Editor's Message
Groundwater modeling: Simply powerful[1]

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Groundwater models are widely used today by government agencies, private industry, and universities worldwide in attempts to solve hydrogeologic problems of various types. The popular use of groundwater models results from the development of numerical methods over the past 20 years and the more recent accelerating growth in computing power. Complex applications of this quantitative technology abound. Although the activity surrounding groundwater models certainly demonstrates the potential great value of this technology, the rush to apply these models to more problems by more people overshadows serious questions concerning the fundamental utility of the approach in many of these applications. Logical fallacies in analysis resulting from misapplication and abuse of model technology are widespread.

In 1891, Lord Kelvin gave us a thought that is seemingly a motivation for much of the groundwater modeling done today (Thomson 1891, p. 80-81):

In physical science a first essential step in the direction of learning any subject is to find principles of numerical reckoning and practical methods for measuring some quality connected with it. I often say that when you can measure what you are speaking about and express it in numbers you know something about it: but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind: it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science whatever the matter may be.

M. King Hubbert, a pioneer in the quantitative description of subsurface fluid behavior, responded to Kelvin in a 1974 essay called, "Is being quantitative sufficient?" (Hubbert 1974, p. 47), as follows:

... *the Kelvin dictum equating the reliability of scientific knowledge with the extent to which quantitative methods have been employed may be a somewhat imperfect formulation, and one which in practice may lead to a considerable amount of misdirected effort. For, from what we have seen, some of the most profound results in the history of science have been obtained in geology by means of rigorous but essentially nonquantitative methods of analysis. We have also seen that whereas the employment of elaborate mathematical methods to quantitative data may produce valid results, they equally well may produce results which are fundamentally erroneous and in many situations highly misleading..... a blind adherence to the use of quantitative methods in geology can lead to results which are just as colossally erroneous or just as trivial as may be obtained by any other method.*

The following discussion presents a perspective on the use of groundwater modeling for solving subsurface geotechnical problems, including evaluation of the performance of toxic and nuclear-waste isolation facilities. Although the focus here is on quantitative modeling of groundwater flow, a similar discussion would apply to quantitative characterization of any hydrogeological system, whether in a hydrologic, geochemical, geophysical, geomechanical, or other manner.

A groundwater flow model is a simple calculation stating only: *In a given volume of porous material, the amount of fluid mass that flows in, less the amount of fluid mass that flows out, gives the change in fluid mass in the volume.* Although this algorithm, called a fluid balance, is intuitively obvious, it is the major physical law involved in a groundwater model. Use of a computer to run a groundwater model merely allows the volume for which we wish to calculate a fluid balance to have complex geometry and to be divided into many parts, and the simple mass-balance calculation is applied individually to each sub-volume. Use of a computer may allow calculation of a million of these small balances at once, but it does not change the basic physical meaning of the fluid-balance calculation in a groundwater model, which is indisputably simple.

The fact that a groundwater model is really a simple device is often obscured by the manner in which it is applied. Uninitiated model users and even many experienced model users believe that the numerical model can be made to give an accurate representation of reality if only enough detail and data are included. Modeling efforts exist in which study areas are divided into thousands of sub-volumes for the numerical model and various values of groundwater recharge, transmissivity, and rates of water withdrawal are assigned to these sub-volumes. These values are chosen in time-consuming attempts to match model-calculated pressures with those obtained at measurement points in the field. Such an approach always results in a realistic-looking model, wherein model-parameter distributions appear complex. With modern computer-graphics rendering, such a model can be quite impressive to the uninitiated. In the final analysis, however, such a complex and costly model does no better in reproducing field reality and in making predictions than a simple model with fewer but larger sub-volumes and with constant values of recharge and transmissivity used in the sub-volumes. Because of the simple physical notion upon which the groundwater model is based, both the complex and simple model can calculate the water balance for a study area equally well.

