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Environmental Technology Verification Report

Environmental Decision Support Software

Environmental Systems Research Institute, Inc.

ArcView GIS Version 3.1 using ArcView Spatial Analyst and ArcView 3D Analyst extensions

THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

ETV

EPA
U.S. Environmental Protection Agency

ornl
Oak Ridge National Laboratory

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**ENVIRONMENTAL DECISION SUPPORT SOFTWARE**
APPLICATION:	**INTEGRATION AND VISUALIZATION OF ENVIRONMENTAL DATA SETS**
TECHNOLOGY NAME:	**ArcView GIS Version 3.1 using ArcView Spatial Analyst and ArcView 3D Analyst extensions**
COMPANY:	**Environmental Systems Research Institute**
ADDRESS:	**380 New York Street** **Redlands, CA 92373-8100**
	PHONE: (714) 379-7000
WEBSITE:	**www.esri.com**

The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification Program (ETV) to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV Program is to further environmental protection by substantially accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high-quality, peer-reviewed data on technology performance to those involved in the design, distribution, financing, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations and stakeholder groups consisting of regulators, buyers, and vendor organizations, with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

The Site Characterization and Monitoring Technologies Pilot, one of 12 technology areas under ETV, is administered by EPA's National Exposure Research Laboratory (NERL). With the support of the U.S. Department of Energy's Environmental Management program, NERL selected a team from Brookhaven National Laboratory (BNL) and Oak Ridge National Laboratory to perform the verification of environmental decision support software. This verification statement provides a summary of the test results of a demonstration of Environmental Systems Research Institute's (ESRI's) ArcView® environmental decision support software (DSS) and its extensions ArcView Spatial Analyst® and 3D Analyst™.

DEMONSTRATION DESCRIPTION

In September 1998, the performance of five DSS products was evaluated at the New Mexico Engineering Research Institute located in Albuquerque, New Mexico. In October 1998, a sixth DSS product was tested at BNL in Upton, New York. Each technology was independently evaluated by comparing its analysis results with measured field data and, in some cases, known analytical solutions to the problem.

Depending on the software, each was assessed for its ability to evaluate one or more of the following endpoints of environmental contamination problems: visualization, sample optimization, and cost-benefit analysis. The capabilities of the DSS were evaluated in the following areas: (1) the effectiveness of integrating data and models to produce information that supports the decision, and (2) the information and approach used to support the analysis. Secondary evaluation objectives were to examine the DSS for its reliability, resource requirements, range of applicability, and ease of operation. The verification study focused on the developers' analysis of multiple test problems with different levels of complexity. Each developer analyzed a minimum of three test problems. These test problems, generated mostly from actual environmental data from six real remediation sites, were identified as Sites A, B, D, N, S, and T. The use of real data challenged the software systems because of the variability in natural systems. The technical evaluation team performed a complete baseline analysis for each problem. These results, along with the data were used as a baseline for comparison with the DSS results.

ESRI staff used ArcView GIS Version 3.1 and its Spatial Analyst and 3D Analyst extensions to perform the visualization endpoint using data from Sites A, B, and N. The Site A test problem, a three-dimensional groundwater cost-benefit problem, required an analysis of remediation volume as a function of cleanup levels for two volatile organic compounds (perchloroethene and trichloroethane). Data were supplied at a series of wells for one representative period. Within each well, data were collected on a 5-ft vertical spacing from the top of the water table to the confining bedrock. The Site B test problem was a two-dimensional groundwater contamination sample optimization problem for three contaminants (trichloroethene, vinyl chloride, and technetium-99). Developers were provided with a series of wells containing contaminant concentrations and were asked to specify additional locations in which to collect more data to better define the nature and extent of contamination. The Site N test problem was a two-dimensional soil contamination cost-benefit problem. This problem included three heavy metal contaminants (arsenic, cadmium, and chromium). The objective was to define the cost (area) of remediation as a function of two cleanup levels for each contaminant.

The intent of the ArcView analyses was to demonstrate the capability to integrate large quantities of data into a visual framework to assist in understanding a site's contamination problem. For the Site N analysis, ArcView was used to estimate the area and costs associated with cleanup to different threshold levels. Sample optimization components of the test problems were not performed.

Details of the demonstration, including an evaluation of the software's performance, may be found in the report entitled *Environmental Technology Verification Report: Environmental Systems Research Institute, ArcView GIS Version 3.1 using ArcView Spatial Analyst and ArcView 3D Analyst Extensions,* EPA/600/R-99/094.

TECHNOLOGY DESCRIPTION

ArcView GIS version 3.1 is a geographic information system (GIS). One function of the software is to help environmental professionals quickly and comprehensively characterize, manage, and visualize information relevant to understanding environmental contamination problems. The ArcView GIS integrates common database operations, such as query and statistical analysis, with the visualization and geographic analysis benefits offered by maps. The Spatial Analyst extension was developed to solve problems requiring that distance or other continuous surface modeling information be considered as part of the analysis. The 3D Analyst extension permits the creation of three-dimensional surface models and assists users with three primary tasks—surface model construction, analysis, and display. ArcView and its extensions operate on Windows 95, 98, and NT platforms.

VERIFICATION OF PERFORMANCE

The following performance characteristics of ArcView GIS Version 3.1 and its extensions Spatial Analyst and 3D Analyst were observed:

Decision Support: ArcView GIS version 3.1 was able to quickly import data on contaminant concentrations, geologic structure, and surface structure from a variety of sources with different formats and integrate this information on a single platform. It was able to place the information in a visual context that supports data interpretation.

Documentation of the ArcView Analysis: ArcView generated reports that provided an adequate explanation of the process and parameters used to analyze each problem. Documentation of data transfer, manipulation of the data (e.g., how to treat contamination data as a function of depth in a well), and analyses were included. Model selection and parameters for contouring were also provided in the exportable documentation. ArcView generated graphical output in . jpg format and incorporated this directly into a Microsoft Word file.

Comparison with Baseline Analysis and Data: ArcView generated hydraulic head, ground surface elevation, bedrock elevation, and contaminant concentration maps. The maps ranged from posting of a marker at each data location, in which the size was proportional to the value of the parameter being represented (e.g., contamination level), to generation of concentration contours. Comparison of the contours of concentration and hydraulic head with the data and the baseline analysis showed that ArcView results were consistent with the measured values. ArcView accurately mapped wells, buildings, and site features. It accurately posted data to sample locations and hot-linked data to well locations. The Site N cost-benefit analysis performed using ArcView estimated the volume of contamination and the cost of remediation and was found to be consistent with the data and baseline analysis.

Multiple Lines of Reasoning: ESRI staff used ArcView, Spatial Analyst, and 3D Analyst to provide multiple interpretations of the data with different contouring algorithms and contouring parameters. The best fit to the data was provided for review. The multiple representations of the data permitted a better understanding of the extent of the contamination problem.

In addition to performance criteria, the following secondary criteria were evaluated.

Ease of Use: The demonstration showed that the basic features in ArcView were easy to use. An analyst with a background in environmental problems and a basic knowledge of database and GIS operations can use ArcView after one to two days of training. The ArcView platform has a graphical user interface with a logical menu structure to permit use of the options in the software package. ArcView supports data queries that permit evaluation of the data based on user-defined criteria, for example, using only trichloroethene data collected in 1999 for contouring. This query capability is a powerful data analysis tool. ArcView was demonstrated to accept a wide range of formats when importing data (e.g., database files, drawing files in .shp and .jpg formats) and can export files using a large number of formats. Use of advanced features, such as the Avenue scripting language, would require additional training and regular use.

Efficiency and Representativeness: ESRI staff completed three visualization problems and generated the report documenting the analysis with 12 person-days of effort. ArcView has a flexible database structure that supports multiple data input formats. This provides a platform that addresses problems efficiently and can be tailored to the problem under study. ArcView permits queries on any field (e.g., chemical name, date, concentration, well identifiers) and also permits filtering (e.g., include only data between certain dates, maximum concentration at a location over a range of sample dates). The software has the capability to evaluate a wide range of environmental conditions (e.g., contaminant in groundwater, soil, multiple contaminants on a single site).

Training and Technical Support: ArcView offers several options for training and technical support. A detailed on-line help system is supplied with the software package, and a user's manual is available to assist in operation of the software. A step-by-step tutorial that covers the major features is provided with the software package. A one-day training course is available if desired. Technical support is available for a yearly maintenance fee.

Operator Skill Base: To use ArcView efficiently, the operator should have a basic understanding of the use of computer software in analyzing environmental problems. This includes fundamental knowledge about GIS and relational database files. In addition, knowledge about contouring environmental data sets is beneficial.

Platform: ArcView was demonstrated on a Windows NT 4.0 operating system. It requires a minimum of 128 megabytes (MB) of random access memory (RAM). During the demonstration, two machines were used. For Sites B and N, a 233-MHz Pentium II laptop with 128 MB of RAM, a 5-gigabyte hard drive and standard 1024×768 video monitor was used. The laptop was equipped with an internal CD drive, a 1-gigabyte Jazz drive, and a PCMCIA network adapter. For the Site A analysis, the computer contained a 300-MHz Pentium II processor with 128 MB of RAM and an Elsa Gloria XLM graphics card with 16 MB of video RAM and an Open GL chipset. This computer was equipped with an internal CD drive, a 1-gigabyte Jazz drive, an internal network adapter, and a 19-in. monitor.

