Visualizing Ground-Water-Flow Fields and Contaminant Plumes in an Undergraduate Hydrogeology Course

Paul Francis Hudak
Department of Geography
University of North Texas
Denton, Texas 76203-5279
hudak@unt.edu

ABSTRACT

An undergraduate hydrogeology class used personal computers equipped with numerical modeling and data-visualization software to study ground-water flow and contaminant transport in an aquifer. Hydraulic head and solute concentration matrices from the numerical models were input to visualization software packages, which rendered contaminant isosurfaces and vector plots of ground-water velocity. The isosurfaces and vector plots effectively conveyed the three-dimensional spatial characteristics of contaminant plumes and ground-water-flow fields. Using isosurfaces, students viewed plumes from various perspectives within the context of a three-dimensional coordinate system. This fostered comprehension of physical processes, such as hydrodynamic dispersion, that control the shape of a plume. Vector plots were useful for evaluating alternative pumping schemes to remediate ground-water contamination. The results of this study suggest that three-dimensional visualization methods can effectively augment traditional contouring methods in an undergraduate ground-water course.

Keywords: Education – computer assisted; hydrology and hydrogeology.

Introduction

Scientific visualization is a class of computer graphics and imaging techniques used to create visual representations of data (Colet and Anderson, 1995). In the past, these techniques were accomplished only on workstations or supercomputers running expensive software. However, recent innovations in the architecture of desktop computers and the availability of inexpensive software now facilitate the use of advanced visualization methods in undergraduate classrooms.

Hydrogeology is among the geologic fields that are well suited to three-dimensional visualization, because it involves physical and chemical observations distributed in three-dimensional aquifers. Traditionally, contour lines have been used to study ground-water velocity and solute concentration distributions in aquifers. Although they convey useful information, conventional contouring methods are restricted to a two-dimensional coordinate system. In this study, junior- and senior-level hydrogeology students used visualization methods to study the formation of contaminant plumes and evaluate various ground-water-remediation schemes.

Background

Visualization has become an important part of the scientific discovery process, allowing engineers and scientists to examine large amounts of data and computed results with higher efficiency and greater comprehension (Nielson, 1991; Follin, 1992). The data often come from field surveys, statistical and numerical models, and remote sensing. With numerical models, scientists use visualization in the iterative process of designing a system, observing a response, and making refinements.

Recent enhancements in the processing speed of personal computers facilitate using data visualization in undergraduate math and science classes. For example, Gordin and Pea (1995) discuss a scientific visualization project for an undergraduate class in planetary atmospheres at the University of Chicago. Scientific visualizations were used to illustrate and analyze basic climate patterns, such as rates of change in ocean and land temperatures, with CD-ROM drives on an Apple Macintosh platform.

By offering a picture of the data and its internal relationships, visualization makes it easier to understand information that is too difficult to perceive numerically (Weber, 1993; Gordin and Pea, 1995). It facilitates mental processing by showing relationships that would otherwise have to be extracted from sequential problem statements (Breuker, 1984). Images of phenomena provide students with referents for their inquiry and discussion (Gordin and Pea, 1995), rendering them extremely effective for causal understanding (Nishida, 1992). The images are interpreted to arrive at an understanding of the real-world phenomenon being modeled (Lee, 1994).

Visualizations allow students to learn interactively, by seeing and experimenting, rather than by memorizing text or searching for patterns in numerical matrices (Brown, 1992). Interactions involve producing and manipulating imagery by operations such as rotating, panning and zooming, slicing and probing the interior of volumes, and animation. Rotating is particularly effective for volumetric objects such as contaminant plumes. Multiple views reveal details of objects that might otherwise be missed.

Common three-dimensional visualization techniques include slices, isosurfaces, volume rendering, and streamlines/vectors (Spyglass, 1994). Slices are two-dimensional cuts through a data volume. They are displayed as color images and then placed in perspective in a cube that represents the boundaries of a data set. Slicing is the fastest three-dimensional visualization technique. However, the slices, positioned by hand, may miss an important feature. It may also be

an encryption program so that specially formatted disks will not work on other computers. Another option is to remove or disable the disk drive and have the student use the hard disk with a password to access his/her folder. However, back-up files should be kept by the instructors in case of disk problems.

