THREE-DIMENSIONAL GIS FOR THE EARTH SCIENCES

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ABSTRACT

Earth scientists are frequently confronted with problems that involve 3-dimensional phenomena, but up until now the main computerized geoprocessing tool available to them has been the 2-dimensional GIS. New 3-dimensional geoprocessing capabilities are being developed and will be in their hands in 1989. These systems address a class of problems that could not be dealt with before and will provide answers to questions that we did not realize we could ask.

INTRODUCTION

Different application groups have been using Geographic Information Systems (GIS) for various reasons. In talking to these people you soon realize that GIS means different things to different people. Over the years there have been attempts to define what a GIS is and how it is used. Recent GIS reviews include Cowen (1988) and Clarke (1986). For the purposes of this paper we will use the following definition of a GIS. A GIS is a software system that contains functions to perform input, storage, editing, manipulation, analysis and display of geographically located data.

Up to now the main uses of a GIS have dealt with data on the earth's surface. If the data was above or below the surface it was conveniently projected to the surface. This allowed the system to deal with everything in a 2-dimensional format. Early GIS's often used a data structure of regular grid cells but current systems seem to favor polygons. All of these deal with many flat files that are oriented over the same location of the earth. Sometimes a system could draw a perspective view of the surface and even present data on the surface, below the surface and above the surface. These presentation techniques still deal with flat files but add the capability to present the data in what we will call a 2 1/2 -dimensional format.

WHY 3-DIMENSIONAL GEOPROCESSING

Many earth scientists who have tried their hand at geoprocessing have come up short. The use of flat, 2-dimensional files does not fit their needs. These scientists are usually dealing with geology, geophysics, meteorology, hydrology, mining, ground water, hazardous contaminations, and the like. These phenomena are 3-dimensional in nature and when you try to fit them into 2-dimensional systems you can not accurately model, analyze or display the information.

To help explain things throughout this paper we will use an example from a situation that we all hear about these days; the problems with hazardous chemicals in the ground. At this particular site they discovered, in the ground, PCB concentrations that were above safe levels. This indicated to the site owner that an expensive undertaking was necessary to first determine the extent of the problem and then to correct the situation.

It is impossible to model, analyze or display this situation, with any satisfaction, when you are using a 2-dimensional tool. You might be partially successful in using stacked 2-dimensional data layers but you are basically forced to ignore the fact that the phenomena is actually 3-dimensional. Applying a 2-dimensional tool to 3-dimensional situations limits the scientist's work in many ways. It is not possible to accurately model the vertical relationships between the stacked 2-dimensional layers. It is not possible to perform true 3-dimensional analytic operations between different models. It is not possible to accurately visualize the 3-dimensional situation and make decisions about the data.

THREE-DIMENSIONAL DATA

Let's go to our example site and take a look at the source data that is available. Contamination was discovered in the ground and new wells were drilled to gather additional data. Samples were taken at various locations down these wells and sent to the lab for analysis. High levels of PCB were discovered. The site was contaminated and had to be cleaned up. The PCB values were reported in a tabular fashion with the geographic location of each sample. With a 3-dimensional data set you need to know X,Y,Z&V where X,Y,Z give the location of the property, and V is the value of the property at that location. The property in this situation is the concentration level of PCBs. A portion of the data file is shown in Table 1.

Well-ID	X-coord	Y-coord	Elevation	PCB-level
2002	-1165	763	-80	0.33
2002	-1165	763	-140	0.16
2002	-1165	763	-200	0.66
2003	-1140	743	-20	0.05
2003	-1140	743	-80	0.06
2003	-1140	743	-140	0.09
2003	-1140	743	-200	0.13
2004	-1165	718	-20	0.13
2004	-1165	718	-80	0.45
2004	-1165	718	-140	0.10
2005	-1200	743	-20	0.13
2005	-1200	743	-80	0.72
2005	-1200	743	-140	0.09
2005	-1200	743	-200	0.33
2006	-1175	600	-20	0.19
2006	-1175	600	-80	0.22
2006	-1175	600	-140	0.14

Table 1. Portion of the Source File

With a 2-dimensional system the X&Y location of each well can be displayed and selected horizontal planes can be utilized in an attempt to model, analyze and display slices through the earth. With a 3-dimensional system the data is input, edited, modeled, analyzed and displayed in its true 3-dimensional form. Figure 1 shows a display of source data with a 3-dimensional system.