Cost: Pricing varies for single stand-alone systems through enterprise-wide systems. Currently, the government price for the Windows version of a single stand-alone system of ArcView GIS Version 3.1 is $996; for Spatial Analyst and 3D Analyst, the Government Services Administration price is $2342 each. Prices for these products for private industry or for use on a UNIX-based operating system are slightly higher.

Overall Evaluations: The main strength of ArcView, Spatial Analyst, and 3D Analyst is their ability to easily integrate data and maps in a single platform to allow spatial visualization of the data. The visualization output was clear and easy to understand. The ability to sort and query data makes examination of a subset of the data easy to perform. ArcView's ability to manage data files from a wide range of sources makes it suitable for managing complex environmental contamination problems. The ease of use makes ArcView and its extensions accessible for the occasional user who wants to view the spatial correlation between data. For the more advanced user, the scripting language, Avenue, makes the ArcView products extremely flexible and customizable for problem-specific applications. ArcView is a mature product with a large customer base.

The technical team concluded that for visualization of environmental data sets, there were no major limitations in the ArcView set of programs. Minor problems noticed by the technical team included the inability to open some of the project files provided at the demonstration and, for a new user, the need to learn the terminology to understand the operation of ArcView (e.g., “scenes”, “themes”, “program files”).

The credibility of a computer analysis of environmental problems depends on good data, reliable and appropriate software, adequate conceptualization of the site, and a technically defensible problem analysis. The results of the demonstration show that the ArcView software can be used to generate reliable and useful analyses for evaluating environmental contamination problems. This is the only component of a credible analysis that can be addressed by the software. The results of an ArcView analysis can support decision-making. ArcView has been employed in a variety of environmental applications. Although ArcView has been demonstrated to have the capability to produce reliable and useful analyses, improper use of the software can cause the results of the analysis to be misleading or inconsistent with the data. As with any complex environmental DSS product, the quality of the output is directly dependent on the skill of the operator.

As with any technology selection, the user must determine if this technology is appropriate for the application and the project data quality objectives. For more information on this and other verified technologies visit, the ETV web site at *http://www.epa.gov/etv*.

Gary J. Foley, Ph.D
Director
National Exposure Research Laboratory
Office of Research and Development

David E. Reichle
ORNL Associate Laboratory Director
Life Sciences and Environmental Technologies

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ArcView GIS Version 3.1 using ArcView Spatial Analyst and ArcView 3D Analyst extensions

By

Terry Sullivan
Brookhaven National Laboratory
Upton, New York 11983

Anthony Q. Armstrong
Amy B. Dindal
Roger A. Jenkins
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831

Eric N. Koglin
U.S. Environmental Protection Agency
Environmental Sciences Division
National Exposure Research Laboratory
Las Vegas, Nevada 89193-3478

Notice

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Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the nation's natural resources. The National Exposure Research Laboratory (NERL) is EPA's center for the investigation of technical and management approaches for identifying and quantifying risks to human health and the environment. NERL's research goals are to (1) develop and evaluate technologies for the characterization and monitoring of air, soil, and water; (2) support regulatory and policy decisions; and (3) provide the science support needed to ensure effective implementation of environmental regulations and strategies.

EPA created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative technologies through performance verification and information dissemination. The goal of the ETV Program is to further environmental protection by substantially accelerating the acceptance and use of improved and cost-effective technologies. The ETV Program is intended to assist and inform those involved in the design, distribution, permitting, and purchase of environmental technologies. This program is administered by NERL's Environmental Sciences Division in Las Vegas, Nevada.

The U.S. Department of Energy's (DOE's) Environmental Management (EM) program has entered into active partnership with EPA, providing cooperative technical management and funding support. DOE EM realizes that its goals for rapid and cost-effective cleanup hinge on the deployment of innovative environmental characterization and monitoring technologies. To this end, DOE EM shares the goals and objectives of the ETV.

Candidate technologies for these programs originate from the private sector and must be commercially ready. Through the ETV Program, developers are given the opportunity to conduct rigorous demonstrations of their technologies under realistic field conditions. By completing the evaluation and distributing the results, EPA establishes a baseline for acceptance and use of these technologies.

Gary J. Foley, Ph.D.
Director
National Exposure Research Laboratory
Office of Research and Development

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For more information on the Decision Support Software Technology Demonstration, contact

Eric N. Koglin
Project Technical Leader
Environmental Protection Agency
Environmental Sciences Division
National Exposure Research Laboratory
P. O. Box 93478
Las Vegas, Nevada 89193-3478
(702) 798-2432

For more information on the Environmental Software SitePro products, contact

Jennifer Harar
ESRI
8620 Westwood Center Drive
Vienna, VA 22180
703 506-9515 extension 8055
JHarar@ESRI.com

Abbreviations and Acronyms

2-D	two dimensional
3-D	three dimensional
3D Analyst	ArcView 3D Analyst
As	arsenic
.bmp	bitmap file
BNL	Brookhaven National Laboratory
CTC	carbon tetrachloride
Cd	cadmium
CD	compact disk
COSIMA	Contaminated Sites Management
Cr	chromium
DBCP	dibromochloroproprane
.dbf	database file
DCA	dichloroethane
DCE	dichloroethene
DCP	dichloropropane
DOE	U.S. Department of Energy
DSS	Decision Support Software
.dxf	data exchange format file
EDB	ethylene dibromide
EPA	U.S. Environmental Protection Agency
ESRI	Environmental Systems Research Institute, Inc.
ETV	Environmental Technology Verification Program
ETVR	environmental technology verification report
EVS	Environmental Visualization System
FTP	file transfer protocol
GEO-AS	Geostatistical Environmental Assessment Software
GIS	geographical information system
GUI	graphical user interface
GSA	Government Services Administration
GSLIB	Geostatistical Software Library
GW	Groundwater
IDW	inverse distance weighting
.jpg	JPEG file format
MB	megabyte
msl	mean sea level
NERL	National Exposure Research Laboratory
ORNL	Oak Ridge National Laboratory
PCE	perchloroethene or tetrachloroethene
ppb	parts per billion
ppm	parts per million
QA	quality assurance
QC	quality control
RAM	random access memory
ROM	read-only memory
SCMT	Site Characterization and Monitoring Technology
.shp	Shape file format
Spatial Analyst	ArcView Spatial Analyst
TCA	trichloroethane
TCE	trichloroethene

Tc-99	technetium-99
VC	vinyl chloride
VOC	volatile organic compound

Section 1 — Introduction

Background

The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification Program (ETV) to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of ETV is to further environmental protection by substantially accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high-quality, peer-reviewed data on technology performance to those involved in the design, distribution, financing, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations and stakeholder groups consisting of regulators, buyers, and vendor organizations, with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance (QA) protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

ETV is a voluntary program that seeks to provide objective performance information to all of the actors in the environmental marketplace for their consideration and to assist them in making informed technology decisions. ETV does not rank technologies or compare their performance, label or list technologies as acceptable or unacceptable, seek to determine “best available technology,” nor approve or disapprove technologies. The program does not evaluate technologies at the bench or pilot scale and does not conduct or support research.

The program now operates 12 pilots covering a broad range of environmental areas. ETV has begun with a 5-year pilot phase (1995–2000) to test a wide range of partner and procedural alternatives in various pilot areas, as well as the true market demand for and response to such a program. In these pilots, EPA uses the expertise of partner “verification organizations” to design efficient processes for testing the performance of innovative technologies. These expert partners are both public and private organizations, including federal laboratories, states, industry consortia, and private sector facilities. Verification organizations oversee and report verification activities based on testing and QA protocols developed with input from all major stakeholder/customer groups associated with the technology area. The demonstration described in this report was administered by the Site Characterization and Monitoring Technology (SCMT) Pilot. (To learn more about ETV, visit ETV’s Web site at http://www.epa.gov/etv).

The SCMT pilot is administered by EPA’s National Exposure Research Laboratory (NERL). With the support of the U.S. Department of Energy’s (DOE’s) National Analytical Management Program, NERL selected a team from Brookhaven National Laboratory (BNL) and Oak Ridge National Laboratory (ORNL) to perform the verification of environmental decision support software (DSS). DSS is designed to integrate measured or modeled data (such as soil or groundwater contamination levels) into a framework that can be used for decision-making. There are many potential ways to use such software, including visualizing the nature and extent of contamination, locating optimum future samples, assessing costs of cleanup versus benefits obtained, or estimating the human health or ecological risks. The primary objective of this demonstration was to conduct an independent evaluation of each software’s capability to evaluate three common endpoints of environmental remediation problems: visualization, sample optimization, and cost-benefit analysis. These endpoints were defined as follows.

- *Visualization*—using the software to organize and display site and contamination data in ways that promote understanding of current conditions, problems, potential solutions, and eventual cleanup choices

- *Sample optimization*—selecting the minimum number of samples needed to define a contaminated area within a predetermined statistical confidence

- *Cost-benefit analysis*—either assessing the size of the zone to be remediated according to cleanup goals, or estimating human health risks due to the contaminants. These can be related to costs of cleanup

The developers were permitted to select the endpoints that they wished to demonstrate because each piece of software had unique features and focused on different aspects of the three endpoints. Some focused entirely on visualization and did not attempt sample optimization or cost-benefit, while others focused on the technical aspects of generating cost-benefit or sample optimization analysis, with a minor emphasis on visualization. Because the software products were not required to address all three endpoints, partial analysis of a test problem was permitted and the review of each DSS was based only on the parts of the problem to which it was applied.