Conclusion

The use of computers at geology field camp has been an unqualified success, and the students have accepted them with enthusiasm. They have not changed the time-proven curriculum but have enhanced it and brought field camp into the modern world. We hope to be able to use the Internet as an additional teaching tool and resource at camp soon. When this happens, we will be able to place satellite images, geological maps, thin-section images, and so forth on a home server and access them at camp via the Web.

Software Used

The software discussed here is only what we currently use, but many other products from other vendors are available. *Microsoft Word* and *Excel* are used for word processing and graphing analysis, respectively. Our stereonet software is *SpheriStat* by Pangaea Scientific. The Markov chain analysis software was written by the author and will be available via the Internet at the University of Toledo's Geology Department web site (<http://www.geology.utoledo.edu>) in the near future.

Contour and perspective (surface) maps are made by digitizing locations and elevations of numerous

closely spaced points on a topographic base. We use an inexpensive program from the United States Geological Survey called GSDIG. The output from this program is an ASCII file in a spreadsheet format that can be imported to *Excel* for modification and then imported to *Surfer*, our contouring package by Golden Software. This contouring package is very versatile in producing both contour and surface maps.

Acknowledgments

Financial support for acquisition of the computer equipment and some of the software was graciously provided by The University of Toledo with matching funds from an Instrumentation and Laboratory Improvement grant from the National Science Foundation (DUE-9450858). Additional funding for software was provided by the Center for Teaching Excellence at the University of Toledo.

References Cited

Davis, John C., 1986, *Statistics and data analysis in geology*; John Wiley and Sons, 646 p.

About the Author

Vernon Max Brown is an associate professor of geology at The University of Toledo, Toledo, Ohio. His interests include igneous and metamorphic petrology, geoarchaeology of ancient Egyptian and Roman rock quarries, and geological education. He has been teaching geology field camp in the Black Hills of South Dakota and Wyoming since 1981.

Food for Thought

Some of the major indicators of the relatively narrow place science, as properly understood, occupies in the total culture are quantitative. A nationwide survey found that nearly 40 percent of the men and women who had attended college in the United States confessed that they had not taken a single course in the physical and biological sciences. Similarly, the mass media pay only negligible attention to the subject: the newspapers have been found to give less than 5 percent of their (nonadvertising) space to factual presentation of science, technology, and medicine; and television devotes even less. In short, all our voracious consumption of technological devices, all our talk about the threats or beauties of science, and all our money spent on engineering development should not draw attention away from the fact that the pursuit of scientific knowledge itself is not a strong component of the operative system of general values.

Gerald Holton, 1996, *Einstein, history, and other passions — The rebellion against science at the end of the twentieth century*. Reading MA, Addison-Wesley Publishing Company, 240 p. (from p. 41).

difficult to construct the shape of a three-dimensional object. Conventional solute concentration contour plots are a form of slicing, depicting data within horizontal or vertical planes cutting through a three-dimensional plume. Contours, sometimes referred to as isolines, are also one of the most popular methods for visualizing two-dimensional data.

Isosurfaces represent an extension of contouring to three-dimensional space. In a three-dimensional matrix, it takes not a line but a surface to connect data values that are equal (Weber, 1993; Spyglass, 1994). The connecting surface is known as an isosurface. Isosurfaces rapidly illustrate the three-dimensional shape of volumetric data. For a contaminated aquifer, isosurfaces can be used to visualize volumes of pollution within various concentration thresholds.

In volumetric visualizations, each data value is converted to a color intensity. All values are shown, and intensities are added together where data overlap on the computer screen. Where data values are low along a line of sight, the observer can see through the volume. In contrast, where data values are high, the volume is opaque. Volumetric visualizations require more computer power. Another drawback is that internal data are often obscured by data values around the periphery of an object.