Another example of a complex model that often gives no better results than a simple model is one with a clearly detailed representation of a known structure. Consider, for example, a cross-sectional representation of a landfill with various liners and covers. A very refined division of the landfill into sub-volumes by the model user and careful assignment of flow at the boundaries and transmissivity of each sub-volume results in a groundwater model that implies the same level of certainty as a sophisticated standard engineering analysis. In reality, the flow through the landfill may be very sensitive to the transmissivity values of

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each layer and at any point depends only on the vertical structure of these layers. Although the structure may indeed be represented exactly in the model, the hydraulic properties of the layers are likely only estimates from laboratory analyses on similar materials. Here, the real questions revolve not about the fine details of the structure of the modeled layers, as a layman would guess from pictures of the geometrically precise model in a report, but about the uncertainty in model parameters used for each layer. A simpler one-dimensional vertical model would describe the same system and focus analysis on the appropriate questions. The groundwater model user with a complex model commonly has so many details to deal with that the basic questions that ought to be identified by the analysis are never even considered.

Another logical problem in model use is where an analyst is forced to create a model to solve a particular problem. In many cases, the question to be answered is not even suitable for analysis by numerical modeling. However, the model must be created in order to fulfill contractual obligations. The analyst tries to find a way of using a groundwater model to answer a question that can only really be answered by other means, or perhaps cannot be answered at all.

As an example of this type of modeling fallacy, consider a problem of potential groundwater contamination from a briny waste-disposal pond. The pond is located in a thin unconfined aquifer underlain by a semi-confining unit below which is another aquifer tapped by supply wells down-gradient of the pond. Few data are available beyond general stratigraphy and estimates of bulk hydraulic conductivity of the layers. The question posed by the contract for this work is *How much waste water will reach the well screens in the lower aquifer?*, with the requirement that the answer be determined through use of a groundwater model. A preliminary analysis of the site may indicate that even though the hydraulic head is lower at the well screens than in the pond, the semi-confining layer will isolate the lower aquifer from contamination because of its low hydraulic conductivity. Preliminary analysis may further indicate that diffusion of contaminants through the layer would be even faster than flow through the layer. After a long time, the contaminant finally diffuses through the layer; however, the lateral flow in the lower aquifer is great enough such that the diffusing contaminant is diluted substantially below concentrations of concern before reaching the well screens. If an analyst had done these basic calculations, it would have become apparent that a groundwater model is not needed to determine whether and in what concentrations the contaminant will reach the wells. In this case, the model serves only to generate realistic-looking illustrations.

But what would happen if a break or fracture existed in the semi-confining layer, or if old wells penetrate both aquifers and have leaky corroded casings? This question may appear to be a candidate for modeling analysis, especially considering that the contaminated fluid is highly dense and would tend to sink through an opening. The nature of the opening and its transmissivity are unknown in this case, as no openings have been observed at the site. Here again, the model analysis of groundwater flow required by the contract would have little value, because the model can be made to allow any amount of contaminant to migrate through an opening, depending on how the analyst describes it. For this study, the analyst needed to spend most effort just defining and running the required model, while the real hydrogeologic question on the structure of the confining layer and the possibility of crossflow in old wells was overlooked. In this case, requiring the best answer to the question of contamination, rather than requiring a model analysis of groundwater flow, would have been more effective for the clients.

A widely held view among model users and purchasers of model services is that simulation of a particular problem or field area will yield inherently true results. Some perceived reasons for this are: 1) Models are a sophisticated technology involving computers; 2) All data that exist for a problem can be included in a model; and 3) The model well represents the physics of subsurface flow. This view holds that the model itself is the vehicle for understanding, and that creation of a site model is the main objective of the work. The initiated know that this perception is far from the truth. Transferable knowledge is contained in a report, not in the numerical model. The report describes all of the considerations that went into the analysis and hypothesis testing that lead to the final form of the model. The real goal of hydrogeological work is the development of understanding, not creation of a model. Thus the most important aspect of modeling is not which model to use, not the sophistication of the model's numerical methods, not the creation of realistic-looking simulated distributions, but rather the process of analysis.

The groundwater flow model is merely the tool of the analyst, much as a pocket calculator is a common tool for most people. Although numerically correct, calculations by use of both are useless if not applied in a meaningful way to solve problems. The view that the model itself is the object of a study will eventually disappear as clients who request model analyses come to realize how little practical information they are gaining from many of these requests. Then, requiring hydrogeologic expertise will once again become more important than requiring a model.