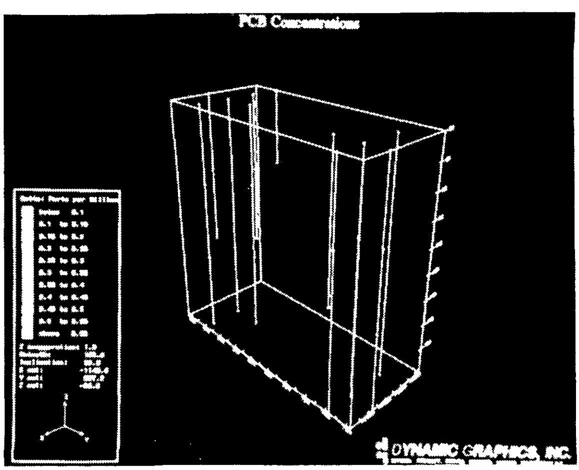

Figure 1. Three-Dimensional Source Data

In 2-dimensional systems the user often models the scattered or randomly located source data into a uniform or regular data structure. These have typically been uniform grids or triangles. The reason for this modeling is that the resources required to analyze and display data that is located in a scattered format is significantly higher than dealing with data in a regular format. Each time the scattered data needs to be contoured, or each time volumes need to be calculated, a modeling step would have to take place. The intention is to perform the modeling step once. As long as the mathematical model fits the physical model, the savings in resources are worth it.

The situation with 3-dimensional phenomena is similar. It is more efficient to model the scattered data once onto a uniform grid than to deal with it in its scattered format. The objective of the modeling step is to apply a mathematical model that best fits the physical model. The model will never be truth. In situations with subsurface problems there is usually only a limited amount of data available because of the high cost of drilling wells to collect new data. The analysts never have as much data as they would like. It's not like topography, where you can go out and stand on the site and see it first hand.

Many phenomena in nature follow a model known as minimum-tension. A computer-generated minimum-tension model can be calculated using an iterative tension reduction method. See Briggs (1974). If there is no other information known about the phenomenon except for its value at particular spot locations, then the minimum-tension algorithm provides a smooth, unbiased model of the data. If any additional facts are known about the phenomenon then, of course, that has to be taken into account by applying another model which better fits the situation.

For example, if the phenomenon is moving through a ground water zone and it is known that the zone has an East-to-West flow, then an appropriate flow model should be applied, not a minimum-tension model. Sometimes a flow model will create a non-uniform grid and a minimum-tension algorithm can then be used to model the non-uniform data onto a uniform-grid. This is done when the data needs to be correlated with other non-uniform data sets, or when particular display techniques need to be used that require a uniform grid.

Another modeling technique involves the use of geostatistics to provide the scientist or analyst with information. Geostatistical models, such as kriging, are often used for applications in mining or petroleum exploration. Geostatistical routines are not used to develop a mathematical model of a physical phenomenon like the minimum-tension model does, but rather they strive to develop a block average description of the phenomenon. As the blocks are larger the results seem more valid.

DATA EDITING

The ability to input source data and run a model is very useful, but often the user is confronted with the need to edit the data. Sometimes the source data needs to be queried and/or edited, and other times the model results need to be queried and/or edited. Editing tools, often involving interactive graphic editors, can be applied to 2-dimensional data without a great amount of difficulty, but with 3-dimensional data the problem is much more difficult. Working in 3-dimensions the tools have to be more helpful to the user and have to be graphically more powerful. It is not easy to point and query data locations in 3-dimensions and it is more difficult to edit the source data and then remodel around it.

THREE-DIMENSIONAL ANALYSIS

One of the more simple techniques that can be used to analyze 3-dimensional data is to apply a set of grid operations. These operations could include such things as:

- grid-to-grid mathematical calculations
- grid refinement
- grid smoothing
- back interpolation
- trend grids

These grid operations would provide a user with a basic set of tools to perform a wide range of analytic functions. Three-dimensional grid models of permeability, porosity, temperature and pressure could be compared, correlated and analyzed together to determine the most likely locations for oil to be found. Hazardous chemical plumes in the ground could be analyzed over time to determine the movement of the plume and any changes in its size or chemical make-up.

