Ground-Water-Simulation Apparatus for Introductory and Advanced Courses in Environmental Geology

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ABSTRACT
We have developed a new advanced hydrogeology pollutant-transport simulation apparatus that is widely adaptable and can be used for quantitative experiments. It allows students to readily observe processes that are otherwise unobservable because of temporal and spatial constraints and because they take place in the subsurface. The simulator is a gently inclined, 61 cm x 122 cm terrarium with input and outflow ports on either side. The terrarium is filled with layers of sand and clay to simulate stratigraphy. “Wells” are simulated by clear plastic tubes with screened ports that are spaced at regular intervals and depths. In one experiment, water-based dye is injected as a plume in the top center of the terrarium, creating a slug that moves down the gradient towards the wells. Groups of students pipette samples from the wells at regular intervals and qualitatively estimate dye concentrations using a color-tone calibration set. Flow models and time-integrated displays of plume concentrations can be constructed. A second experiment involves measuring water height in the wells and constructing a flow net for the system using a computer program.

Keywords: Apparatus; education – computer assisted; education – undergraduate; engineering and environmental geology; hydrogeology and hydrology; miscellaneous and mathematical geology.

INTRODUCTION
Laboratory exercises designed to help students study processes of ground-water movement are limited by the difficulty in viewing the processes, by the space over which they occur, by their duration, and by the difficulty in data collection. Consequently, students typically analyze old data sets from laboratory manuals. The exercises are little more than homework assignments done in class. Studies have shown that students learn more and retain more knowledge when research experiences include a “hands on” component (Pinet, 1989; Markovics, 1990; Klasner and others, 1992). An appreciation for ground-water processes is especially important during these times of heightened environmental awareness and the large number of employment opportunities in the field of environmental geology.

To help provide students with this important background, we have designed, constructed, and tested a ground-water-simulation model that appears to be extremely effective. The apparatus can be easily replicated using commonly available materials. It not only visually demonstrates important hydrogeologic principles on the scale of a laboratory class but also allows quantitative analysis of easily collected data. In this paper, we introduce the ground-water-simulation apparatus and describe one introductory and one advanced-level exercise.

Lehr (1963) developed a ground-water-simulation apparatus to illustrate subsurface ground-water movement through stratified rocks. Merritts and Shane (1991) found that this apparatus could be used for simple experiments and computer analysis that are appropriate for an introductory course in environmental geology. Such simple ground-water simulators are now commercially available. The Lehr (1963) model and commercial copies thereof have a fixed stratigraphy and are relatively two-dimensional. Although they are excellent at illustrating processes under fixed conditions, they are limited in the range of possible exercises they can be used for. Processes that involve the third dimension are also not represented. To overcome these problems, we have designed and constructed our own ground-water-simulation model, which improves upon these previous attempts.

GROUND-WATER-FLOW SIMULATOR
Our model was designed and built to simulate ground-water and minor surface-water flow (Figure 1). A custom glass tank was built (l = 122 cm, w = 61 cm, h = 38 cm), and three 2.5 cm holes were drilled into each of the end walls at 6 cm height. (Later, we found that only one outlet hole was needed.) Two Plexiglas barriers were mounted across the width of the tank 9 cm from the ends using silicone sealant. Holes (ports) were drilled in the barriers on a grid at 2.5 cm spacing. The stratified material through which the water flows is placed between the two barriers. The 9 cm open spaces between the barriers and the ends of the tank are used to inject and drain water to ensure an even feed and stable flow on the input side and to avoid ponding of water in the aquifer at the drain end. The bottom layer of the stratified material is a 6 cm thick Styrofoam spacer that is sealed to the tank with silicone sealant. The purpose of the spacer is to raise the usable stratified materials to an easily observable height while keeping the weight to a minimum. Above this spacer, layers of sand, gravel, and clay are placed to simulate particular stratigraphic situations.

Hose fittings are fixed to all of the ports on either side of the tank. On the input side, the hoses are
can be approximated by the movement of the center of the slug through the well field. In the case of our test, the velocity of the ground-water flow was approximately 3.25 cm/min.

Figure 3 (left and above). Contour maps of dye density during a typical laboratory exercise with wells and density values posted. Dye density distribution (drops of dye/vial) and contours (Cl=2): T1 after 240 s, T2 after 480 s, T3 after 720 s, T4 after 960 s, and T5 after 1,200 s.

Varying the stratigraphy leads to differing ground-water-flow patterns and consequently different results. Such scenarios as leaky aquifers, permeable bodies in the aquifer, facies changes in the aquifer, faults, and multiple streams among others can yield interesting results. As an alternative, students can be allowed to design the stratigraphy, which can generate additional interest in the exercise and, ultimately, additional learning.

