The Limitations of Groundwater Models

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ABSTRACT

The ability of groundwater models to accurately predict the behavior of groundwater flow in real-world situations is poor. At best groundwater models, despite their high degree of precision, are qualitative predictors of future behavior. A major cause of the lack of accuracy is the severe discrepancy between the scale of measurement necessary to understand aquifer parameters for accurate modeling and the scale of measurement generally made under the constraints of limited time and limited budgets. In teaching groundwater modeling, it is important that students be made aware of the shortcomings of modeling. Undoubtedly, any model they create will be an extreme idealization of nature and will be nonunique. A nonunique model is one that inherently possesses error. Given these shortcomings, the worth of modeling in making planning decisions can only be derived from analysis of qualitative trends in the overall results.

Keywords: Hydrogeology and hydrology; miscellaneous and mathematical geology.

Introduction

At both the undergraduate and graduate levels, hydrogeology has become one of the most popular specialties in the geology curriculum. Its surge in popularity is not based upon any perception that this field of study is somehow aesthetically more valuable or intellectually more interesting than other fields. If anything, hydrogeology is often judged to be aesthetically wanting among traditional geology faculty (for example, see Stephenson and others, 1991). The dominant appeal of hydrogeology among students is undoubtedly its applicability to real-world problems and usefulness in the job market (Williams, 1989). The appeal of real-world worth is not new to geology. In the not-so-distant past, the number of geology students in a given year was strongly tied to the health of the petroleum-exploration industry (Cody, 1988). In its heyday, ore exploration was also responsible for attracting students into geology.

Unlike the applied aspects of geology that have fueled geology enrollments in the past, hydrogeology is inherently mathematical. Even hydrogeology textbooks that are heavily used by undergraduates (for example, see Fetter, 1994) are riddled with equations. These equations generally are used to quantitatively describe the physical and chemical processes occurring in groundwater. This mathematical approach to hydrogeologic problem solving can prove daunting to both undergraduate and graduate students (and even some geology faculty). The approach makes hydrogeology more akin to geophysics than traditional aspects of geology, and it is not unreasonable to consider hydrogeology a subdiscipline within the geophysical sciences (National Research Council, 1991; Gupta and Kisslinger, 1994).

In both hydrogeology research and applied studies, computer-based models are frequently employed to examine fundamental questions about rates and directions of groundwater flow and associated transport of chemical constituents. Whereas introductory hydrogeology textbooks (for example, see Fetter, 1994; Domenico and Schwartz, 1990) will generally include a section or chapter on groundwater modeling, the actual use and analysis of groundwater models are generally left for advanced courses. Initially, these advanced courses used texts (for example, see Remson, Hornberger and Molz, 1971; Wang and Anderson, 1982) that focused on the mechanics of the computer methods used to simulate groundwater flow. This approach and the courses being taught along these lines emphasized the minimization of computational error associated with computer simulation. Over the last three decades the issue of computational error has been greatly muted by the development of computer programs such as MODFLOW (McDonald and Harbaugh, 1988) and MOC (Konikow and Bredehoeft, 1978), which have been extensively tested and have been applied so frequently that they have near brand-name recognition.

The last decade has seen a continuing evolution of teaching groundwater modeling. The tendency is to de-emphasize the actual numerical techniques employed and emphasize the application of commonly used computer programs such as MODFLOW to real-world problems. The assumption in this approach is that because there are so many reliable computer programs in existence, it is likely most students will never write a groundwater-flow program of their own. To use the automobile as a metaphor, education has evolved from teaching students to be mechanics to teaching students how to be good drivers. (While it is desirable for students to be both good mechanics and drivers, the limitations of time often preclude teaching both aspects of modeling.) Textbooks that emphasize the application of groundwater models are only recently being published (Anderson and Woessner, 1992a).