When we first think of 3-dimensional problems we often imagine applying analytic tools similar to those we are familiar with in 2-dimensions. This is a very reasonable assumption to start with. However, a 3-dimensional gridded model of a particular phenomenon does not always provide us with the data structure that we need in order to perform some of these operations. One of the solutions to this is to develop 3-dimensional iso-surfaces through the 3-dimensional grids similar to the way we locate 2-dimensional iso-lines (contours) through 2-dimensional grids. An example of an iso-surface is shown in Figure 2.

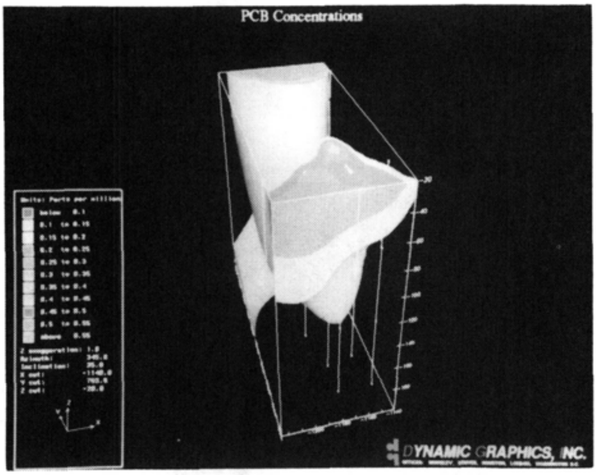

Figure 2. Example Of An Iso-surface

The iso-surface is a polygonized data structure which is positioned through the 3-dimensional grid where the level of the phenomenon is of equal value. An iso-surface in 3-dimensions is similar to an iso-line or contour line in 2-dimensions. The iso-surface is given its shape by forming small triangular polygons through the gridded data and then connecting these triangles together to form a 3-dimensional surface of equal value, or an iso-surface.

Having the phenomenon defined by user-selected iso-surfaces provides the scientist with an additional set of analytic capabilities. Accurate volumes can now be calculated. Iso-surfaces can be intersected by performing 3-dimensional polygon intersection. This operation could allow a scientist to accurately model the movement of a contaminated plume through the ground.

Iso-surfaces can be constrained or limited above and below by 2-dimensional surfaces. This could be used to generate an accurate geologic model where particular materials are limited by geologic structures and faults. Polygons defining features on the earth's surface, such as lease tract boundaries, could be used to cut down through the 3-dimensional iso-surfaces by using a 3-dimensional polygon intersection routine. This would be useful, for example, when a user wants to calculate volumes under lease tracts, or when some underground phenomenon needs to be associated with particular land-use features.

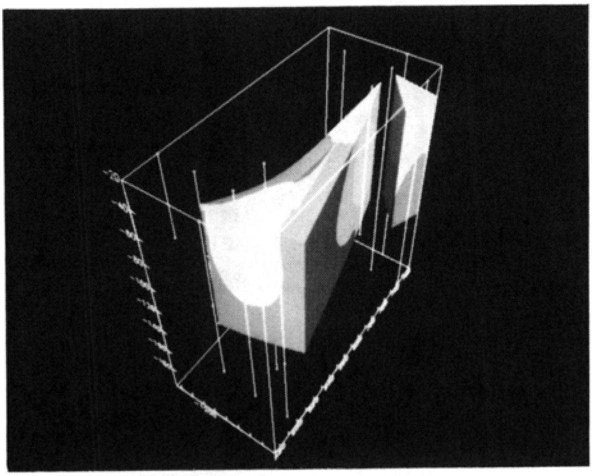

Figure 3. Iso-surfaces Cut By Polygons

THREE-DIMENSIONAL DYNAMIC DISPLAYS

One of the more powerful and useful functions of a 3-dimensional geoprocessing system is its ability to display information in ways that have never before been seen. This provides the user with a scientific visualization tool that allows him to better understand the phenomenon he is studying and to make more informed decisions about it. The display capability needs to include dynamic movement of the graphic and dynamic selection of options. There is a tremendous advantage in having dynamic capabilities in a 3-dimensional system because of the complexity of the problems. Many of the relationships and features of 3-dimensional phenomena simply cannot be comprehended by the users without these tools.