Three-dimensional streamlines/vectors can point in any direction in three-dimensional space, and each vector can be positioned anywhere. Vectors are often used to illustrate flow fields. But discerning what direction each vector points and where each vector is positioned in three-dimensional space is often difficult. This problem can be circumvented by showing vectors in a single plane and coding the arrows to indicate whether flow is upward or downward relative to the plane. In this project, students used vectors to study ground-water-flow fields around pumping wells, and isosurfaces to visualize time-dependent, three-dimensional solute-concentration data.

Methods

Visualization technology is well-suited to numerical groundwater flow and mass transport models, which yield estimates of hydraulic head or solute concentrations at nodes distributed in three-dimensional space. In this project, students used two numerical models, MODFLOW (McDonald and Harbaugh, 1988) and MT3D (Zheng, 1990), to study the evolution of contaminant plumes and examine the effect of alternative ground-water-remediation schemes in a hypothetical aquifer. Results from the numerical models were input to VELPLOT (Geraghty and Miller, 1993) and SPYGLASS SLICER (Spyglass, 1994) for visualization purposes. Exercises were conducted in a laboratory facility with 20 personal computers, including a combination of Pentium and model 486 machines, running DOS 6.22 and Windows 3.1. The numerical models and VELPLOT run under the DOS environment, whereas SPYGLASS SLICER runs under Windows.

MODFLOW employs a block-centered finite-difference approach to solve the partial differential equations governing ground-water flow. The contaminant transport model, MT3D, uses a mixed Eulerian-Lagrangian

approach to simulate advection, dispersion, and chemical reactions of solutes in ground-water systems. MT3D retrieves hydraulic head values and flow terms saved by the flow model, MODFLOW. Data input files, quantifying aquifer properties such as hydraulic conductivity, boundary and initial conditions, and transport parameters, were created with MODELCAD (Rumbaugh, 1993), a menu-based data preprocessor.

SPYGLASS SLICER is visualization software that graphically analyzes three-dimensional (volumetric) data. With this software, students have the ability to create animations, slices, and isosurfaces of three-dimensional data. They can also rotate and resize images, make different data values transparent or translucent, adjust ambient lighting and data volume reflectivity, and manipulate the mapping of colors to data values. These tools allow students to fully explore the spatial structure and characteristics of a volumetric image.

The visualization software uses ray tracing to display (render) three-dimensional images on a computer monitor (Spyglass, 1994). A ray is shot perpendicular to the screen into each pixel in a view window. When the ray hits an object (for example, an isosurface), the software analyzes its characteristics and sets the pixel according to user-defined parameters for that object. If no object is encountered, the ray hits a wall or the background. The process is repeated for all pixels in the window.

Utilizing numerical output from MODFLOW, VELPLOT computes vectors to illustrate the magnitude and direction of ground-water velocity at nodes within each layer of an aquifer. It depicts the vertical direction of flow by coding arrowheads in each vector. Layers can be juxtaposed to illustrate variations in ground-water velocity throughout a multi-layered aquifer. XYLINE files output by VELPLOT were displayed with SURFER, a package manufactured by Golden Software.

Students were instructed to use the software packages described above in a modeling and visualization exercise. First, they used MODFLOW to simulate regional ground-water flow within a three-dimensional, confined aquifer. The aquifer was partitioned into 45 columns, 31 rows and 10 layers, with a uniform cell spacing of 1 m. Hydraulic head values and cell-by-cell flow terms calculated by MODFLOW were input to MT3D, which generated solute concentration distributions at specified time periods.

Initially, the models were assigned a porosity of 0.3, hydraulic conductivity of 1 m/d, hydraulic gradient of 0.002, longitudinal dispersivity of 1 m, horizontal and vertical transverse dispersivities of 0.1 m, effective molecular diffusion coefficient of 3.3×10^{-5} m²/d, and a point source concentration of 1,000 mg/l at the top of aquifer. In subsequent simulations, students were instructed to vary parameters, one at a time, to study the effect of each aquifer property on ground-water flow and mass transport.