The capabilities of each DSS were evaluated to determine its effectiveness in integrating data and models to produce information that supports remedial action decisions pertaining to soil and groundwater contamination problems. Secondary evaluation objectives for this demonstration were the reliability, resource requirements, ease of use, and availability of training and technical support of each DSS.

Evaluation of a software used for complex environmental problems is by necessity primarily qualitative in nature. It is not meaningful to evaluate quantitatively how well predictions match at locations where data have not been collected. (This issue is discussed in more detail in Appendix B.) In addition, the selection of a software product for a particular application relies heavily on the users' backgrounds, personal preferences (e.g., some people prefer Microsoft Word, while others prefer Corel WordPerfect for word processing), and intended use of the software (e.g., spreadsheets can be used for managing data; however programs specifically designed for database management would be a better choice for such an application). The objective of these reports is to provide sufficient information to judge whether the DSS product has the analysis capabilities and features to be useful on the types of problems typically encountered by the reader.

Demonstration Overview

In September, 1998, a demonstration was conducted to verify the performance of five environmental software programs: Environmental Visualizations System (C Tech Development Corporation), ArcView and associated software extenders [Environmental Systems Research Institute (ESRI)], Groundwater*FX* (Decision*FX*), Sampling*FX* (Decision*FX,* Inc.), and SitePro (Environmental Software Corporation). In October, a sixth software package from the University of Tennessee Research Corporation, Spatial Analysis and Decision Assistance, was tested. This report contains the evaluation for ArcView GIS Version 3.1 and its extensions Spatial Analyst and 3D Analyst.

Each developer was asked to use its own software to address a minimum of three test problems. In preparation for the demonstration, ten sites were identified as having data sets that might provide useful test cases for the demonstration. All of these data received a quality control (QC) review to screen out sites that did not have adequate data sets. After the review, ten test problems were developed from field data at six different sites. Each site was given a unique identifier (Sites A, B, D, N, S, and T). Each test problem focused on different aspects of environmental remediation problems. From the complete data sets, test problems that were subsets of the entire data set were prepared. The demonstration technical team performed an independent analysis of each of the ten test problems to ensure that the data sets were complete.

All developers were required to choose either Site S or Site N as one of their three problems because these sites had the most data available for developing a quantitative evaluation of DSS performance.

Each DSS was evaluated on its own merits based on the evaluation criteria presented in Section 3. Because of the inherent variability in soil and subsurface contamination, most of the evaluation criteria are qualitative. Even when a direct comparison is made between the developer's analysis and the baseline analysis, different numerical algorithms and assumptions used to interpolate data between measured values at known locations make it almost impossible to make a quantitative judgement as to which technical approach is superior. The comparisons, however, do permit an evaluation of whether the analysis is consistent with the data supplied for the analysis and therefore useful in supporting remediation decisions.

Summary of Analysis Performed by ArcView GIS Version 3.1 and Its Extensions

ArcView GIS version 3.1 is a computer-based tool for mapping and analyzing processes and events that are related by their location. Geographic information systems (GIS) technology integrates common database operations, such as query and statistical analysis, with the visualization and geographic analysis benefits offered by maps. ArcView GIS version 3.1 provides environmental decision support through its integration of data from multiple sources (i.e., spreadsheet, drawing, and database files) into a platform that supports query operations, data manipulation and visualization. ArcView can generate two-dimensional maps of data and surface features. The 3D Analyst extension provides the capability to layer two-dimensional maps to provide a quasi–three-dimensional representation of site features (e.g., geologic layers, contamination). ArcView GIS version 3.1 allows analysts to manage and share their site data using a project file that integrates the different data and visualization files.

ESRI staff chose to use ArcView to perform the visualization endpoint for data from Sites A, B, and N. The intent of the ArcView analyses was to demonstrate the capability to integrate large quantities of data into a visual framework for assistance in understanding a site's contamination problem. ESRI staff chose to apply three different levels of ArcView visualization functionality. On Site B, they used the standard ArcView product. On Site N, they added the Spatial Analyst extension to perform and display contoured surfaces. On Site A, they added the 3D Analyst extension and three other extensions available free from the ESRI website to develop and display three-dimensional surfaces and data. These extensions are discussed in more detail in Sections 2 and 4.

The Site B problem involved groundwater contamination in two-dimensions. The data supplied for analysis of Site B included surface maps of buildings, roads, and water bodies; concentration data on three contaminants (trichloroethene (TCE), vinyl chloride (VC), and technetium-99 (Tc-99)) in groundwater wells and hydraulic head data. ArcView was used to generate maps containing color-coded well locations, buildings, roads, railroads, and water bodies. The color coding was used to show the location of high-concentration regions in the mapped domain. ESRI staff demonstrated ArcView's capabilities to integrate the data from a wide range of sources (aerial photographs, database files, and drawing files) to assist in the understanding of the problem.

The Site N problem analyzed by ESRI was a two-dimensional soil contamination cost-benefit analysis. The data supplied for analysis of Site N included concentration data on three contaminants, arsenic (As), cadmium (Cd), and chromium (Cr), at 524 locations. In addition, drawing files containing roads and surface water bodies were supplied. The objective of this problem was to analyze the data and supply an estimate of the contaminated area based on two different cleanup levels for each contaminant. The information could then be used in a cost-benefit analysis. ESRI used ArcView with the Spatial Analyst extension to generate maps for each contaminant at the two cleanup levels. ESRI then combined the maps for all three contaminants and provided an estimate of the contaminated area and costs for remediation based on cleanup level.

The Site A problem was a three-dimensional groundwater contamination cost-benefit analysis. The data supplied included surface drawings of buildings, roads, and water bodies, and groundwater contamination concentrations at more than 50 wells with data supplied on a 5-ft vertical spacing in each well. The contaminants of concern were perchloroethene (PCE) and trichloroethane (TCA). ESRI demonstrated ArcView's capability to query the data and select data for contouring as a function of elevation and contaminant type. ArcView generated contour maps of contaminant concentrations on a 10-ft spacing from the water table to the bedrock (nine layers). These maps were used to generate a quasi three-dimensional representation of the contamination above certain specified threshold values. Buildings and surface features were included on the map to provide a frame of reference. In addition, ArcView 3D Analyst was used to generate a three-dimensional representation of the bedrock elevation and a two-dimensional representation of water levels at the site.

Section 2 contains a brief description of the capabilities of ArcView, Spatial Analyst and 3D Analyst. Section 3 outlines the process followed in conducting the demonstration. This includes the approach used to develop the test problems, a summary description of the ten test problems, the approach used to perform the baseline analyses for comparison with the developers’ analyses, and the evaluation criteria. (More detailed descriptions of the test problems can be found in Appendix A.) Section 4 presents the technical review of the analyses performed by ArcView, Spatial Analyst, and 3D Analyst. This includes a detailed discussion of the problems attempted, comparisons of the ArcView analyses and the baseline results, and an evaluation of ArcView against the criteria established in Section 3. Section 5 presents an update on the ArcView technology and provides examples of representative applications of ArcView in environmental problem solving.

Section 2 — ArcView Version 3.1, Spatial Analyst, and 3D Analyst Description

The following section provides a general overview of the capabilities of ESRI's ArcView GIS version 3.1 and its extensions Spatial Analyst and 3D Analyst. The information was supplied by ESRI.

ArcView GIS version 3.1 is a computer-based tool for mapping and analyzing processes and events that are related by their location. GIS technology integrates common database operations such as query and statistical analysis with the unique visualization and geographic analysis benefits offered by maps. These abilities distinguish GIS from other information systems and make it valuable to a wide range of public and private enterprises for explaining events, predicting outcomes, and planning strategies.

ArcView GIS version 3.1 was used to demonstrate database connectivity, geographic display and mapping functionality, and model interfaces, which are vital tools for site characterization, risk assessment, and groundwater remediation analysis. ArcView GIS can take environmental/facility site data, aerial photo and satellite imagery, waste site location data, natural resource data, well and boring log data, and project impact data and integrate them in a single software platform. Users can produce tailored products by analyzing data layers to determine patterns, relationships and trends. The extensible software architecture of ArcView GIS delivers a scaleable platform for GIS computing. This new architecture has enabled ESRI to develop a series of "plug-in" modules for ArcView that extend its functional capabilities. Two of these extensions, Spatial Analyst and 3D Analyst, were used in the demonstration.

ArcView Spatial Analyst version 1.1 introduces a broad range of new spatial modeling and analysis features previously not available to desktop users. It allows a user to create, query, map, and analyze spatially continuous data (cell-based raster data) and perform integrated raster-vector analysis. For example, Spatial Analyst can take contaminant concentration data and form an interpolated spatially continuous surface for the data. It can then be used to define the area of the map in which the concentration exceeds a specified value. Spatial Analyst can work with spatially continuous data (including overlaying, querying, and displaying multiple themes) and perform integrated analysis. This analysis could include a task such as aggregating properties of continuous data (contaminant concentrations) based on an overlaid discrete data theme (locations of buildings and roads).

Spatial Analyst provides solutions to problems that require consideration of distance or other continuous surface modeling information as part of the analysis. For example, site suitability analysis often requires combining information about slope [information best represented as a continuous interpolated surface (raster data)] and the locations of roads and property boundaries [information best represented as lines (vector data) on the map] to arrive at the best location for a new facility. Spatial Analyst not only can generate the appropriate surface representation of information from a variety of existing data sources, but also can derive new information from the overlay of multiple surface maps (e.g., roads, buildings, property lines, surface slope). The results can then be used to suggest possible solutions to the original problem.