Whether we teach students how to write their own groundwater modeling programs or teach them

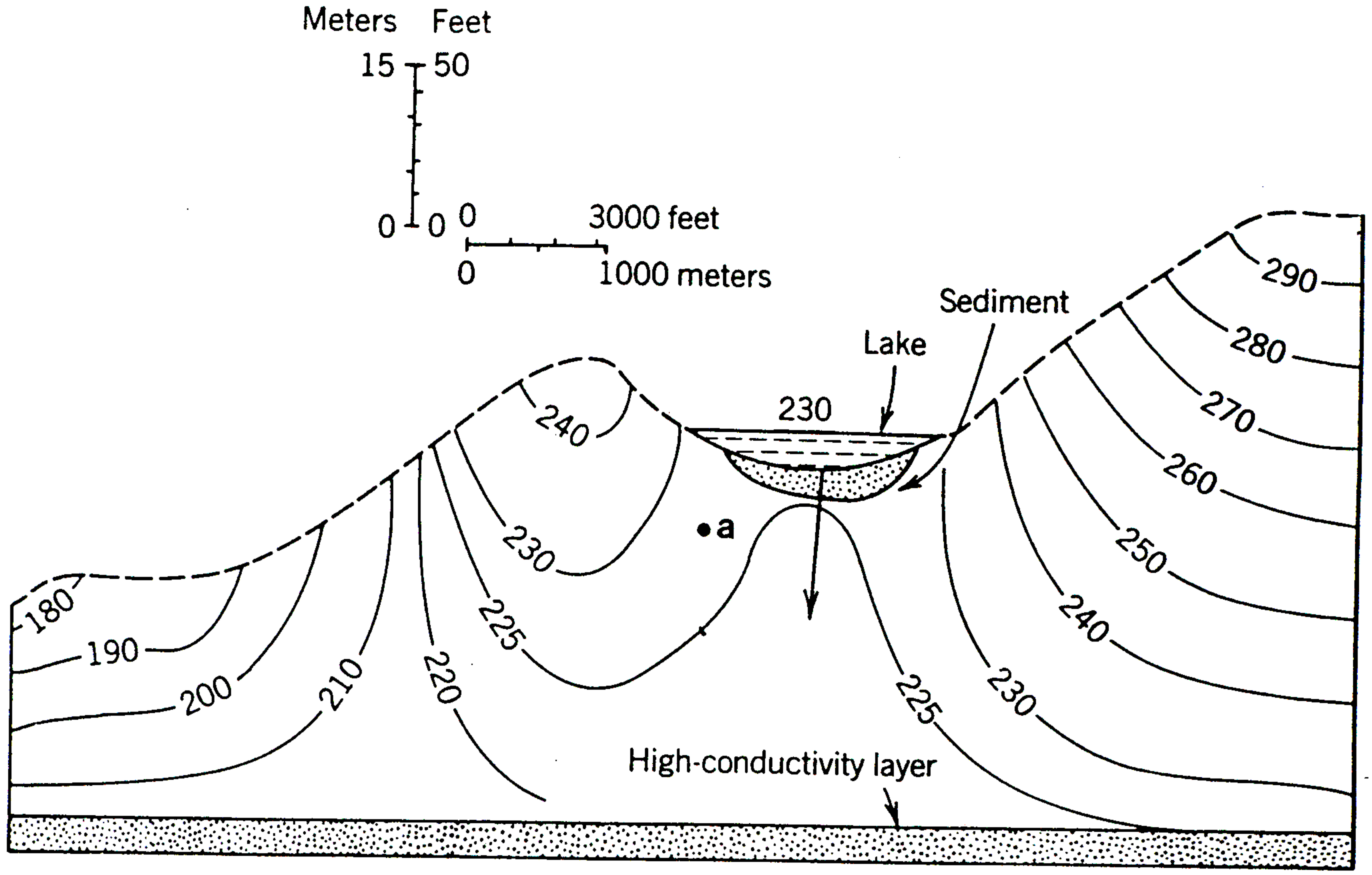

Figure 1. Flow conditions in the vicinity of a hypothetical lake demonstrating the effect of a high hydraulic-conductivity layer at depth on groundwater flow. Contours represent values of hydraulic head. Dotted areas have a hydraulic conductivity 100 times greater than the nonshaded areas (from Winter, 1976).

how to use existing programs, the implicit assumption behind teaching groundwater modeling is that it has inherent value. Presumably, modeling allows us to examine in a quantitative fashion both theoretical and applied questions in hydrogeology. For example, we may wish to understand the role of heterogeneity in hydraulic conductivity on groundwater and lake interaction (Winter, 1976) or the movement of a zone of contaminated groundwater in a municipality that uses groundwater for its municipal water supply. Modeling of groundwater systems can give us answers to these and other problems. It will also give these answers with a high degree of precision. However, the precision offered by a groundwater model does not in any way imply that it provides an accurate description of nature. Even if we understand the physical and chemical processes of groundwater flow and associated transport perfectly, our understanding of the geology and recharge of any region is always too vague to allow for accurate assessment of real-world problems.