The MT3D post-processor was used to produce ASCII text columns of the X, Y, and Z coordinates and corresponding solute concentration for all nodes

Figure 1. 1 mg/l isosurface of solute plume after 1,400 days.

in each layer of the model. A SPYGLASS transform utility converted the text files to HDF (Hierarchical Data Format) files. The HDF files were imported to SPYGLASS SLICER, which combined the layers to form a volumetric data set. Subsequently, SPYGLASS SLICER was used to display isosurfaces of contaminant distributions. While studying isosurfaces, students were able to examine contaminant distributions from different viewing perspectives, calculate the volume of contaminant within a particular range of concentrations, and probe the interior of contaminant isosurfaces. Probing involves generating a profile of data perpendicular to the screen through the data at a point chosen.

After the contaminant plumes were rendered, students were asked to design and evaluate alternative ground-water-remediation schemes. MODFLOW was also used for that purpose, but with extraction and injection wells superimposed on the regional flow field. Ultimately, SPYGLASS SLICER can be used to study ground-water remediation schemes with isosurfaces, but the added complexity of pumping wells requires a substantially longer MT3D execution time. However, by examining the flow field induced by pumping wells, students can quickly determine the probable success of a ground-water-remediation scheme. Consequently, VELPLOT was employed to create ground-water-velocity vector maps from MODFLOW output.

Results and Discussion

Coupled with numerical models, isosurfaces and vector plots helped students understand how solutes move in aquifers, and how various pumping configurations alter a ground-water-flow system. Displaying isosurfaces in several viewing perspectives was effective for studying the three-dimensional shape of a contaminant plume (Figure 1). Multiple perspectives allowed students to study the entire interior and exterior of isosurfaces corresponding to various solute concentrations. Isosurfaces can be used in conjunction with conventional contour maps by illustrating the contaminant shells corresponding to each contour line. Used together, these techniques effectively convey

the distribution of solute concentrations in three-dimensional space.

A drawback of viewing isosurfaces instead of slicing a volume or contouring data within a plane is the longer time interval required to render an image. The amount of time required to render an isosurface depends on several factors, including the computer processing speed, number of nodes in a data set, and sampling parameters that control image resolution. Typically, it took only about one to two minutes to render isosurfaces in this project. However, the data set was fairly small, consisting of only 13,950 nodes. Larger problems would require more time. An efficient strategy employed in this study was to display preliminary images with a low resolution until the desired viewing perspective and parameters were identified. At that point, students can invoke a higher resolution to enhance the view.

Vector plots required considerably less time to render, yet allowed students to gain insights into the probable success of alternative ground-water remediation schemes. With vector displays, students could see whether there were zones within a flow field that did not discharge to extraction wells. In addition, they could identify stagnant zones, characterized by a low ground-water velocity, that would require considerable time to remediate. After identifying uncaptured areas and stagnant zones, the students modified the locations of wells or rate of pumping in a remediation scheme, modeled the resulting configuration, and displayed a new vector field to measure improvement. Using this iterative exploration process, the students learned which pumping patterns routinely failed and which consistently performed well.

One of the more efficient ground-water remediation schemes identified in the project is illustrated in Figure 2. That configuration consists of a central pumping well, located at the most contaminated area within the plume, and two peripheral injection wells. Each well is open in layers 1 through 5, the upper part of the aquifer within which the contaminant plume resides. The extraction well pumps ground water at a rate of 20 m³/d, and each injection well discharges 10 m³/d. This scheme is effective because

Figure 2. Log-velocity distribution at 4-5 m depth interval; triangular arrowheads designate downward flow.

it draws ground water throughout the contaminated area into the extraction well but does not cause substantial drawdown within the aquifer. The maximum drawdown, incurred in the upper layer at the extraction well, was only 2.2 m.