The 3D Analyst allows for the viewing and analysis of three-dimensional data in a new ArcView document type called a "scene." The 3D Analyst provides functionality to assist users with three primary tasks—surface model construction, analysis, and display. Three-dimensional surfaces can be edited directly in 3D Analyst. This capability helps define high-quality three-dimensional surfaces and permits the user to make changes due to changes in data (e.g., new roads or buildings) without re-creating the entire representation. The 3D Analyst goes beyond common forms of surface analysis, such as contouring and slope/aspect derivation, by providing attribute support, low-level navigation tools, and iterators. Numeric values representing user-defined attributes can be assigned to triangle nodes (point features) and facets (areal features). Thus for any location on a modeled surface, the user can access not only the surface geometry, but also other thematic characteristics such as land cover. The navigation tools and iterators are useful to applications that need to walk through the triangulation or run through a collection of triangles that satisfy some criterion. For example, the iterator can be used to define all modeled regions (triangles) that contribute to the water flow to a point location. Interactive perspective viewing of the three-dimensional surfaces is possible.

Customization for site-specific applications is possible using the ArcView program language, Avenue. In preparation for the demonstration, ESRI employees wrote three additional extensions using Avenue. One extension called “Scene Text” handles the user-defined properties and placement of text that can be added to three-dimensional scenes when 3D Analyst is used. A second extension, “3D Scene Axes,” uses Scene Text and adds functionality for making and labeling the three-dimensional coordinate axes in three-dimensional scenes. The third extension, “Interpolate Multi Z-Value Data,” handles the stratification, interpolation, and display of the three-dimensional well sample data. It manages user input for changing the properties of the interpolation that will be used on the stratified data points. The result is a contour surface of contamination for each stratum. This extension also handles display properties for the generated contour surfaces. These additional extensions are available free at www.esri.com. The Web page contains links to many extensions of the ArcView GIS product. ESRI customers often supply these extensions, and ESRI does not provide technical support for any of them.

ArcView GIS can be used as a stand-alone project system or extended into an entire department, division, or organization. It can be used to access and view ARC/INFO® databases, including personal computer ARC/INFO data. ArcView can also directly use raster image data (continuous surface map) in a wide variety of formats. Users can access and visualize geographic data stored either locally or remotely on a network.

ESRI offers training courses in the use of its products at the ESRI headquarters in Redlands, California, at ESRI regional offices, and through ESRI authorized instructors. A “virtual campus” also offers access to training classes over the Internet at www.esri.com. ESRI has prepared several tutorials to train users on the application of various ArcView features and concepts. On-line help is available for ArcView and its extensions, and ESRI provides a technical support hotline to assist users in implementing the software during the original warranty period. There is a 60-day complimentary technical support period for ArcView and its optional extensions. Additional technical support services are available from ESRI through software maintenance and support programs.

Section 3 — Demonstration Process and Design

Introduction

The objective of this demonstration was to conduct an independent evaluation of the capabilities of several DSSs in the following areas:
(1) effectiveness in integrating data and models to produce information that supports decisions pertaining to environmental contamination problems, and (2) the information and approach used to support the analysis. Specifically, three endpoints were evaluated:

- *Visualization* — Visualization software was evaluated in terms of its ability to integrate site and contamination data in a coherent and accurate fashion that aids in understanding the contamination problem. Tools used in visualization can range from data display in graphical or contour form to integrating site maps and aerial photos into the results.

- *Sample optimization* — Sample optimization was evaluated for soil and groundwater contamination problems in terms of the software's ability to select the minimum number of samples needed to define a contaminated region with a specified level of confidence.

- *Cost-benefit analysis* — Cost-benefit analysis involved either defining the size of remediation zone as a function of the cleanup goal or evaluating the potential human health risk. For problems that defined the contamination zone, the cost could be evaluated in terms of the size of the zone, and cost-benefit analysis could be performed for different cleanup levels or different statistical confidence levels. For problems that calculated human health risk, the cost-benefit calculation would require computing the cost to remediate the contamination as a function of reduction in health risk.

Secondary evaluation objectives for this demonstration were to examine the reliability, resource requirements, range of applicability, and ease of operation of the DSS. The developers participated in this demonstration in order to highlight the range and utility of their software in addressing the three endpoints discussed above. Actual users might achieve results that are less reliable, as reliable, or more reliable than those achieved in this demonstration, depending on their expertise in using a given software to solve environmental problems.

Development of Test Problems

Test Problem Definition

A problem development team was formed to collect, prepare, and conduct the baseline analysis of the data. A large effort was initiated to collect data sets from actual sites with an extensive data collection history. Literature review and contact with different government agencies (EPA field offices, DOE, the U.S. Department of Defense, and the United States Geological Survey) identified ten different sites throughout the United States that had the potential for developing test problems for the demonstration. The data from these ten sites were screened for completeness of data, range of environmental conditions covered, and potential for developing challenging and defensible test problems for the three endpoints of the demonstration. The objective of the screening was to obtain a set of problems that covered a wide range of contaminants (metals, organics, and radionuclides), site conditions, and source conditions (spills, continual slow release, and multiple releases over time). On the basis of this screening, six sites were selected for development of test problems. Of these six sites, four had sufficient information to provide multiple test problems. This provided a total of ten test problems for use in the demonstration.

Summary of Test Problems

A detailed description of the ten test problems was supplied to the developers as part of the demonstration (Sullivan, Armstrong, and Osleeb 1998). A general description of each of the problems can be found in Appendix A. This description includes the operating history of the site, the contaminants of concern, and the objectives of the test problem (e.g., define the volume over which the contaminant concentration exceeds 100 μg/L). The test problems analyzed by ESRI are discussed in Section 4 as part of the evaluation of the performance of ArcView and its extensions Spatial Analyst and 3D Analyst.

Table 1 summarizes the ten problems by site identifier, location of contamination (soil or groundwater), problem endpoints, and contaminants of concern. The visualization endpoint could be performed on all ten problems. In addition, there were four sample optimization problems, four cost-benefit problems, and two problems that combined sample optimization and cost-benefit issues. The range of contaminants considered included metals, volatile organic compounds (VOCs), and radionuclides. The range of environmental conditions included two- and three-dimensional soil and groundwater contamination problems over varying geologic, hydrologic, and environmental settings. Table 2 provides a summary of the types of data supplied with each problem.

Analysis of Test Problems

Prior to the demonstration, the demonstration technical team performed a quality control examination of all data sets and test problems. This involved reviewing database files for improper data (e.g., negative concentrations), removing information that was not necessary for the demonstration (e.g., site descriptors), and limiting the data to the contaminants, the region of the site, and the time frame covered by the test problems (e.g., only data from one year for three contaminants). For sample optimization problems, a limited data set was prepared for the developers as a starting point for the analysis. The remainder of the data were reserved to provide input concentrations to developers for their sample optimization analysis. For cost-benefit problems, the analysts were provided with an extensive data set for each test problem with a few data points reserved for checking the DSS analysis. The data quality review also involved importing all graphics files (e.g., .dxf and .bmp) that contained information on surface structures such as buildings, roads, and water bodies to ensure that they were readable and useful for problem development. Many of the drawing files were prepared as ESRI shape files compatible with ArcView. ArcView was also used to examine the graphics files.

Once the quality control evaluation was completed, the test problems were developed. The test problems were designed to be manageable within the time frame of the demonstration and were often a subset of the total data set. For example, in some cases, test problems were developed for a selected region of the site. In other cases, the database could have contained information for tens of contaminants, while the test problems themselves were limited to the three or four principal contaminants. At some sites, data were available over time periods exceeding 10 years. For the DSS test problems, the analysts were typically supplied chemical and hydrologic data for a few sampling periods.

Once the test problems were developed, the demonstration technical team conducted a complete analysis of each test problem. These analyses served as the baseline for evaluating results from the developers. Each analysis consisted of taking the

Table 1. Summary of test problems

Site identifier	Media	Problem endpoints	Contaminants
A	Groundwater	Visualization, sample optimization	Dichloroethene, trichloroethene
A	Groundwater	Visualization, cost-benefit	Perchloroethene, trichloroethane
B	Groundwater	Visualization, sample optimization, cost-benefit	Trichloroethene, vinyl-chloride, technetium-99
D	Groundwater	Visualization, sample optimization, cost-benefit	Dichloroethene, dichlorethane, trichloroethene, perchloroethene
N	Soil	Visualization, sample optimization	Arsenic, cadmium, chromium
N	Soil	Visualization, cost-benefit	Arsenic, cadmium, chromium
S	Groundwater	Visualization, sample optimization	Carbon tetrachloride
S	Groundwater	Visualization, cost-benefit	Chlordane
T	Soil	Visualization, sample optimization	Ethylene dibromide, dibromochloropropane, dichloropropane, carbon tetrachloride
T	Groundwater	Visualization, cost-benefit	Ethylene dibromide, dibromochloropropane, dichloropropane, carbon tetrachloride

Table 2. Data supplied for the test problems

Site history	Industrial operations, environmental settings, site descriptions
Surface structure	Road and building locations, topography, aerial photos
Sample locations	x, y, z coordinates for soil surface samples soil borings groundwater wells
Contaminants	Concentration data as a function of time and location (x, y, and z) for metals, inorganics, organics, radioactive contaminants
Geology	Soil boring profiles, bedrock stratigraphy
Hydrogeology	Hydraulic conductivities in each stratigraphic unit; hydraulic head measurements and locations
Transport parameters	Sorption coefficient (K_d), biodegradation rates, dispersion coefficients, porosity, bulk density
Human health risk	Exposure pathways and parameters, receptor location

entire data set and obtaining an estimate of the plume boundaries for the specified threshold contaminant concentrations and estimating the area of contamination above the specified thresholds for each contaminant.