Recently, the worth of groundwater modeling as a tool to solve real-world problems has been strongly questioned (Oreskes and others, 1994; Konikow and Bredehoeft, 1992). A major point of criticism is that groundwater models are able to mimic past patterns of groundwater flow in the real world but are poor predictors of future behavior. While this criticism has met with significant dissent (Rykiel, 1994; de Marsily and others, 1992), there are now many examples where groundwater modeling has failed to provide accurate predictions (Lewis and Goldstein, 1982; Konikow and Patten, 1985; Alley and Emery, 1986; Konikow and Person, 1985; Konikow, 1986; Person and Konikow, 1987; Konikow and Swain, 1990; Flavelle and others, 1991; Anderson and Woessner, 1992b). Given the observed inaccuracy in prediction, the value of models in planning decisions where groundwater resources play a role (such as the planning of a high-level radioactive-waste storage facility) is significantly limited. In teaching groundwater modeling, it is important to emphasize this shortcoming, especially since the motivation of most students studying hydrogeology is its applicability to the real world. It is the thesis of this paper that should teach more than how to model. We need to emphasize in our teaching that models can very seldom provide accurate descriptions of real-world hydrogeology.

Theoretical Models: Why They Work

Initially, the principal application of computer-based groundwater modeling was to examine theoretical questions in groundwater hydrology where analytical solutions to the groundwater-flow equation were not feasible. Probably the prime early example of this type of application was that of Freeze and Witherspoon (1966; 1967). In their papers Freeze and Witherspoon used a computer model to examine the role of hydraulic-conductivity heterogeneity on groundwater flow driven by topography. Figure 1 shows an example of another theoretical model (Winter, 1976). In this work, the question examined was the role of hydraulic-conductivity heterogeneity on the interaction between groundwater and lakes. In problems such as Freeze and Witherspoon's and Winter's, the groundwater systems examined are systems that do not exist in nature. No one (including Winter) would claim that the cross section shown in Figure 1 could be found anywhere in the real world. Instead, the examination of theoretical problems such as these represent an idealization of nature.

In theoretical modeling, we have a significant advantage. Because we are dealing with a world we create in a computer, there is no uncertainty. We know exactly the distribution of hydraulic conductivity in our system. We know exactly the nature of recharge entering the surface. We know exactly what is happening at all boundaries in our groundwater system. Under these conditions, as long as our computational methods are correct, we can accurately determine the rates and directions of groundwater flow. If, in our computer model based on Figure 1, our computer results indicate that groundwater flow is occurring at 1.8 m/year in a direction 32 degrees upward from horizontal at point *a*, then groundwater flow is indeed at that rate and in that direction. If we wish to examine where the center of mass of a conservative contaminant at point *a* will be in five years, we can accurately do so. In this case, the computer provides us with a powerful tool to examine how simple, fully understood groundwater flow paths behave.

Analysis of theoretical groundwater models provides us with a means of understanding key controls on groundwater behavior. Their value as research tools is significant. However, the success of theoretical groundwater modeling does not mean that the same techniques are readily translatable to real-world problems. Imbedded in our theoretical models are highly idealized descriptions of the real world. Unfortunately, nature only slightly resembles the world we create in our computers.