One of the basic elements of any geographic display is the need to accurately identify the geo-referencing system. The user needs to know where things are, not only in X and Y coordinates, but also in Z coordinates. The user can easily get lost when the system provides the capabilities to rotate the model left, right, up or down. The system needs to provide the user with an appropriate geographic referencing system.

Users need to be able to see and browse thru displays of the scattered source point data. They also need to be able to examine and understand the 3-dimensional grid values and how they relate to the source data. Another very informative display of the 3-dimensional model is a colored cube display which presents ranges of the values in the model.

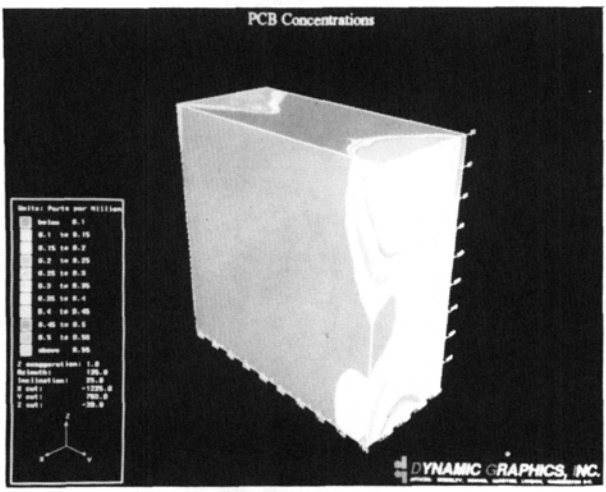

Figure 4. Full Cube Display

The user needs to be able to slice off edges of the cube display to get views of the inside of the model in order to better understand what the model really looks like.

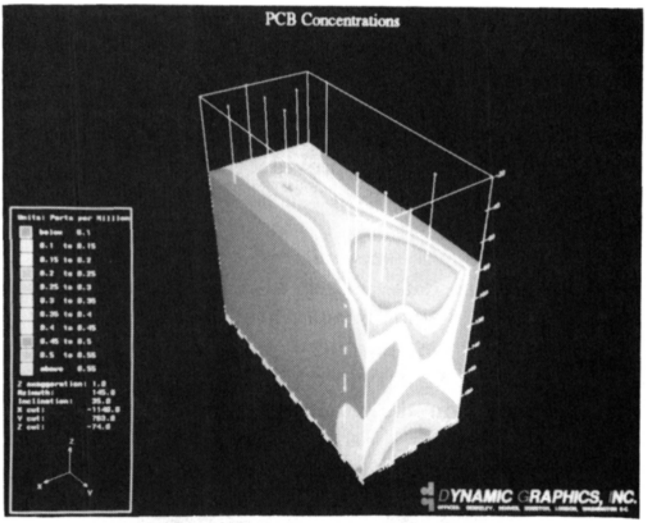

Figure 5. Sliced Cube Display

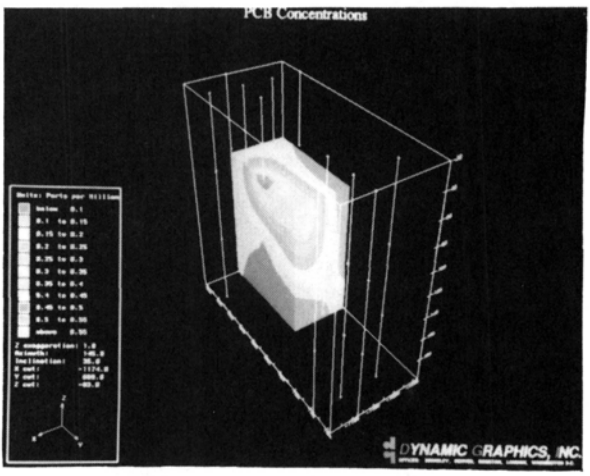

Figure 6. Sliced Cube Display

Often the user is searching for a particular value in the data and the system needs to provide tools to locate and display this value.

For example, when the ground is contaminated with PCB's as in the sample used here, the user is trying to determine if the values found are above the safe levels for that particular chemical, and if so, what the volume is and where it is located. In a 3-dimensional geoprocessing system the user could select a particular iso-surface level, have the display generated, and then dynamically slice through it to gain a full understanding of the situation.