The independent data analysis was performed using Surfer™. Surfer was selected for the task because it is a widely used, commercially available software package with the functionality necessary to examine the data. This functionality includes the ability to import drawing files to use as layers in the map, and the ability to interpolate data in two dimensions. Surfer has eight different interpolation methods, each of which can be customized by changing model parameters, to generate contours. These different contouring options were used to generate multiple views of the interpolated regions of contamination and hydrologic information. The best fit to the data was used as the baseline analysis. For three-dimensional problems, the data were grouped by elevation to provide a series of two-dimensional slices of the problem. The distance between slices ranged between 5 and 10 ft depending on the availability of data. Compilation of vertical slices generated three-dimensional depictions of the data sets. Comparisons of the baseline analysis to the results from ArcView and its extensions are presented in Section 4.

In addition to Surfer, two other software packages were used to provide an independent analysis of the data and to provide an alternative representation for comparison with the Surfer results. The Geostatistical Software Library Version 2.0 (GSLIB) and Geostatistical Environmental Assessment Software Version 1.1 (Geo-EAS) were selected because both provide enhanced geostatistical routines that assist in data exploration and selection of modeling parameters to provide extensive evaluations of the data from a spatial context. These three analyses provide multiple lines of reasoning, particularly for the test problems that involved geostatistics. The results from Surfer, GSLIB, and Geo-EAS were compared and contrasted to determine the best fit of the data, thus providing a more robust baseline analysis for comparison to the developers' results.

Under actual site conditions, uncertainties and natural variability make it impossible to define plume boundaries exactly. In these case studies, the baseline analyses serve as a guideline for evaluating the accuracy of the analyses prepared by the developers. Reasonable agreement should be obtained between the baseline and the developer's results. A discussion of the technical approaches and limitations to estimating physical properties at locations that are between data collection points is provided in Appendix B.

To minimize problems in evaluating the software associated with uncertainties in the data, the developers were required to perform an analysis of one problem from either Site N or Site S. For Site N, with over 5,000 soil contamination data points, the baseline analysis reflected the actual site conditions closely; and if the developers performed an accurate analysis, the correlation between the two should be high. For Site S, the test problems used actual contamination data as the basis for developing a problem with a known solution. In both Site S problems, the data were modified to simulate a constant source term to the aquifer in which the movement of the contaminant can be described by the classic advective-dispersive transport equation. Transport parameters were based on the actual data. These assumptions permitted release to the aquifer and subsequent transport to be represented by a partial differential equation that was solved analytically. This analytical solution could be used to determine the concentration at any point in the aquifer at any time. Therefore, the developer's results can be compared against calculated concentrations with known accuracy.

After completion of the development of the ten test problems, a predemonstration test was conducted. In the predemonstration, the developers were supplied with a problem taken from Site D that was similar to test problems for the demonstration. The objective of the predemonstration was to provide the developers with a sample problem with the level of complexity envisioned for the demonstration. In addition, the predemonstration allowed the developers to process data from a typical problem in advance of the demonstration and allowed the demonstration technical team to determine if any problems occurred during data transfer or because of problem definition. The results of the predemonstration were used to refine the problems used in the demonstration.

Preparation of Demonstration Plan

In conjunction with the development of the test problems, a demonstration plan (Sullivan and Armstrong 1998) was prepared to ensure that all aspects of the demonstration were documented and scientifically sound and that operational procedures were conducted within QA/QC specifications. The demonstration plan covered

- the roles and responsibilities of demonstration participants;
- the procedures governing demonstration activities such as data collection to define test problems and data preparation, analysis, and interpretation;
- the experimental design of the demonstration;
- the evaluation criteria against which the DSS would be judged; and
- QA and QC procedures for conducting the demonstration and for assessing the quality of the information generated from the demonstration.

All parties involved with implementation of the plan approved and signed the demonstration plan prior to the start of the demonstration.

Summary of Demonstration Activities

On September 14–25, 1998, the Site Characterization and Monitoring Technology Pilot, in cooperation with DOE's National Analytical Management Program, conducted a demonstration to verify the performance of five environmental DSS packages. The demonstration was conducted at the New Mexico Engineering Research Institute, Albuquerque, New Mexico. An additional software package was tested on October 26–29, 1998, at BNL, Upton, New York.

The first morning of the demonstration was devoted to a brief presentation of the ten test problems, a discussion of the output requirements to be provided from the developers for evaluation, and transferring the data to the developers. The data from all ten test problems—along with a narrative that provided a description of the each site, the problems to be solved, the names of data files, structure of the data files, and a list of output requirements—were given to the developers. The developers were asked to address a minimum of three test problems for each software product.

Upon completion of the review of the ten test problems and the discussion of the outputs required from the developers, the developers received data sets for the problems by file transfer protocol (FTP) from a remote server or on a high-capacity removable disk. Developers downloaded the data sets to their own personal computers, which they had supplied for the demonstration. Once the data transfers of the test problems were complete and the technical team had verified that each developer had received the data sets intact, the developers were allowed to proceed with the analysis at their own pace. During the demonstration, the technical team observed the developers, answered questions, and provided data as requested by the developers for the sample optimization test problems. The developers were given 2 weeks to complete the analysis for the test problems that they selected.

The third day of the demonstration was visitors' day, an open house during which people interested in DSS could learn about the various products being tested. During the morning of visitors' day, presenters from EPA, DOE, and the demonstration technical team outlined the format and content of the demonstration. This was followed by a presentation from the developers on the capabilities of their respective software products. In the afternoon, attendees were free to meet with the developers for a demonstration of the software products and further discussion.

Prior to leaving the test facility, the developers were required to provide the demonstration technical team with the final output files generated by their software. These output files were transferred by FTP to an anonymous server or copied to a zip drive or CD-ROM. The technical team verified that all files generated by the developers during the demonstration were provided and intact. The developers were given a 10-day period after the demonstration to provide a written narrative of the work that was performed and a discussion of their results.

Evaluation Criteria

One important objective of DSS is to integrate data and models to produce information that supports an environmental decision. Therefore, the overriding performance goal in this demonstration was to provide a credible analysis. The credibility of a software and computer analysis is built on four components:

- good data,
- adequate and reliable software,
- adequate conceptualization of the site, and
- well-executed problem analysis (van der Heijde and Kanzer 1997).

In this demonstration, substantial efforts were taken to evaluate the data and remove data of poor quality prior to presenting it to the developers. Therefore, the developers were directed to assume that the data were of good quality. The technical team provided the developers with detailed site maps and test problem instructions on the requested analysis and assisted in site conceptualization. Thus, the demonstration was primarily to test the adequacy of the software and the skills of the analyst. The developers operated their own software on their own computers throughout the demonstration.

Attempting to define and measure credibility makes this demonstration far different from most demonstrations in the ETV program in which measurement devices are evaluated. In the typical ETV demonstrations, quality can be measured in a quantitative and statistical manner. This is not true for DSS. While there are some quantitative measures, there are also many qualitative measures. The criteria for evaluating the DSS's ability to support a credible analysis are discussed below. In addition a number of secondary objectives, also discussed below, were used to evaluate the software. These included documentation of software, training and technical support, ease of use of the software, efficiency, and range of applicability.

Criteria for Assessing Decision Support

The developers were asked to use their software to answer questions pertaining to environmental contamination problems. For visualization tools, integration of geologic data, contaminant data, and site maps to define the contamination region at specified concentration levels was requested. For software tools that address sample optimization questions, the developers were asked to suggest optimum sampling locations, subject to constraints on the number of samples or on the confidence with which contamination concentrations were known. For software tools that address cost-benefit problems, the developers were asked either to define the volume (or area) of contamination and, if possible, supply the statistical confidence with which the estimate was made, or to estimate human health risks resulting from exposure to the contamination.

The criterion for evaluation was the credibility of the analyses to support the decision. This evaluation was based on several points, including

- documentation of the use of the models, input parameters, and assumptions;
- presentation of the results in a clear and consistent manner;
- comparison of model results with the data and baseline analyses;
- evaluation of the use of the models; and
- use of multiple lines of reasoning to support the decision.

The following sections provide more detail on each of these topics.

Documentation of the Analysis and Evaluation of the Technical Approach

The developers were requested to supply a concise description of the objectives of the analysis, the procedures used in the analysis, the conclusions of the analysis with technical justification of the conclusions, and a graphical display of the results of the analysis. Documentation of key input parameters and modeling assumptions was also requested. Guidance was provided on the quantity and type of information requested to perform the evaluation.

Based on observations obtained during the demonstration and the documentation supplied by the developers, the use of the models was evaluated and compared to standard practices. Issues in proper use of the models include selection of appropriate contouring parameters, spatial and temporal discretization, solution techniques, and parameter selection.

This evaluation was performed as a QA check to determine if standard practices were followed. This evaluation was useful in determining whether the cause of discrepancies between model projections and the data resulted from operator actions or from the model itself and was instrumental in understanding the role of the operator in obtaining quality results.