Real-World Complexity

The nature of contaminant transport in the subsurface has been the most studied topic in hydrogeology for over a decade. Figure 2 shows the results from one of the first extensive field examinations of a planned injection of a contaminant into the subsurface (Mackay and others, 1986). The field site for this experiment, the Borden aquifer, was partially chosen because of its apparent geologic simplicity; the Borden is a medium- to fine-grained sandy aquifer underlain by low-permeability clay. Prior to injection of chloride and bromide, a small but extensive well field was installed to monitor early movement of the contaminant. Examination of the contamination plume relative to the well field indicates that the direction of groundwater flow

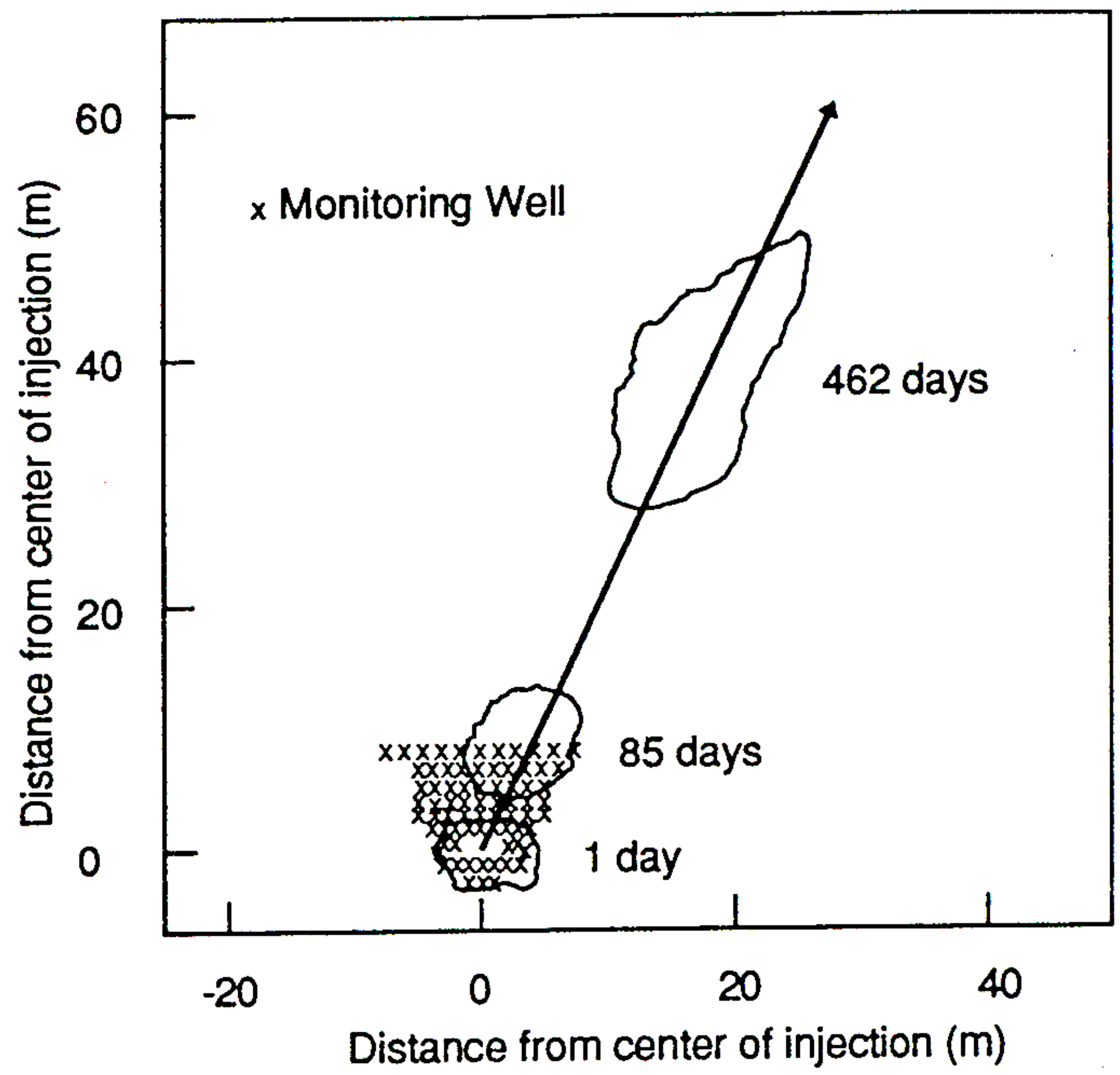

Figure 2. Migration and spreading of chloride plume in the Borden aquifer at various times after injection. Arrow indicates trajectory of chloride plume (from Mackay and others, 1986).

and contaminant transport unexpectedly shifted 25 degrees from the orientation of the well field.

