area, and to a large extent hypothesize the hydraulic conditions at the boundaries of aquifers. This combination of spatio-temporal variation, measurement error, and uncertainty has led in the last 30 years to the development of stochastic sub-surface hydrology.

The stochastic framework views parameters and variables no longer as deterministic, but rather, it treats them as exhibiting random fluctuations from one point to another. At the same time, due to the underlying geologic continuity, it views them as remaining correlated over distances and with each other; or, as defined in geostatistical terminology, as random fields. *Stochastic Methods for Flow in Porous Media, Coping with Uncertainties*, written by one of the most active researchers in the area of stochastic hydrology, surveys a broad range of approaches used by scientists in the sub-surface hydrologic community, and presents some of the most recent accomplishments in the development of stochastic methods.

The book commences with a discussion of one-dimensional saturated and unsaturated flows, and uses these two simple cases to illuminate the influence of various sources of uncertainty. This task is accomplished by separately analyzing cases of uncertain water inputs or sinks, such as those encountered during agricultural applications; cases of varying boundary conditions, such as of aquifers connected to rivers of fluctuating stages; or by investigating cases of heterogeneous hydraulic conductivity fields. The book thus highlights early on the need for stochastic concepts and techniques to real flow problems and naturally introduces the reader to these topics.

Although the book requires some mathematical sophistication, the topics are presented in a tutorial way so that knowledge of the theory of stochastic processes is not an a priori requirement. The brief overview of random field theory should suffice for helping readers follow the development of methods presented in subsequent chapters.

The introductory material is expanded in chapters 3 and 4 to cover the more general cases of three-dimensional, steady-state, and transient saturated flows, respectively. Chapters 5 and 6 present three-dimensional unsaturated (both steady-state and transient) and two-phase

flows, respectively; while chapter 7 is dedicated to flow in fractured porous media. Uncertainty is introduced in all cases by the presence of heterogeneous material through which flow takes place, as well as from uncertain sources/sinks and boundary conditions.

The chapters introduce a number of stochastic methods that allow computation of the statistical moments for variables, such as hydraulic head and flux, which are of interest to hydrogeologic studies. Techniques such as perturbation expansions, spectral methods, adjoint methods, Green's function methods, and closure approximations—which have been used in the hydrologic literature to develop solutions—are covered extensively. Numerical applications and a large number of examples are an added bonus that this book offers, as these help illustrate the practical use of mathematical techniques.

Given the complexity of the topic, the book succeeds admirably in presenting the material in as straightforward and reader-friendly a manner as possible, by illustrating the advantages and limitations of each technique to the problem at hand, or by showing that results can be developed independently through different approaches. In that respect, both an advanced audience that has been exposed to the stochastic groundwater literature, and a novice reader of this material have a lot to gain by exposure to the arsenal of tools utilized today in the field of stochastic hydrology. Perhaps the most important aspect offered by the book is the complete and authoritative manner with which the topics are covered, thus allowing stochastic sub-surface hydrology to claim that it has outgrown the research environment, and is ready for use by practicing hydrologists.

—EVANGELOS K. PALEOLOGOS, University of South Carolina, Columbia

ABOUT AGU

Schubert Receives 2002 Harry H. Hess Medal

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Gerald Schubert was awarded the Hess Medal at the AGU Fall Meeting Honors Ceremony, which was held on 8 December 2002, in San Francisco, California. The medal is given for outstanding achievements in research in the constitution and evolution of Earth and sister planets.

Citation

"It is good we are here this evening, not only to honor our friend and colleague Jerry Schubert, but also, perhaps as important, to set the record straight. Otherwise, it is likely that centuries from now historians will struggle with

the mystery of whether Gerald Schubert was one person or, rather more plausibly, a pseudonym for a group of individuals. Great effort could be expended on this enigma, tracts written, conferences held, university departments created, and countless academics gainfully employed. But we here tonight can save them all the trouble and expense.