Comparison of Projected Results with the Data and Baseline Analysis

Quantitative comparisons between DSS-generated predictions and the data or baseline analyses were performed and evaluated. In addition, DSS-generated estimates of the mass and volume of contamination were compared to the baseline analyses to evaluate the ability of the software to determine the extent of contamination. For visualization and cost-benefit problems, developers were given a detailed data set for the test problem with only a few data points held back for checking the consistency of the analysis. For sample optimization problems, the developers were provided with a limited data set to begin the problem. In this case, the data not supplied to the developers were used for checking the accuracy of the sample optimization analysis. However, because of the inherent variability in environmental systems and the choice of different models and parameters by the analysts, quantitative measures of the accuracy of the analysis are difficult to obtain and defend. Therefore, qualitative evaluations of how well the model projections reproduced the trends in the data were also performed.

A major component of the analysis of environmental data sets involves predicting physical or chemical properties (contaminant concentrations, hydraulic head, thickness of a geologic layer, etc.) at locations between measured data. This process, called interpolation, is often critical in developing an understanding of the nature and extent of the environmental problem. The premise of interpolation is that the estimated value of a parameter is a weighted average of measured values around it. Different interpolation routines use different criteria to select the weights. Due to the importance of obtaining estimates of data between measured data points in many fields of science, a wide number of interpolation routines exist. Three classes of interpolation routines commonly used in environmental analysis are nearest neighbor, inverse distance, and kriging. These three classes of interpolation, and their strengths and limitations, are discussed in detail in Appendix B.

Use of Multiple Lines of Reasoning

Environmental decisions are often made with uncertainties because of an incomplete understanding of the problem and lack of information, time, and/or resources. Therefore, multiple lines of reasoning are valuable in obtaining a credible analysis. Multiple lines of reasoning may incorporate statistical analyses, which in addition to providing an answer, provide an estimate of the probability that the answer is correct. Multiple lines of reasoning may also incorporate alternative conceptual models or multiple simulations with different parameter sets. The DSS packages were evaluated on their capabilities to provide multiple lines of reasoning.

Secondary Evaluation Criteria

Documentation of Software

The software was evaluated in terms of its documentation. Complete documentation includes detailed instructions on how to use the software package, examples of verification tests performed with the software package, a discussion of all output files generated by the software package, a discussion of how the output files may be used by other programs (e.g., ability to be directly imported into an Excel spreadsheet), and an explanation of the theory behind the technical approach used in the software package.

Training and Technical Support

The developers were asked to list the necessary background knowledge necessary to successfully operate the software package (i.e., basic understanding of hydrology, geology, geostatistics, etc.) and the auxiliary software used by the software package (e.g., Excel). In addition, the operating systems (e.g., Unix, Windows NT) under which the DSS can be used was requested. A discussion of training, software documentation, and technical support provided by the developers was also required.

Ease of Use

Ease of use is one of the most important factors to users of computer software. Ease of use was evaluated by an examination of the software package's operation and on the basis of adequate on-line help, the availability of technical support, the flexibility to change input parameters and databases used by the software package, and the time required for an experienced user to set up the model and prepare the analysis (that is, input preparation time, time required to run the simulation, and time required to prepare graphical output).

The demonstration technical team observed the operation of each software product during the demonstration to assist in determining the ease of use. These observations documented operation and the technical skills required for operation. In addition, several members of the technical team were given a 4-hour tutorial by each developer on their respective software to gain an understanding of the training level required for software operation as well as the functionalities of each software.

Efficiency and Range of Applicability

Efficiency was evaluated on the basis of the resource requirements used to evaluate the test problems. This was assessed through the number of problems completed as a function of time required for the analysis and computing capabilities.

Range of applicability is defined as a measure of the software's ability to represent a wide range of environmental conditions and was evaluated through the range of conditions over which the software was tested and the number of problems analyzed.

Section 4 — Evaluation of ArcView Version 3.1, Spatial Analyst, and 3D Analyst

Description of Test Problems

ESRI's ArcView is a data integration and visualization tool. ArcView and its extensions Spatial Analyst and 3D Analyst assimilate site, well, and contaminant data and can generate two- and three-dimensional representations of the information. In the DSS demonstration, ESRI staff selected problems for Sites B, N, and A. For Site B, ESRI used the standard ArcView GIS version 3.1 software. For Site N, ESRI added the Spatial Analyst extension to generate and display contoured surfaces. For Site A, ESRI added the 3D Analyst extension to generate and display three-dimensional surfaces and data. As part of the demonstration, several dozen visualization outputs were generated. A few examples that display the range of ArcView's capabilities and features are included in this report. A general description of each test problem and the analysis performed using ArcView follows. Detailed descriptions of all test problems are provided in Sullivan, Armstrong, and Osleeb (1998).

Site B

The objective of this test problem was to challenge the software's capabilities as a sample optimization and cost-benefit tool. The test problem presents a two-dimensional groundwater contamination scenario with three contaminants, VC, TCE, and Tc-99. Other contaminants were supplied in the database but were not part of the original problem. Chemical analysis data were collected at a series of groundwater monitoring wells on quarterly basis for more than 10 years along the direction of flow near the centerline of the plume. The analysts were supplied with data from one year.

ESRI staff chose to demonstrate the basic capabilities of ArcView GIS version 3.1 and did not perform the sample optimization/cost benefit analysis requested in the problem description. ArcView was used to generate the following output for this problem:

- Map with buildings, roads, railroads, water bodies, and well locations.
- Map with an aerial photo overlain on previous map.
- Maps based on queries of the database. For example, a map containing roads, buildings, and water bodies was produced that highlighted all wells with measured neptunium concentrations greater than zero.

Site N Cost-Benefit Problem

The objective of this test problem was to challenge the ability of the software to perform cost-benefit analysis as defined in terms of area of contaminated soil above two threshold concentrations. The Site N data set contained the most extensive and reliable data set for evaluating the accuracy of the analysis for a soil contamination problem. To focus only on the accuracy of the soil cost-benefit analysis, the problem was simplified by removing information regarding groundwater contamination at this site, and it was limited to three contaminants.

This test problem considers surface soil contamination (two-dimensional) for As, Cd, and Cr. The analysts were given an extensive data set for a small region of the site and asked to conduct a cost-benefit analysis to evaluate the area and cost for remediation to achieve specified threshold concentrations provided in Table 3.

ArcView estimated the areal extent of the soil contamination by using Spatial Analyst to generate contours at the specified threshold concentrations for each contaminant. The following output was generated for this problem:

Table 3. Site N soil contamination threshold concentrations

Contaminant	Minimum threshold concentration (mg/kg)	Maximum threshold concentration (mg/kg)
Arsenic	75	500
Cadmium	70	700
Chromium	370	3700

- For each contaminant (As, Cd, and Cr), a map with roads and water bodies overlain with concentration contours at the specified threshold concentrations.
- An estimate of the area of contamination above the respective minimum threshold concentration for each contaminant.

Site A

The objective of this test problem was to determine the accuracy with which the software predicts plume boundaries that define the extent of a three-dimensional groundwater contamination problem on a large scale (the problem domain is approximately 1 mile^2). The VOC contaminants of concern for the cost-benefit problem were PCE and TCA.

The design objective of this test problem was for the analyst to define the location and depth of the plume at PCE concentrations of 100 and 500 ppb and TCA concentrations of 5 and 50 ppb at confidence levels of 10% (maximum plume), 50% (nominal plume), and 90% (minimum plume). The analysts were provided with geological information, borehole logs, hydraulic data, and an extensive chemical analysis data set consisting of more than 80 wells. Chemical analysis data were collected at 5-ft intervals from each well. Data from a few wells were withheld from the analysts to provide a reference to check interpolation routines.

ESRI used ArcView GIS version 3.1 with the 3D Analyst extension to generate the contours of the contaminant concentration data as a function of depth below ground surface. ESRI used ArcView to query the data and divided the data into 10-ft-thick sections from the top of the water table to the bedrock. The data were supplied on 5-ft spacings, so each layer had two data points. The maximum contaminant concentration in each layer was used to generate the two-dimensional contour for each layer. Output from the ESRI analysis included the following:

- Three-dimensional surface maps of contaminant concentrations in monitoring wells as a function of elevation. Contamination was displayed using markers (circles) that increased in size with increasing concentration.
- A three-dimensional surface map of the bedrock layer with a semi-transparent ground layer containing buildings and wells.
- A three-dimensional surface map of the interpolated bedrock surface with well depths shown visually as extruded lines.
- A three-dimensional surface map of the bedrock layer with semi-transparent water level contour map.
- Two-dimensional contour maps of the bedrock surface and ground surface elevation.
- Two-dimensional water level maps with buildings and surface water bodies.
- Two-dimensional concentration contour maps for each of the ten groundwater layers for PCE and TCA (20 maps total).
- A layered view of a three-dimensional surface map of concentration contours in selected layers for TCA.
- A layered view of a three-dimensional surface map of regions where the TCE concentrations exceeded 600 μg/L, with the bedrock and water levels incorporated on the map. The data for this problem were taken from the sample optimization test problem for Site A. Additional analysis of the sample optimization problem was not presented; however, ESRI staff decided to demonstrate the visualization capabilities of the 3D Analyst extension of ArcView.

Evaluation of ArcView GIS Version 3.1 with Its Extensions

Decision Support

During the demonstration, it was observed that ArcView provides a platform that can quickly import data on contaminant concentrations, geologic structure, and surface structure from a variety of sources with different formats and integrate the information on a single platform. ArcView and its extensions Spatial Analyst and 3D Analyst were used to place this information in a visual context that supports data interpretation. Multiple queries and views of the data could be generated to assist in data interpretation. The accuracy of the analysis is discussed in the section on comparison of ArcView results with baseline analysis and data.

