ground water

Technical Commentary/

On Modeling Philosophies

by J. Bredehoeft

It is my intent to explore the several philosophies that have governed ground water modeling from its inception. I want to focus on the water supply problem—the problem of maintaining a particular ground water development.

Sustainability

Sustainable development is defined as that which meets the needs of the present without compromising the ability of future generations to meet their own needs. Implicit in this definition is a conservation ethic that states our generation should not use the resources of the planet, in the broadest context, in a manner that leaves future generations with problems of degraded or impossibly depleted resources. The idea introduces value judgments to be made by society.

One of the usual goals in planning a ground water development is to maintain the supply for a prolonged period. It is important to recognize that while this is usually a necessary condition for sustainability, it is, by itself, insufficient to establish sustainability. Let me try to clarify this idea with two examples. The first example is that of an aquifer where part or all of a given ground water development is balanced by a reduction in the consumptive use by phreatophytes. It may be possible to maintain this ground water development indefinitely but only by killing the phreatophyte vegetation. If loss of the vegetation is unacceptable to society, the development, while it may be technically feasible, is unsustainable.

Alley and Leake (2004) provide a second example. They explored the concept of sustainability, using a proposed ground water development in Paradise Valley in northern Nevada as their illustration. There are four sources of water that support the pumping: (1) ground water from storage; (2) capture of evapotranspiration (ET); (3) capture of surface water that flows out of Paradise Valley; and (4) induced recharge from the Humboldt River. The ground water system in Paradise Valley takes a long time to reach a new equilibrium state; even after 300 years, 3% of the water pumped is still coming from storage. The induced recharge from the Humboldt River grows from zero in the early years to ~19% of the total in year 300. The capture of surface water outflow from the valley grows to 3% in 300 years. The analysis suggests that the Paradise Valley pumping can be maintained indefinitely, i.e., the pumping will at some point (after 300 years) be balanced by the capture. However, the system reaches a new steady state by depleting streamflow in the Humboldt River; this is river flow to which the downstream users have appropriated water rights. Any reasonable application of the principles of sustainability suggests that the Paradise Valley ground water development is not sustainable; it infringes on the prior rights of others.

Maintaining a Long-Term Ground Water Development

Theis (1940) explained that the problem of maintaining a well for a prolonged period is one of determining its *capture*. The USGS (Lohman 1972) in *Definitions of Selected Ground Water Terms* published the following definition of capture:

> Water withdrawn artificially from an aquifer is derived from a decrease in storage in the aquifer, a reduction in the previous discharge from the aquifer, an increase in recharge, or a combination of these changes. The decrease in discharge plus the increase in recharge is termed capture.

Neither recharge nor discharge are of interest in determining capture; rather it is the changes in these quantities, caused by the pumping, that we seek—the relevant quantity to determine the maintenance of a ground water development is capture. How do hydrogeologists determine capture?

In discussing these ideas, other investigators point to the importance of knowing the virgin recharge and/or virgin discharge in determining the long-term viability of a ground water development—especially the virgin

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recharge. They argue that these parameters are an important element of ground water modeling. It is my intent to examine this idea from a different perspective.

Analytic Methods

Before hydrogeologists had analog or numerical models, classical analytic methods were used to determine capture. For example, there is a long tradition of published analytic solutions that assess the impact of pumping ground water on an associated stream. These methods calculate only the changes in head and flow associated with the pumping. Actual values of head during the pumping are determined by superposing the calculated changes on the values of head prevailing prior to the pumping. This is the principle of superposition.

One of the earliest uses of the principle was in a paper by Theis (1941) entitled *The Effect of a Well on the Flow of a Nearby Stream.* In this approach, the stream is treated as a line source for a well pumping in a semi-infinite space. One solves for the hydraulic head change due to the pumping in the semi-infinite domain at any particular time; initial heads are assumed to be uniform and equal to the stream level prior to pumping. This, in turn, implies that head throughout the domain of the analysis can be taken as zero prior to pumping. By determining (1) the pumping-induced hydraulic gradient along the stream boundary that can be derived from the solution; (2) applying Darcy's law; and (3) integrating along the boundary, one can determine the capture (flow into the aquifer) from the stream at any time. If one then projects the pumping to infinite time, one can determine the ultimate stream capture. It should be clear, in this case, that the stream capture is the flow of water from the stream to the aquifer caused by the pumping.

What was needed to make the previously described analysis? One needs the aquifer properties—transmissivity and storativity; the boundary condition—in this case the stream as a line source; and the geometry of the system, especially the distance the well is from the stream. What is not needed is the recharge or the discharge to/from the aquifer; these are irrelevant for solving the problem at hand.

If one is interested in the actual values of the water table and ground water flow under the pumping regime, the changes in head and flow calculated by the analytic method are superposed on (i.e., added algebraically to) the corresponding heads and flows prevailing prior to the pumping. For example, this may be done to estimate the extent to which the stream-aquifer interaction involves actual flow from the stream into the aquifer, as opposed to a reduction in ground water flow from the aquifer to the stream. It is important to note that the head prevailing prior to pumping already reflects the prepumping recharge and discharge. The head distribution calculated by superposition reflects the recharge and/or the discharge from the aquifer under the pumping regime, although knowledge of either the recharge or the discharge was not needed for the analysis.