"For although Jerry Schubert is an incomparable polymath, with a list of major contributions to make us seethe with jealousy, we can attest to the fact that he is indeed just one man. However, Jerry's prodigiousness and diversity aside, what is most remarkable is that so many of his contributions have endured to become classics of geophysics. Many of us would be happy to make a lasting impression in one field; but to have made such an impression in so many fields is simply extraordinary, not to mention intimidating. Since Jerry has more papers than words



'officially' allowed in this citation, I will give you only a brief flavor of some of his major contributions.

"Jerry began his career in aeronautical engineering in the 1960s, but was coaxed first into astrophysics, and then later into planetary

physics. Early in his career, in the 1960s and 70s, Jerry was one of the primary investigators for the Apollo program's lunar magnetometer instruments, which were used to infer lunar crustal magnetism. As is typical in Jerry's career, he has come full circle and recently used apparent magnetic lineations on Mars to constrain the onset and demise of the Martian dynamo.

"Also in the 1960s, when seismology and mineral physics suggested the existence of phase transitions in the mantle at 410 and 660 km depths, Jerry presented several pioneering studies on how phase transitions could either inhibit or facilitate whole mantle convection. And again later in the 1990s, Jerry was at the forefront of similar studies involving catastrophic mantle overturn events. However, before leaving the 1960s, Jerry's 'moving-flame model' provided what remains one of the primary theories to explain why Venus's atmosphere moves faster than, but opposite to, the planet's slow rotation.

"Jerry was also one of the pioneers of planetary thermal history models and was one of the first people to propose that secular cooling contributed to Earth's heat loss, which is therefore not, as was commonly assumed, in equilibrium with the heat produced by radioactivity. Similarly, Jerry was involved in work with David Stevenson that explained the lack of a strong magnetic field on Venus as being due to a central temperature too high and pressure too low to initiate freezing of an inner core. Jerry's contribution to global-scale mantle dynamics also entailed many of the first papers on three-dimensional spherical convection which showed that even simple convection had many of the features we associate with plate tectonics. Jerry's work on the physics of mantle plumes offered some of the first strongly nonlinear analyses of plume initiation, conduit solitary waves (possibly leading to discrete island formation), and the nature of lithospheric thinning by plumes. His studies on the thermal structure of subducting lithosphere, the lifting force on slabs associated with mantle corner flow, lithospheric flexure at trenches, migration of slabs, and subduction initiation are all fundamental to our present understanding of subduction zones. Moreover, Jerry's hypothesis that Venus's coronae are the sites of Venusian subduction generated considerable excitement during the height of the Magellan program.

"Jerry's seminal studies of the propagation of continental freeboard gave the first estimates of Phanerozoic and Precambrian crustal production. His investigation of river morphology was one of the first attempts to quantify the nonlinear processes behind meandering and fluvial erosion. His papers on glacial surges due to shear heating and melting provided a model for the evolution and motion of large ice sheets during climate changes. And his many works on flow and convection in porous media are still considered fundamental studies of geothermal processes.

"After the discovery of intense volcanism on Jupiter's innermost moon Io, Jerry and students investigated the role of tidal heating in a model of Io accounting for both an elastic lithosphere

and a partially molten asthenosphere. Their papers predicted a heat flow pattern on Io that was born out nearly 15 years later by telescopic and satellite measurements. Jerry and colleagues also provided the most recent models of tidal heating in Europa, and have presented evidence of subsurface oceans on both Europa and Callisto with obvious relevance to the existence of extraterrestrial life.

"Jerry has worked at length on the effect of upper atmosphere gravity waves and tidal forcing on OH nightglow and ozone, on topography-driven gravity waves on Venus, and on wave disturbances induced by the impact of Comet Shoemaker-Levy with Jupiter. Jerry led one of the first groups to numerically simulate zonal winds as on Jupiter from deep convection in a rapidly rotating atmosphere. And, because Jerry Schubert hasn't worked on enough problems, he has lately become involved in geodynamo studies which led to the discovery of a new phenomenon called 'teleconvection.'