Documentation of the ArcView Analysis and Evaluation of the Technical Approach

For each analysis, ESRI staff provided a step-by-step description of the manipulations necessary to import the data provided into ArcView and perform the desired analysis. The steps proceeded logically and in a straightforward manner. Manipulations to format the data within the ArcView architecture were relatively simple. For example, a Site B data file (.dbf) containing sample locations and measured contaminant concentrations, and a drawing file (.shp) containing site maps were imported into the ArcView data management system. The ArcView database provided an integrated structure and was coupled with the ArcView analysis tools (e.g., contouring/mapping, graphing, and reporting). In addition, Site B data were hot-linked to the Site B map that was generated from the drawing files by ArcView according to the sample locations. These hot links enabled the user to view the site map and click on the sample location to access the database information. Another useful feature of the software was direct export of the output into standard commercially available word processing software. Graphical images were generated in .jpg format and imported directly into commercially available software (Microsoft Word). Documentation of data transfer and manipulation (for example, how to treat contamination data as a function of depth in a well) and analyses were included. Model selection and parameters for contouring were also provided in the test problem documentation.

The technical approach used by ESRI staff did not always conform to standard practices, nor did the staff address the test problems as it was posed. In particular, for Site A, the information supplied for some wells at some elevations contained null values (blanks); ESRI staff decided to treat the null values as zero. In general, assuming values is not recommended. This approach was an operator choice. The software has the capability to exclude null values from further use in the analysis. For Site B, ESRI did not follow the test problem directions. ESRI staff did not evaluate any of the three contaminants (TCE, VC, Tc-99) requested in the problem description. However, ESRI did evaluate contaminant data for neptunium-237. While the deviation from the requested problem did not impact ESRI's ability to demonstrate the capabilities of its software products, it did make the evaluation of technical accuracy more difficult.

Comparison of ArcView Results with the Baseline Analysis and Data

Site B

ESRI staff used ArcView GIS version 3.1 to import drawing files containing information on roads, railroads, surface water bodies, and buildings. Likewise, database files containing well locations and contaminant concentrations were imported and integrated into a single map with the drawing files (Figure 1). All figures provided by ESRI as a result of this demonstration are screen captures from ArcView. Each screen capture is composed of two regions. On the left is a list of the files used to create the visualization. Only files that are checked are used to create the view. In this case, all files (well locations, geologic samples, streets, railroads, streams/rivers, and lake) are activated for creating Figure 1. Changing the files that are activated can create multiple views of the data. The right of the screen capture contains the ArcView visualization. ArcView hot-links database information to the map. Color coding is used to distinguish between the different features (e.g., railroads are displayed in yellow). Moving the pointer to a well and clicking on the well allows database information to be accessible for viewing. ESRI staff also demonstrated that ArcView had the capability to import and view aerial photos (supplied in .jpg format) as an overlay to the map. ESRI staff imported the .jpg file and registered the file location to locations on the map to create Figure 2. The capability to query the database and highlight monitoring well locations that passed the query criteria was also demonstrated (Figure 3). In Figure 3, the database was queried and all well locations that had positive measurement for the radionuclide neptunium-237 were highlighted in yellow. An example of the query is presented in the lower left-hand corner of Figure 3. The technical evaluation team examined each of the output figures and determined that the mapping of surface features and posting of the well locations was consistent with the baseline data.

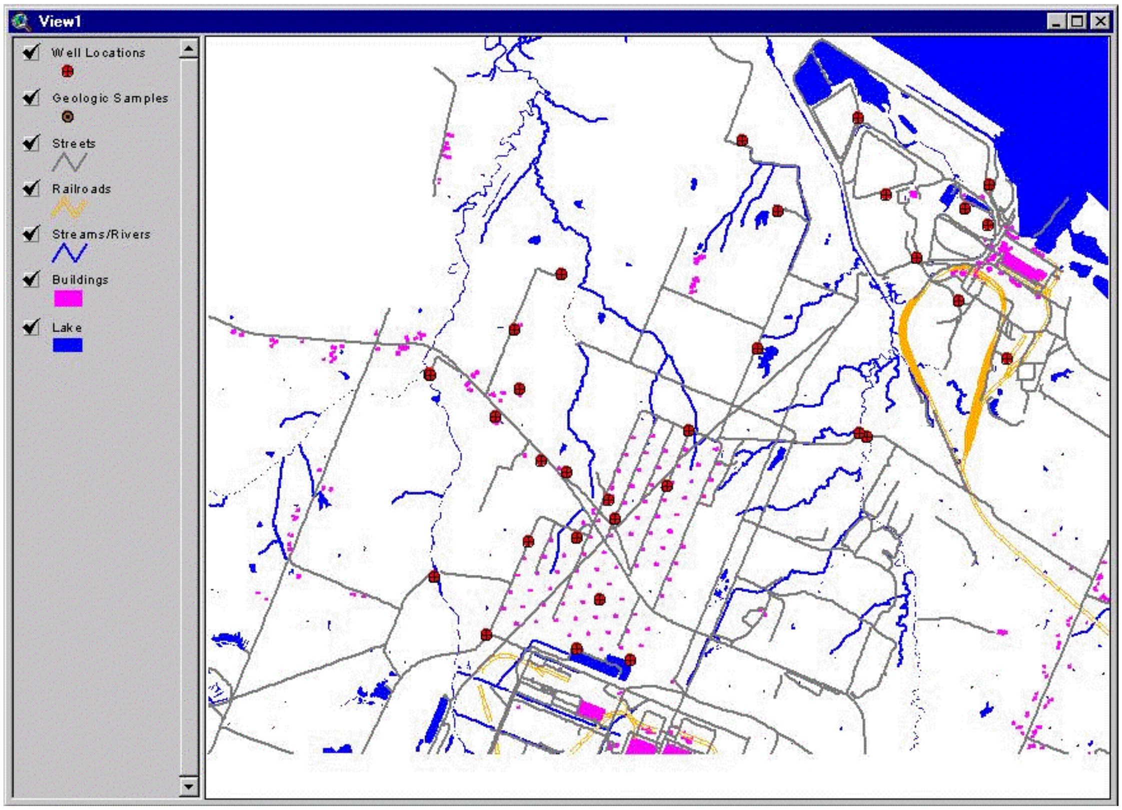


Figure 1. Site B map integrating surface features (roads, streams, railroad, and lakes) with monitoring well locations (red dots).

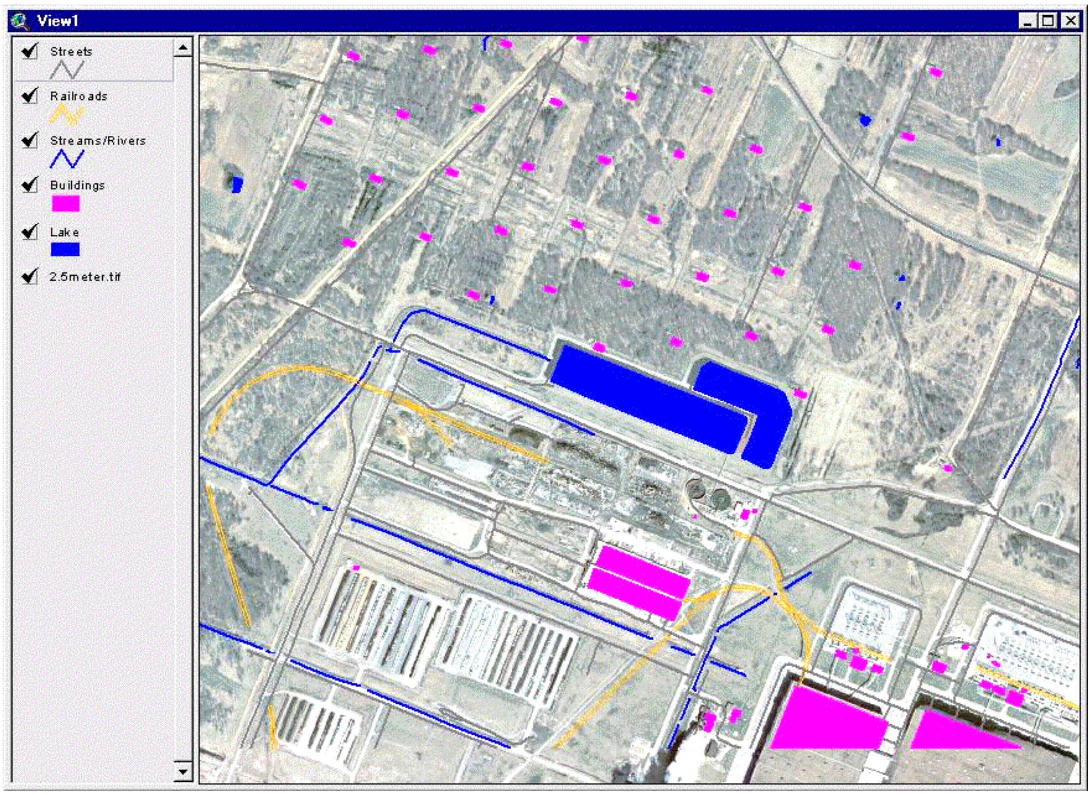
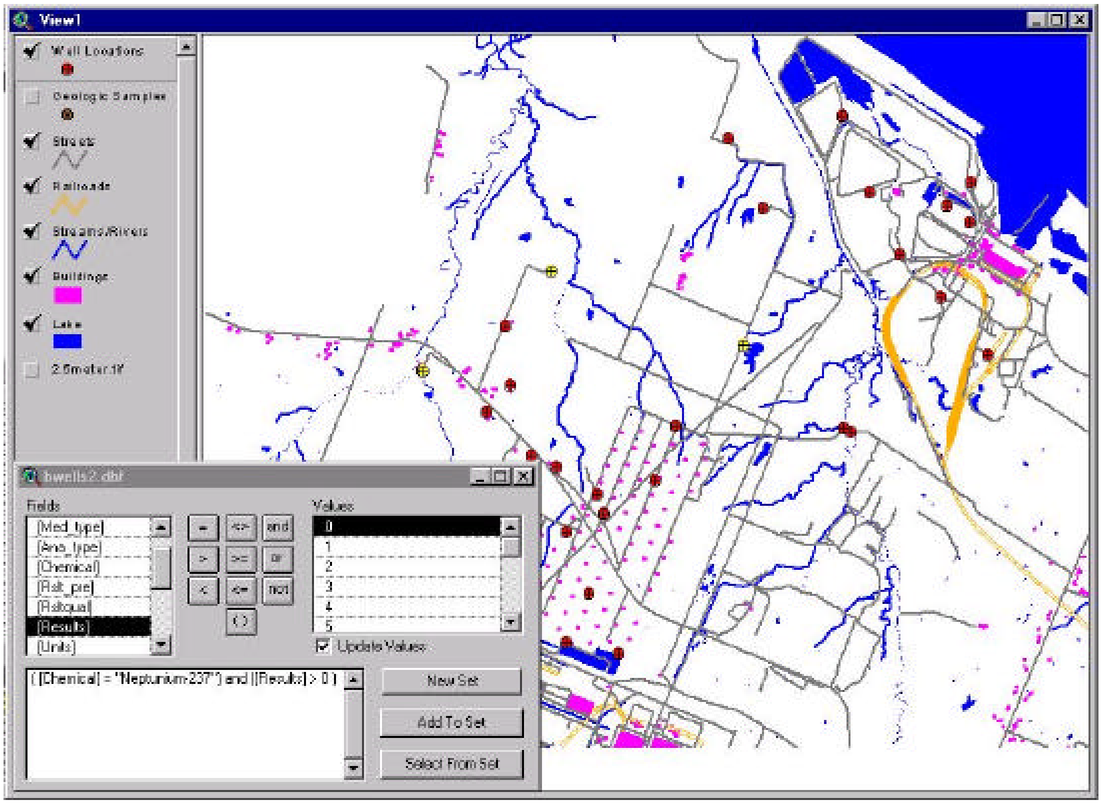


