Uncertain Future of Hydrogeology

Daniel M. Tartakovsky[1] and C. L. Winter[2]

Abstract: Many of hydrogeology's most fundamental questions remain unresolved today, a hundred years after the basic governing equations for groundwater flow and transport were formulated. This paper provides a brief overview of the field and outlines the future directions, with a special emphasis on uncertainty quantification.

DOI: 10.1061/(ASCE)1084-0699(2008)13:1(37)

CE Database subject headings: Hydrogeology; Ground-water flow; Uncertainty principles.

Introduction

The last several years have seen a considerable debate about the future of hydrogeology as a quantitative science. Several sessions of the AGU Annual Meetings have been devoted to this subject, the latest of which was organized by the guest editors of the present special issue of the ASCE *Journal of Hydrologic Engineering*. At their invitation, we provide our subjective assessment of the field.

Hydrogeology as a Quantitative Science

Reports of the death of continuum-scale hydrogeology (Schwartz and Ibaraki 2001) seem a little premature. As far as we can see, hydrogeology has never been more exciting, or more challenging. While it may look like a mature field at first glance, on closer examination many of hydrogeology's most fundamental questions remain unresolved today, a hundred years after the basic governing equations for groundwater flow and transport were formulated. There remains much work to do because the classic deterministic statement of groundwater theory is incomplete by necessity: It ignores half of the challenge of hydrogeology, which is to represent conductivity (and other system parameters) in a form that reflects our incomplete knowledge of them. We still lack both theory and practice—and perhaps, the will—to deal realistically with basic observational limits.

Groundwater hydrology would be deterministic if we knew conductivity and all other parameters at every point in an aquifer. For that matter, we could solve the Navier-Stokes equations directly if we knew the exact geometry of the pore space. Although raw computer power is enough to solve most practical problems in fluid mechanics, including those involving turbulence, the situation is different in hydrogeology. Our ability to model subsurface flow and transport is severely undermined by lack of information, a problem that cannot be resolved with more computational resources. Enhanced site characterization also has its limits. For the foreseeable future, we cannot know the detailed properties of an aquifer without destroying it, and even that might not be enough for a complete characterization. While the basis of hydrogeologic uncertainty is epistemological, it is no less fundamental in our field than is the Uncertainty Principle (a physical property) in particle physics.

The focus of hydrogeology actually changes once our models take uncertainty into account. We move from a physics that deterministically specifies a system's state to one that estimates its statistical distribution, i.e., provides a probabilistic description of a system's behavior. It is hardly surprising that this fundamental shift is not universally accepted, since various studies (Kahneman et al. 1982) show that "in making predictions and judgments under uncertainty, people do not appear to follow the calculus of chance or the statistical theory of prediction. Instead, they rely on a limited number of heuristics that sometimes yield reasonable judgments and sometimes lead to severe and systematic errors" (Kahneman and Tversky 1973). Whether this state of human cognition can be explained (Gigerenzer 2002) by evolutionary psychology (the evolution of the human brain did not require the concept of probability) or by neuropsychology (the human brain is wired to operate with whole numbers), there exists a general consensus that probability and statistics are not taught properly (Keeler and Steinhorst 2001).

A number of competing models of hydrogeologic uncertainty have emerged in recent years including Monte Carlo simulations, interval arithmetic, fuzzy logic, moment equations, and fractal representations. The very fact of the existence of so many alternative approaches to representation and manipulation of uncertainty arising from limited measurements of groundwater parameters is the sign of a vital field that is still addressing basic questions.

Although consensus on the best way to quantify conceptual (structural, model) and parametric uncertainties in subsurface hydrology has not yet emerged, its general outline is becoming clearer. There seems to be a general agreement that subsurface models have to be probabilistic and the corresponding probabilities have to be subjective, i.e., they have to account for soft data

---

[1] Dept. of Mechanical and Aerospace Engineering, Univ. of California, San Diego, La Jolla, CA 92093; and, Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87505.

[2] Institute for Mathematics Applied to Geoscience, National Center for Atmospheric Research, Boulder, CO 80503.

Note. Discussion open until June 1, 2008. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on August 29, 2006; approved on September 11, 2007. This paper is part of the ***Journal of Hydrologic Engineering***, Vol. 13, No. 1, January 1, 2008. ©ASCE, ISSN 1084-0699/2008/1-37–39/$25.00.

such as expert knowledge (Tartakovsky 2007, and the references therein). With these goals in mind, a scientifically defensible groundwater model should:

- Clearly state its parameters and the scales on which they apply. Among others, parameters will include moments of the spatial distribution of conductivity (and other flow and transport parameters) at different scales.
- Provide unambiguous estimates of the support scale and error bars for any site characterization technique.
- Recognize that all applications of hydrogeology are local. Hence, a satisfactory theory must accommodate data naturally, which is to say it must be Bayesian.
- Specify a means for rescaling measurements. The vast disparity between the scales on which parameters are measured and the scales on which they are used in numerical simulations demands that a theory incorporate methods for scaling measurements up and then interpolating them to spatially distributed random fields.
- Specify a means for computing effective parameters. Although closely related to upscaling measurements, the issue here is one of homogenization rather than interpolation.
- Rigorously trace the effect of measurement uncertainty on estimates of parameter statistics and ultimately, on estimates of the statistics of flow and transport.
- Account for heterogeneity at relevant scales. While simple stochastic models of conductivity have become a mainstay of academic hydrogeology, most models do not accommodate the high degrees of heterogeneity found in many aquifers, and most include scale effects as an afterthought, if at all.