Potentiometric Surface Model and Flow Nets
In our second exercise, we modeled the potentiometric surface. The data are easy to collect for this exercise, but the analysis is a bit involved; therefore, it would be more appropriate for a hydrogeology or an advanced environmental geology class. The tank is assembled as described, and water is introduced to the system and allowed to achieve equilibrium as in
the pollutant-plume exercise. Using a level, lines of equal height are drawn as high on the plastic well tubes as possible. A series of 14 wooden sticks (mixing sticks, thin dowels, or popsicle sticks) of equal 10 cm length are collected. A straight line is marked across each stick 2 cm from the end using a black marker. Each stick is inserted into a well so that the mark on the well aligns with the mark on the stick. The bottom of the stick should be in the water. The sticks are then withdrawn from the well, and the distance from the mark to the wet part of the stick is measured. This procedure is repeated for each of the 12 wells in the field as well as the injection well. Finally, the level of the lines on the wells is extended to the stream using a straight edge, and the water level there is also determined. If the tank is set up only to perform this exercise, then the well distribution should be changed so that they traverse the entire tank, and the stream should be eliminated. The measuring procedure is the same. The collected data are the water heights and the well positions.

As an example of how the box model can be used in conjunction with aquifer-modeling software, we used AQMODEL for Macintosh® to create flow nets and potentiometric surfaces (Figure 4). AQMODEL is a ground-water-modeling program designed to yield solutions to the problem of wells pumping within a confined aquifer under uniform flow conditions in a homogeneous and isotropic setting.

The objective was to create a simple model representing flow through the box. Because AQMODEL is restricted in the dimensions it allows for input, the box was rescaled at 1 cm = 100 ft. This provided scaled dimensions of 6,000 x 10,000 ft for the box, with approximately 1,000 ft between wells A through J. In our model, we had a stream into which the aquifer discharged. We simulated this with a series of 15 pumping wells. The input values required for the program were:

- Direction of regional flow (degrees);
- Hydraulic gradient of regional flow (dimensionless);
- Aquifer thickness (ft);
- Aquifer transmissivity (ft²/day);
- Pumping rate for each of the wells used to model the stream (gpm).

The program output includes:
1) a grid of the drawdown from the pumping wells used to model the stream;
2) a grid of the potentiometric surface;
3) a grid of stream functions;
4) estimates of the drawdown expected at each of the observation wells.

AQMODEL was calibrated to the box model by varying the input parameters until the calculated

Figure 4. Flow net for ground-water flow in the simulator using the same set-up as in the plume experiment.

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drawdowns matched the drawdowns measured with the wooden sticks (Figure 4). No attempt should be made to duplicate the measured drawdowns. Instead, the box should be calibrated until there is a linear relationship between the observed and calculated drawdowns. This procedure should be performed by the instructor prior to class. Once the numerical model has been calibrated, the physical and numerical models together make an excellent tool for describing how changes in initial conditions can affect an aquifer. For example, a reduction in the assumed regional hydraulic gradient can be input into AQMODEL, and the effect on the potentiometric surface and flow rate can be calculated. This same change can be physically modeled by reducing the flow rate into the box, reducing the head on the input side of the tank, and thus reducing the hydraulic gradient. Another example would be changing the transmissivity in AQMODEL by rebuilding the model with a finer-grained aquifer.

Our model was poorly adapted to AQMODEL because of the stream on its outflow end. A simpler model, containing only a confined aquifer that is penetrated by a well field provides a better physical analog to AQMODEL. An individual well can be “pumped” by introducing a siphon in the form of a small plastic tube. The pumping rate can be kept constant by changing the elevation of the lower end of the siphon tube. In this manner, the effect of pumping from an individual well can be modeled. Repeated measurements with wooden sticks can be used to determine when steady-state conditions have been reached. Then the pumping rate in the numerical model can be varied until the output values match the observed drawdown. Note that the actual pumping rate cannot be scaled between the box and the numerical model, because a scale for time intervals is lacking. However, once the model is calibrated, both the model and box-well pumping rates can be doubled and the results compared.

The numerical model provides an invaluable adjunct to the physical model because it demonstrates how drawdown, stream functions, and the potentiometric surfaces respond to changing aquifer conditions. The numerical model provides a two-dimensional plan view that demonstrates how the aquifer operates under changing conditions.

IMPACT ON STUDENTS

In our test of the plume experiment, the students became quite animated, and their energy increased with each test. They were especially impressed when the dye appeared in the flowing stream. At the end of the experiment, they began speculating on what the results might be using different stratigraphic conditions and different flow conditions. This enthusiasm contrasts sharply with previous attempts at integrating environmental exercises into introductory geology courses. Because the exercises simply amounted to contouring figures in laboratory manuals and answering questions, students typically lost interest quickly. For real learning to take place, it is imperative that the exercises keep the attention of the students. The enthusiasm for geology that can be generated in introductory courses can convince students to continue in geology or at least maintain an appreciation for it throughout their careers. With the dwindling public support for geology, it is essential that such appreciation be at its maximum.

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REFERENCES CITED


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