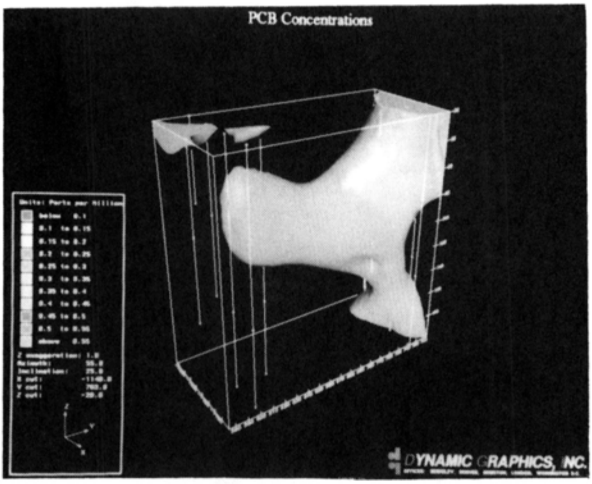

Figure 7. Iso-surface Display

Phenomena in 3-dimensions are difficult to understand and all of the display functions in a 3-dimensional geoprocessing system need to work together to provide the users with the maximum utility. The user needs to be able to see the source data, to select different iso-surface levels, to assign colors to these levels, to slice edges from the model, to peel off iso-surfaces, to rotate around the display and to zoom in and out.

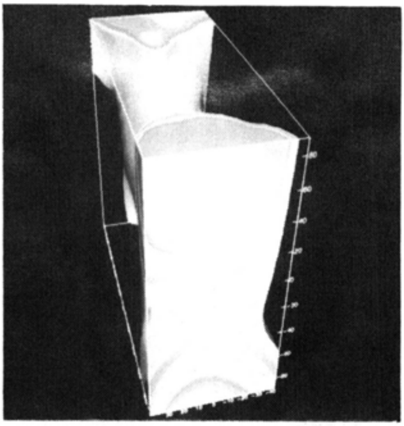

Figure 8. Concentrations Above a Value

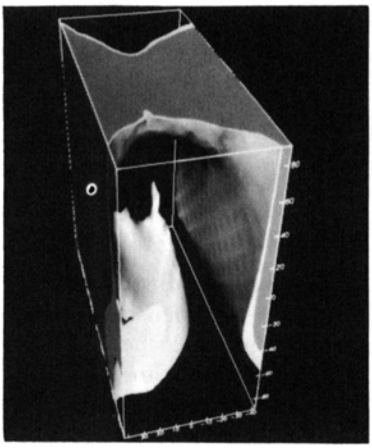

Figure 9. Concentrations Below a Value

HARDWARE ISSUES

The capabilities needed to work with 3-dimensional data are greatly enhanced by the hardware functions in new graphic workstations. Three-dimensional modeling is compute intensive and is well suited for the new high-performance 3-D graphic workstations. The scientific visualization aspects of a 3-dimensional geoprocessing system are only available by utilizing the 3-dimensional graphic functions in the new workstations. No one view can properly communicate to the user what is going on in a 3-dimensional model. Fortunately for the user community, 3-D workstations are becoming more common in the work place and prices are dropping.

CONCLUSION

These new 3-dimensional geoprocessing capabilities are addressing a class of problems that could not be dealt with before. Manual methods can be successful with 2-dimensional problems and many of these are now addressed by computerized systems. The 3-dimensional problems in the earth sciences are generally too complicated to do by hand and computerized systems to date have not been that successful. Applying 2-dimensional tools to 3-dimensional problems has been only moderately successful at best. As the new 3-dimensional geoprocessing tools get into the hands of the users, answers will be discovered to questions that we currently don't understand or even realize we can ask. For earth scientists the move from 2-dimensional geoprocessing into 3-dimensional geoprocessing will be both exciting and rewarding.

REFERENCES

Briggs, I.C., 1974. Machine Contouring Using Minimum Curvature, Geophysics, Vol 39 - No 1, pp 39-48.

Clarke, K.C., 1986. Advances in Geographic Information Systems, Computers, Environment and Urban Systems, Vol 10, pp 175-184.

Cowen, D.J., 1988. GIS versus CAD versus DBMS: What Are the Differences?, Photogrametric Engineering & Remote Sensing, Vol 54 - No. 11, pp 1551-1555.

McCormick, B.H., 1987. Visualization in Scientific Computing, ACSM SIGGRAPH, Vol 21 - No 6.