A meaningful analysis requires a good analyst. Clever, insightful application of groundwater models requires a healthy attitude. Those who specialize in field techniques are generally concerned with small-scale phenomena and may not have the broad perspective needed to model the data insightfully. Concurrently, those who run numerical models exclusively may use existing field data blindly and literally. Such modelers commonly focus on getting numerical results from the models rather than defining and answering basic questions about a field problem. Finally, those who both collect and interpret field data and who use numerical models, are the ones most likely to develop a proper attitude toward analysis. These analysts know the futility of making a model too complex; yet they also have a detailed understanding of the data and access to circumstantial information, possibly never recorded, that results from hands-on field work. This combination leads to insights regarding the functioning of groundwater systems. Thus, the analyst with the benefit of combined field and modeling experience is the one who is best equipped to make the expert judgments required to define and answer complex questions required for geotechnical analysis.

What are the results of a properly done quantitative hydrogeologic analysis, if a groundwater model is used only if needed? First, the fundamental results of an analysis — what was learned — usually can be stated in a few sentences. The results should include a descriptive list of factors controlling the system studied, the relations among these factors, the sensitivity of groundwater flow field and hydraulic heads to model parameters, and the interactions among parameters over their ranges. The results also should include alternative explanations of the data, or alternative modes of behavior that would be possible with competing model assumptions. A properly done analysis clearly separates things known about the system from things that are still undefined or unknown. However, stating that a calibrated model used for the analysis is suitable for predictions or that it is validated in any way gives a false sense of confidence to those who will apply the results of the analysis.

What is the utility of groundwater models in assessment of safety of sites intended for toxic or nuclear waste repositories? Perhaps the most fundamental problem causing widespread misuse of models today is that the wrong questions are being posed to earth scientists concerning both characterization and licensing of such facilities and clean-up of contaminated sites. Characterization and prediction of the fate of contaminants at sites are often required in an absolute sense; for example, how much contaminant will reach the site boundary and when? This is an impossible requirement considering: 1) the natural heterogeneity in the geologic environment, which can never be described in detail, and, 2) if long-term prediction is required, considering the uncertainty of climatic processes that affect a site. Determination of the probability of contaminant release from a repository also is not possible in a hydrogeologic system, because uncertainties associated with measured field properties, conceptual hydraulic models, future scenarios, and consequences cannot be expressed meaningfully in this way. Assigning likelihood to a given scenario is an even less certain procedure than making predictions using groundwater models. The compound probability of all assumptions required to determine whether a specific release consequence will occur thus has little practical meaning.

Absolute criteria for safe disposal of wastes are and will be in the foreseeable future impossible to guarantee from any conceivable program of site characterization and quantitative modeling. Any legislation that specifically mandates such characterization and subsequent risk-based modeling does not necessarily result in the most effective reduction in public risk that is possible today. A more meaningful approach would be to determine whether one disposal site is better than another site. Relative rankings of sites and isolation technologies is a matter that modern earth sciences can deal with realistically. Performance assessment for underground disposal must be based on a consensus of expert judgment of safety, and not on any calculated criterion. Quantitative safety assessment and modeling are valuable only if they can identify issues that must be considered when reaching such a consensus.

We must hope that the regulations will adapt as awareness grows concerning the significant ***uncertainty concerning the uncertainty*** in hydrogeologic systems, and more realistic goals will instead be set. Disposal of toxic wastes is, in principle, an engineering project, but inasmuch as the safety assessment depends on hydrogeology, the analysis will always be in large part an art requiring expert judgment.

Groundwater models are, without a doubt, among the most valuable tools available today for hydrogeologic analysis. However, they are rarely useful for quantitative prediction of consequences. Their true benefit is primarily found in building the hydrogeologic intuition of modelers. Critical implementation of such models indeed develops skill in the 'art' of safety assessment and in general hydrogeologic analysis as well. With improved intuition and understanding, technically sound but simple and incisive analyses can be selected for any subsurface problem.

A post-script to this perspective on the importance of simplicity in groundwater modeling is again borrowed from M. King Hubbert, who concludes his essay, "Is being quantitative sufficient?" (Hubbert 1974) with the thoughts of Maurice Biot on the analysis of complex problems (Biot 1963, p. 89):

Deeper physical insight combined with theoretical simplicity provides the short-cuts leading immediately to the core of extremely complex problems and to straightforward solutions. This cannot be achieved by methods which are sophisticated and ponderous even in simple cases.

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