This list is by no means exhaustive. Other outstanding questions remain to be resolved, as are theoretical and computational challenges in other areas of science engineering (e.g., inverse modeling, data assimilation, and sensitivity analysis) on which quantitative hydrology has come to rely.

The paradigm shift from the deterministic framework to probabilistic framework begs the question of whether we are conceptually and technically equipped to deal with it. The short answer is that we are not, since most of our community does not appreciate the central role of uncertainty as a salient feature of subsurface modeling. This state of affairs can be observed at all levels, from students to academicians to practitioners to decision makers. A vast majority of students, and many professors, come to hydrogeology from descriptive fields such as geology and environmental sciences. This leaves them ill-equipped to deal with the physical and mathematical complexities of deterministic hydrogeology, much less its stochastic versions. On the one hand, a significant educational effort is needed to bridge this gap. On the other hand, further breakthroughs in uncertainty assessment in subsurface hydrology will likely come from incorporation of descriptive geology into quantitative modeling.

Instead, the common practice is to use large off-the-shelf numerical codes and treat their results as reality. Practitioners routinely use only a few data points to parametrize computational models containing thousands of degrees of freedom. To make matters worse, data are usually sampled on scales that are many orders of magnitude smaller than the size of a computational cell. Such models are then used to make predictions without any attempt to provide error bars. When decision makers base their actions on such simulations, they are often unprepared for surprises that uncertainty is bound to produce.

While still scarce, the proper use of such codes includes Monte Carlo simulations and evaluation of relative merits of alternative conceptual models. Coupled with mathematical tools and the corresponding software, these codes are increasingly being used for inverse modeling, rigorous calibration procedures, and sensitivity analyses. As the computational power increases, one can expect to see more analyses, in which predictions are accompanied by error bars. At the same time, without further theoretical developments in quantification of conceptual and parametric uncertainties, the brute-force use of deterministic codes will not be sufficient since the ever-increasing size of models (the number of degrees of freedom) is likely to match any increase in computing power.

Rather than advocating more research in uncertainty quantification, a certain segment of hydrogeologists maintain that probabilistic (stochastic) methods—with a possible exception of brute-force Monte Carlo simulations, which require neither further development nor special training—are a dead end that has failed to impact practical applications in any significant way. Rather than attempting to bridge the gap between theory and applications, they call for an end to such research by restricting or eliminating funding and publication venues! This sentiment was on display, for example, during the oral discussion at the 2002 Fall Meeting of the American Geophysical Union (session H61E). However, no amount of wishing will make hydrologic uncertainty go away.

Since one is most afraid of the unknown, the way out of this predicament lies in education. As with other modern fields of engineering, a radical overhaul is needed in educational curricula from high school through graduate school with the goal of improving quantitative skills. Sadly, current trends are in the opposite direction, as can be observed in a number of hydrology programs across the country. Efforts to remedy this situation are under way, as witnessed by the NSF's Collaborations in Mathematical Geosciences program and summer schools, and a newly established Institute for Mathematics in Geosciences at NCAR. The future development of hydrogeology depends on recognizing its quantitative nature.

While the focus of this brief paper is on uncertainty quantification, subsurface sciences include many other research areas that are developing vigorously and provide a plethora of challenging theoretical and computational challenges. These include, but are not limited to, biogeochemical processes, ecohydrology, effects of global change, and scientifically sound management of water resources.

The development of hydrogeology, like any other field of human endeavor, occurs in spurts (and often follows funding cycles). In the past, major breakthroughs in subsurface modeling have been occasioned by the entry into our field of physicists, mathematicians, chemists, biologists, and others. This influx has usually been encouraged by increased funding for subsurface modeling (both hydrogeology and petroleum engineering). Fluid mechanics has recently been reinvigorated through applications in biomedicine where funding is plentiful. The same can happen in hydrogeology, if we are clear about the major challenges of our field. As the population of the United States and the rest of the world increases exponentially, the demand for potable water will become more and more acute. This bodes well for the long-term prospects of hydrogeology and related disciplines, but our field will only achieve its promise if we level with the public, and each other, and frankly begin to quantify our uncertainty.

References

Gigerenzer, G. (2002). *Reckoning with risk: Learning to live with uncertainty*, Penguin Books, London.

Kahneman, D., Slovic, P., and Tversky, A. (1982). *Judgment under uncertainty: Heuristics and biases*, Cambridge University Press, Cambridge, Mass.

Kahneman, D., and Tversky, A. (1973). "On the psychology of prediction." *Psychol. Rev.*, 80, 237–251.

Keeler, C., and Steinhorst, K. (2001). "A new approach to learning probability in the first statistics course." *J. Statistics Education (Online)*, 9(3), ⟨www.amstat.org/publications⟩.

Schwartz, F. W., and Ibaraki, M. (2001). "Hydrogeological research: Beginning of the end or end of the beginning?" *Ground Water*, 39(4), 492–498.

Tartakovsky, D. M. (2007). "Probabilistic risk analysis in subsurface hydrology." *Geophys. Res. Lett.*, 34, L05404.