This may seem like a simple, perhaps even trivial, example, but all the equations used in analytic methods are solutions to similar boundary value problems. One has to know the boundary conditions, the initial conditions, and the aquifer properties in order to solve the problem. Or conversely, if one is observing the hydraulic head response to a specified stress, one can solve for the aquifer properties—this is the aquifer test method. Again, if one seeks the configuration of the actual hydraulic head, one projects this by superposing the calculated head changes (for example, drawdown) on the observed hydraulic head.

Analog Models

The electrical analog model represented a major advance in analytic capability. The method is based on the analogy between the flow and storage of electricity and the flow and storage of ground water, in which voltage is analogous to hydraulic head and electrical current is analogous to the flow of ground water. The domain of interest was subdivided conceptually into finite-difference cells; an electrical network was overlain on the finite-difference mesh. Electrical resistors represented the transmissive properties of the aquifer in each cell, while capacitors represented the storage capacity of the aquifer at each node.

In an analog model, the geometry of the aquifer could be closely approximated, irregularly shaped boundaries could be simulated, and heterogeneous aquifer properties could now be represented. Multiple layers could be included. The USGS maintained an analog model laboratory in Phoenix where very large models were routinely constructed and operated. Some of the USGS analog models incorporated several tens of thousands of nodes.

The analog models were operated, almost without exception, in the superposition mode. The model replaced the analytic method; the intent of the model was to determine capture directly. It was frequently difficult to simulate virgin recharge and virgin discharge in the analog model, and in practice, it was almost never done (Moore and Wood 1967).

The analog model approach effectively superceded the classic theoretical analysis, but as with the analytic approach, superposition was an integral part of the analog method.

Numerical Ground Water Models

Numerical ground water models have proved to be robust tools for the analysis of ground water problems, especially with the advent of today's powerful PCs. Although they can be used in the superposition mode, as was the case for the analytic and analog methods, they also allowed modeling in the full-blown model mode. In this mode, the model is used (1) to simulate conditions that prevail prior to development and (2) to predict conditions during and/or following development.

It was recognized that the virgin piezometric surface or the water table surface contained information on the recharge and discharge from the aquifer system. In theory, if one also knew the transmissivity distribution of the aquifer, one could solve for the distribution of virgin recharge and virgin discharge. Or conversely, if one knew the recharge or discharge, one could, by reproducing the piezometric surface, determine the transmissivity of the aquifer. I was one of the first to apply a steady-state numerical model analysis to the Dakota Aquifer in South Dakota in an effort to determine the hydraulic conductivity of the confining layer over the Dakota Aquifer (Bredehoeft et al. 1983).

In the full-blown mode, a ground water model analysis usually starts with an analysis of conditions that prevail prior to a proposed development—i.e., the initial condition. In this analysis, one inputs recharge, discharge, and the past or existing ground water development. The model is calibrated by adjusting the parameters to best fit an observed hydraulic head distribution. Because the simulation results in calculating hydraulic head, the calibration is facilitated, since the calculated head can be compared to the observed head. Depending upon the nature of the recharge/discharge and the existing development, this analysis could be conducted as either steady state or transient. Having a representation of the initial conditions, one can then impose the proposed stress upon the system and predict hydraulic head.

For some problems, one may be seeking only the virgin steady-state condition. Often, it is convenient to initiate a numerical ground water model study by doing a steady-state analysis in which one inputs the virgin recharge and discharge and determines a predevelopment water table or piezometric surface that fits the observations and is stable in time. This has become the accepted procedure in modeling ground water systems. Many investigators point to this process for the need to know recharge and/or discharge—especially the recharge. The question is—is this necessary for modeling?

The answer, of course, is that knowledge of the virgin recharge/discharge is not always necessary for ground water modeling. Many models have been built in the superposition mode, both analog and digital, in which the intent was to determine capture—capture of water as defined previously (Longenbaugh 1967; Pinder and Bredehoeft 1968; Young and Bredehoeft 1972). In the superposition mode of analysis, one seeks to determine how much the discharge can be reduced, or the recharge can be increased, by the pumping. As suggested previously, one needs (1) the aquifer geometry; (2) the aquifer properties; and (3) the boundary conditions to make such an analysis. The shape of the piezometric surface/water table or the recharge/discharge are not needed—they are extraneous for such an analysis.

Concluding Remarks

Models can be operated in differing modes to accomplish different goals. Models, both digital and analog, have been operated in what I refer to as the superposition mode to determine capture—capture as defined previously. In the superposition mode, one calculates the change in head caused by the stress and looks at the impacts of that stress on the boundaries. Alternatively, in the full-blown model mode, one first tries to create an initial condition within the aquifer and then imposes the stress of interest. In the full-blown model mode, one is calculating the actual head in the aquifer. Each mode has its advantages and disadvantages.

It is a matter of efficiency, and sometimes data availability, whether one uses the superposition mode or the full-blown model mode analysis. Each method can lead to good analyses if used correctly.

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