This shift was not part of the design of the field experiment, and those who sited the wells did not lose their compasses. The well-field orientation was determined from hydraulic gradients estimated from measurement of hydraulic head in existing wells. Unfortunately, the gradient of hydraulic head was not accurately determined from the initial measurements. The transport of the plume was shifted by 25 degrees relative to the well field because the orientation of the wells was 25 degrees from the apparent average annual hydraulic gradient. Some very smart scientists involved in a very carefully designed field experiment were unable to predict the path of groundwater flow even though the geology was simple at face value. The scientists involved in this study stated that the shift was due to a lack of "thorough analysis of the water-level data" (Mackay, 1986), but this assertion appears to be the result of 20-20 hindsight. Once the entire well field was drilled, it was possible to accurately measure the hydraulic gradient and confirm that the movement of the plume followed a path that was within 2-5 degrees of the true hydraulic gradient (Freyberg, 1986; Sudicky, 1986).

The inability to predict the path of groundwater flow in this simple field setting was imbedded in the design of the experiment. Initially, wells were drilled only near the injection site. Only when the direction of movement was measured were new wells drilled slightly in advance of the contaminant plume. The process of choosing drilling locations based only upon the recent behavior of the plume was repeated until the experiment ended. This methodology of choosing drilling locations based on plume movement (rather than trying to predict the direction of movement by measuring hydraulic-head gradients) was also used in a similar field experiment at Cape Cod, Massachusetts (LeBlanc and others, 1991).

In their field experiments, groundwater hydrologists prefer to be cautious. Rather than predict groundwater flow rates and directions through models that employ Darcy's law, the hydrologists base their experimental design on direct measurement. Apparently, they do not have enough confidence in their models to use them for accurate prediction in their own experiments. If groundwater hydrologists do not use their own models for accurate prediction, why should those who make planning and policy decisions regarding groundwater resources believe in a model's ability to accurately predict the groundwater flow?

Suppose a groundwater hydrologist chose to be bold and make a prediction of contaminant movement at the Borden aquifer based upon initial data on hydraulic head and hydraulic conductivity. As noted by Mackay and others (1986), the initial coverage of wells was relatively representative of monitoring systems used in investigations of contaminant distribution at waste-disposal or chemical sites, so any prediction made would be fairly representative of predictions based on typical sampling schemes and very simple hydrology and geology. If a computer model were employed that incorporated hydraulic-head data from the initial well field and 26 hydraulic-conductivity tests made at Borden, the contaminant would have been expected to flow parallel to the orientation of the well field, and its center of mass would have been expected to move about 15 percent slower than observed. Such a prediction, while not perfect, would certainly be valuable for planning purposes. However, the geology in the Borden was far simpler than can be expected in most settings. The hydraulic gradient is fairly uniform, and seasonal variations in its orientation are fairly modest. The hydraulic conductivity of the aquifer varied by only a factor of 2 in the well tests (and only by a factor of 30 in core tests) (Mackay, 1986; Sudicky, 1986), indicating that the field site was essentially an ideal "sand box" for an experiment. What are the data requirements for a site with complex geology if approximate prediction is the goal of the study?

Real-world Modeling and Nonuniqueness

In some sense, there is little difference between making a geologic map and making a hydrogeologic model. Geologic maps, because they are based on limited data, are inherently nonunique. In making a map, the geologist has data largely limited to outcrops. To understand the nature of the rocks and structures beneath the soil layer, one must interpolate between the outcrops. That interpolation usually takes into account the geologist's notion of the dynamic processes that created the observations. The interpolation is never precise, and two geologists mapping an area can be expected to develop two maps that are significantly different from each other.

In making a hydrogeologic model, one faces much the same difficulties as a geologist making a geologic map. To make a hydrogeologic model of groundwater flow under steady-state conditions, one must make a map of hydraulic conductivity and flow conditions at the boundaries of the groundwater system. The map of hydraulic conductivity is always based on limited data, and the data are usually obtained from well tests. Creation of the hydraulic-conductivity map requires interpolation that usually allows for the hydrogeologist's notion of the dynamic processes that created the aquifer and almost always takes into account the observations of hydraulic head in whatever wells are available. Unfortunately, this interpolation process is inherently nonunique. Two hydrogeologists who have utilized both an understanding of the area's geology and the observations of hydraulic head in known wells will derive significantly different maps of hydraulic conductivity for their hydrogeologic models.