Two types of vectors are shown on the illustration in Figure 2. Vectors with triangular arrowheads indicate that ground water is flowing vertically downward, whereas V-shaped arrowheads designate upward vertical flow. The coded arrowheads, in conjunction with the length and horizontal direction attributes of the vectors, effectively convey the three-dimensional character of flow at the 4-5 m depth interval. Ground-water velocity is highest near the pumping wells, where injection or extraction has caused steep hydraulic gradients. Flow is divergent from the injection wells and convergent toward the extraction well. The divergent flow has a downward component, induced by raising the potentiometric surface. Conversely, lower hydraulic head values near the extraction well have induced upward flow. In Figure 2, the vectors are scaled using a log-scale because there are significant changes in velocity over the model domain. (Vector fields were also constructed for the other layers.)

Summary and Conclusions

The visualization tools employed in this study enable students to effectively see the three-dimensional spatial characteristics of contaminant plumes and

ground-water-velocity distributions. In an undergraduate laboratory equipped with personal computers, students used isosurfaces to study the evolution of contaminant plumes and vector plots to evaluate ground-water-flow fields induced by pumping wells. Used in conjunction with ground-water models, these visualization techniques enable students to understand how mass transport in aquifers is controlled by properties such as hydraulic conductivity and dispersivity, and how various pumping configurations alter a regional flow field.

Scientific visualization is particularly effective for mass transport models such as MT3D, which output solute concentrations referenced to a three-dimensional coordinate system. Isosurfaces can enhance the information contained in conventional solute concentration contour maps. In an educational setting, these tools could also be used to illustrate contaminant distributions interpolated from field measurements of water quality in contaminated aquifers.

Acknowledgment

This project was funded by an Instrumentation and Laboratory Improvement Grant (DUE-9650346) from the National Science Foundation.

References Cited

Breuker, J.A., 1984, A theoretical framework for spatial learning strategies, in C.D. Holley and D.F. Dansereau,

- editors, Spatial learning strategies: Orlando, Academic Press, p. 21-46.
- Brown, J.R., 1992, The multi-faceted blackboard: Computer graphics in higher education, in S. Cunningham and R.J. Hubbard, editors, Interactive learning through visualization: Berlin, Springer-Verlag, p. 103-127.
- Colet, E., and Aaronson, D., 1995, Visualization of multivariate data: Human-factors considerations: Behavior Research Methods, Instruments, & Computers, v. 27, p. 257-263.
- Follin, S.E., 1992, The essentials of scientific visualization: Social Science Computer Review, v. 10, p. 569-580.
- Geraghty and Miller, 1993, MODFLOW utilities: Reston, Geraghty and Miller, 84 p.
- Gordin, D.N., and Pea, R.D., 1995, Prospects for scientific visualization as an educational technology: The Journal of the Learning Sciences, v. 4, p. 249-279.
- Lee, J.P., 1994, Data exploration interactions and the Ex-Base system, in J.P. Lee and G.G. Grinstein, editors, Database issues for data visualization: Berlin, Springer-Verlag, p. 118-137.
- McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water model: Washington D.C., U.S. Government Printing Office, 548 p.
- Nielson, G.M., 1991, Visualization in scientific and engineering computation: Computer, September Issue, p. 58-66.
- Nishida, S., 1992, Hyper-simulator based learning environment to enhance human understanding, in S. Cunningham and R.J. Hubbard, editors, Interactive learning through visualization: Berlin, Springer-Verlag, p. 79-87.
- Rumbaugh, J.O., 1993, ModelCad: Reston, Geraghty and Miller, 196 p.
- Spyglass, 1994, SLICER: Champaign, Spyglass, 146 p.
- Weber, J., 1993, Visualization: Seeing is believing: Byte, April Issue, p. 121-128.
- Zheng, C., 1990, MT3D: A modular three-dimensional transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems: Rockville, S.S. Papadopoulos and Associates, 141 p.

About the Author

Paul F. Hudak is a faculty member in the Department of Geography at the University of North Texas. He received a BS and MS in geology from Allegheny College and Wright State University, respectively, and a PhD in geography from the University of California, Santa Barbara.