"However, perhaps one of Jerry Schubert's greatest contributions is that he, with a few others, was a pioneer in bringing a classical physicist's perspective to the many fields of geology and planetary science. The use of a simple first-principles approach to solving geophysical problems has flourished and thus proven an invaluable gift to our community. There is perhaps no greater testimony of this gift than the book he co-authored with Don Turcotte, *Geodynamics*, one of the most highly cherished texts in our field. Recently, Jerry, with Don Turcotte and Peter Olson, produced a new text, *Mantle Convection in the Earth and Planets*, which promises to be the magnum opus of mantle dynamics.

"Finally, Jerry Schubert has tirelessly served the AGU community through his excellence as a teacher and advisor, evident in the number of his students, essentially all still active in science. He has been a conscientious citizen through his participation in space experiments, his large number of editorial appointments, his chairmanship of the Earth and Space Sciences Department at UCLA, and most recently, his election to president of AGU's Planetary Sciences Section. I should also note that this has been a good two years for Jerry; in addition to this honor we are presenting tonight, Jerry was also inducted into both the American Academy of Arts and Sciences and the National Academy of Sciences.

"In the end, it is clear that Jerry Schubert has made, and will undoubtedly continue to make, a profound and lasting impact on our fundamental understanding of the Earth and planets that is nothing short of astounding, and for which we in the AGU are both proud and honored to present to him the Harry H. Hess Medal."

—DAVID A. BERCOVICI, Yale University

Response

"Mr. President, ladies and gentlemen, colleagues, friends, and family members: I have a number of thanks to offer, so let me begin by

thanking David Bercovici for his kind and generous remarks and his friendship. It was only 6 years ago that Dave and I shared the same stage, but in a reversal of our present roles as citationist and medalist. Thanks also to the Hess Medal Committee for selecting me, and to the colleagues who put my name forward and supported my nomination for this special honor. I did not know Harry Hess personally; he died just a couple of years after I entered geophysics. But this recognition means a great deal to me because I have known almost all of the recipients of this medal since it was established in 1984, and I'm proud to be included among them.

"Harry Hess participated in one of the great revolutions in Earth science. Indeed, he played a major role in establishing the theory of seafloor spreading and plate tectonics. I have no claim of any similar paradigm-setting contribution, but I did follow on from Harry's ideas and spent much of my career studying mantle convection, the cause of seafloor spreading. I have also been fortunate to have participated in the great age of close-up exploration of the solar system, an age Harry Hess anticipated and helped plan when he was at the helm of the Space Studies Board. The thrill of discovery is unparalleled, and it's one I have experienced several times in the Apollo missions to the Moon, the Pioneer and Magellan missions to Venus, and the Galileo mission to Jupiter and its satellites.

"In the last few months, I've done a lot of reading about Harry Hess. I found out that we not only had research interests in common, but we also both served in the Navy and we both managed to get some science done during that service. Harry managed to collect data on the bathymetry of the seafloor while commander of a troop transport in the Pacific during WWII. Again my accomplishment pales in comparison, but I managed to write a Ph.D. thesis while on duty at the U.S. Naval Nuclear Power School near Berkeley.

"All of us stand considerably taller on the shoulders of students and colleagues, and I've been very fortunate to have worked with the very best. You'd be very impatient with me if I tried to name all of them. I won't, of course, but I must acknowledge Don Turcotte, who helped me obtain a master's degree at Cornell in 1961 and with whom I've had an active collaboration and friendship ever since. Don recently entered the eighth decade of his life, and he's been honored at this meeting as the Lorenz lecturer and by a special Union session. I also must mention Bill Kaula, my former UCLA colleague, who encouraged and supported me throughout the years. If he were with us today, he'd take some satisfaction in a prediction he made some 27 years ago at an AGU event like this one.

"The last but most important person I'll single out for thanks is my wife, Joyce. She's made it possible for me to focus my energies on science, and for that I'm especially grateful.

—GERALD SCHUBERT, University of California, Los Angeles