Neither map is the "correct" map. Both maps, while they may honor observations, have error due to interpolation. The use of interpolation implicitly acknowledges that the available data are inadequate. While we may attempt to minimize the error induced by interpolation, the actual magnitude of the error can never be known.

The inherent nonuniqueness in hydrogeologic models is well known (Gilham and Farvolden, 1974). One can easily educate students about this shortcoming by having them work individually on a simple real-world hydrogeologic model. The individual models can then be shown in class and compared. Figure 3 shows the hydraulic-conductivity maps of two graduate students in a modeling class. The region modeled can be found in Anderson and Woessner (1992, p. 272) and consists of a 1500 by 1500 m sand and gravel aquifer of fluvial origin. There are 17 wells in the area, two of which are being pumped, and heads over time are known for all of the wells. While the assigned modeling exercise is fairly simple, the quantity of data available relative to the size of the modeled area is excellent compared to most real-word problems.

In making the hydraulic-conductivity maps, the students were given three major rules of thumb: 1) keep the map as simple as possible; 2) honor the observations; and 3) make sure the hydraulic-conductivity map makes geologic sense. The rule of thumb that the hydraulic-conductivity map must be simple (as homogeneous as possible) introduces a bias in the students' maps that probably has no fundamental basis. Even under the constraints of simplicity and honoring the data (the geologic viability of the maps is debatable), the maps, while qualitatively similar, have significant variability. The variability is not surprising. It is impossible to derive a unique map of hydraulic conductivity given the data that are available. Suppose in this region one wishes to examine the effects of installing a pumping well at point *a* on groundwater-flow rates or understand the rate and

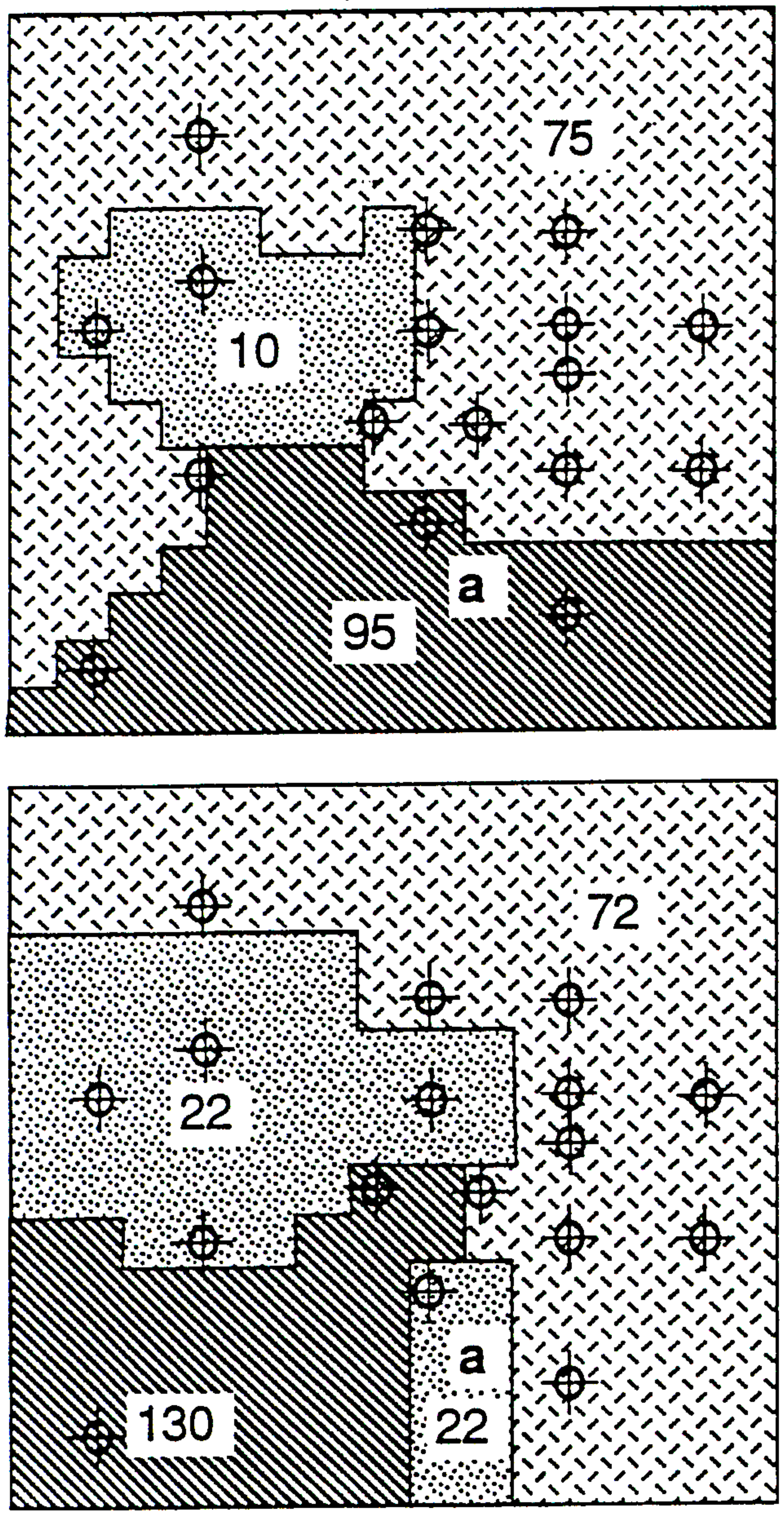

Figure 3. Maps of hydraulic conductivity (in m/day) from two graduate students in a groundwater modeling exercise. Location of wells whose hydraulic head values were used to constrain the model are shown as crossed circles.

direction at which a conservative contaminant at point *a* would move through the aquifer. The results would strongly depend upon the hydraulic-conductivity map chosen.

The nonuniqueness indicates that both of the maps possess conceptual errors. Given the nonuniqueness of the maps and the results, it would be ridiculous to simply choose one model as the best and make planning decisions based upon the one best model. Somehow we need to incorporate an estimate of error in our prediction of future behavior. We could try to include error associated with nonuniqueness by producing a range of results that incorporated simulations from a range of hydraulic-conductivity maps. We could even become systematic and employ stochastic techniques to develop statistical bounds for our results. We would likely find that the range of predictions obtained either through an ad hoc implementation of a limited set of hydraulic-conductivity maps or stochastic simulations would provide error bounds that would be exceeded by the actual future behavior (for example, Luis and McLaughlin, 1992). If previous tests of the predictive capability of models are any indication of the error imbedded in nonuniqueness, (Lewis and Goldstein, 1982; Konikow and Patten, 1985; Alley and Emery, 1986; Konikow and Person, 1985; Konikow, 1986; Person and Konikow, 1987; Flavelle and others, 1991), our predictive-model results generally have only order-of-magnitude accuracy. The assessment of accuracy in these tests, however, is usually clouded by additional errors induced by human-impact effects or changes in climate not included in the original predictions.

Back of the Envelope Versus the Computer

It would appear that, given the inherent inaccuracy of computer-based groundwater models, we are getting little bang for our buck. We run complicated quantitative models and get only very qualitative results. It may seem more efficient to make simple "back-of-the-envelope" calculations to achieve the same qualitative result. For example, we could predict groundwater behavior in the region shown in Figure 3 without recourse to numerical models if we assumed the aquifer was perfectly homogeneous or perhaps had a heterogeneity with a simple geometric structure. Because the numerical models shown are nearly homogeneous, the results of our back-of-the-envelope methods would likely be within an order of magnitude of our numerical model.

Since we have an inaccurate description of the real world in our computer, why bother with the added complexity of heterogeneity? Why not simplify the real world so that predictions of groundwater flow can be made with analytical solutions? Back-of-the-envelope calculations have one significant advantage over computer-based techniques. The process of homogenizing the data is one that requires the student or scientist to think thoroughly about the problem at hand before rushing off to obtain a solution. One must understand what parts of the available data are important and what parts are relatively unimportant and can be discarded. This process of simplifying usually requires intuition gained through experience and often some background in dimensional analysis. Unfortunately, students usually have limited intuition and most students (and most hydrogeologists for that matter) have had very limited exposure to the techniques necessary to make back-of-the-envelope calculations. After thirty years of computer-based approaches to hydrogeologic problem solving, training in computer methods has almost completely supplanted training in analytical methods.

The tendency is to assume that, since computer models are easier to use than analytical methods and can incorporate complexities not possible with analytical methods, back-of-the-envelope methods have become obsolete. Presumably, because numerical models can incorporate all of the data discretely and can include complex aquifer geometry, the qualitative results they generate will be significantly more representative of real-world behavior. The degree to which numerical models are better descriptions of real-world behavior, however, is unknown. At any rate, whether one uses the back of the envelope or a full-fledged groundwater model, the predictive capabilities of either method will still be qualitative in nature. While a computer may deliver a prediction with a great deal of precision, the prediction should be treated as if it was made with a back-of-the-envelope calculation.

Real-World Modeling: When It Works

In the previous sections, I have tried to state the inherent problems in using groundwater models for predictive purposes. Some readers may have interpreted these criticisms to indicate that real-world modeling is a worthless exercise. Nothing could be further from the truth. While real-world models cannot usually be used for quantitative prediction, they can have intrinsic value. Despite their inherent idealization of nature, they provide a valuable tool to test hypotheses.

For example, in the problem shown in Figure 3, we may wish to examine whether a period of drought will have a significant impact on the water supply in the area. To examine this problem we can run our groundwater model and examine the scenario produced by a drought. Obviously, the quantitative results we obtain will be dependent upon the boundary conditions, and the permeability map we employ in our model. It is possible, however, that the results will be qualitatively similar for many feasible maps. If a planning agency were to ask what exactly the effects of drought would be, we would be unable to give them an exact answer with our model. However, our modeling efforts would give us a qualitative feel for the possibility that a drought will significantly impact water supply. Modeling this problem helps us to make an informed, qualitative judgment.

Perhaps more importantly, real-world modeling offers us a way to make a preliminary assessment of a problem. For example, in our efforts to examine the potential impact of drought in a region, we may use a model as a tool prior to performing a site investigation. We can use the available data and run different scenarios in our model with the intent of examining which parameters or regions most sensitively effect results. This effort helps us identify where to make measurements and what measurements we need to make a better assessment of the problem. In this way, modeling can allow us to perform our field work in a more efficient manner. The models we use may be simple, but they are a quantitative tool capable of providing qualitatively useful information.

Conclusions

Faced with the discrepancy between the precision and accuracy of groundwater models, one has two disparate choices. One can challenge the magnitude of the discrepancy and ascribe most model predictive error to inappropriate conceptualization, or one can advocate that, given their inaccuracy, the use of computer models in planning and decision making should probably be abandoned. Both approaches are unrealistic. The first alternative flies in the face of observations of model predictability. Accuracy in prediction is assumed to be a skill or art that is less dependent on the number of measurements than the proficiency of the individual modeler. It is false optimism to assume that a modeler, regardless of his or her skill level, will be immune to significant errors in conceptualization that have befallen other modelers. Errors in conceptualization are inevitable given our limited data sets. It is fortuitous for errors in conceptualization not to lead to errors in prediction.

The second alternative ignores the need of planning agencies to have some predictive power, regardless of inaccuracy. Technically speaking, uncertainty in estimates of hydraulic conductivity and other aquifer parameters precludes the possibility of our ever developing an accurate model. While we are unable to predict the future accurately, examination of performance of past models does indicate that we can usually qualitatively mimic observations. Even a model that can only provide order-of-magnitude estimates of future behavior can sometimes be valuable.

There is an implicit dichotomy between the nature of groundwater modeling and the worth of models for predictive purposes. While groundwater models are highly quantitative and deliver results with great precision, we are generally restricted to using the qualitative trends in modeling results for planning and decision making. Student hydrogeologists and professional hydrogeologists would dearly love to predict the behavior of groundwater systems with great or even partial accuracy. Unfortunately, data incompleteness precludes this possibility, and almost all groundwater models of the real world can be expected to contain significant error. The value of a groundwater model in planning decisions is less a function of the model and more a function of the needs of the planning agency. If a planning decision requires precise determination of future scenarios, a groundwater model will be useless. If the planning agency can live with qualitative interpretation of quantitative results, the model will have value.

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