Figure 2. Site B with aerial photo overlaid on the map of buildings, railroads, and streets.



([Chemical] = "Neptunium-237") and ([Results] > 0)

Figure 3. Site B map with demonstration of database query capabilities.

Site N Cost-Benefit Problem

ArcView GIS version 3.1 and the Spatial Analyst extension were used to evaluate the surface soil contamination data for three contaminants, As, Cr, and Cd, at Site N. Drawing files containing the locations of roads and surface water bodies were imported and incorporated into maps with contours generated by Spatial Analyst from the contaminant data using an inverse distance weighting (IDW) interpolation routine. Sampled locations are marked with a small green circle on these maps. The circles are color coded so that darker green corresponds to higher concentrations. Contour maps (Figures 4, 5, and 6) were generated for each contaminant at the threshold concentrations requested in the test problem definition (Table 3). In these figures, the yellow shaded area is the region in which the interpolated concentration is above the minimum threshold in Table 3, and the red shaded area is the region above the maximum threshold. Using the contoured profiles, a query was performed to select all points in which the concentration exceeded the minimum threshold concentration for the contaminant. This information was used to generate a map that highlighted the area on the site in which any contaminant exceeded the minimum threshold concentration. This map was used by ESRI staff to calculate the area, volume, and cost for remediation using the Data Calculator tool in ArcView. In the test problem definition, the developers were instructed to clean the top foot of soil for all contaminated regions on Site N.

For comparison with the ESRI results, the DSS technical team generated a baseline analysis for the three contaminants at the two threshold concentrations, using Surfer software and using kriging as the interpolation routine. A visual comparison between the baseline analysis and the ArcView Spatial Analyst results (Figures 4, 5, and 6) showed that the two approaches gave similar results. Figure 7 provides the baseline analysis generated by the technical team using Surfer and the arsenic data, which can be compared directly with Figure 4. In Figure 7, the sampling points are marked with a "+," the blue shaded area represents the region in which the interpolated concentration exceeds the minimum threshold for arsenic, and the red shaded area is the region above the maximum threshold. The major difference between the two analyses resulted from the data analysis approach taken by the two groups. In the Site N test problem, the data were provided on a limited portion of the site, thus requiring both the technical team and ESRI analysts to define a boundary

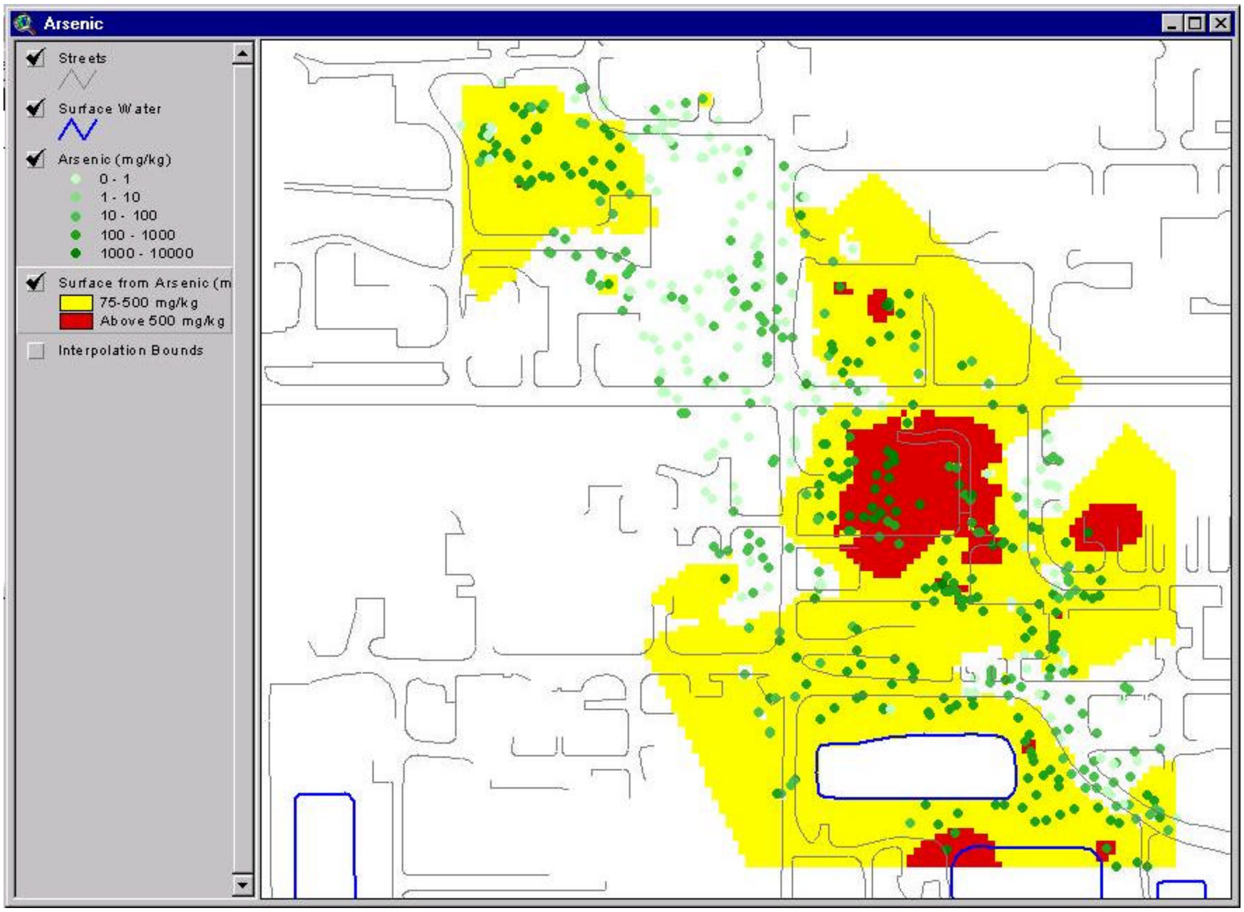


Figure 4. ArcView with Spatial Analyst arsenic contamination map at 75 and 500 mg/kg thresholds**.**

around the data. In both cases, this was done by drawing a boundary around the sampled locations. In ArcView, boundaries were drawn as rectangles, causing a slightly larger area (40%) to be used for the ESRI analysis. In Surfer, a polygon can be used to circumscribe the data locations. The ESRI analyst could have used a polygon and obtained a boundary identical to those of the technical test teams. An examination of Figures 4 and 5 shows large areas near the boundary of the domain that do not contain sampled locations, yet the ArcView Spatial Analyst interpolation routine suggests that contamination concentrations exceeded the threshold concentration (i.e., yellow areas that do not contain green circles that represent sampled locations). These areas were not present in the baseline analysis because of the closer match between the boundary and the outermost data points (Figure 7).

To obtain a more quantitative comparison between the ESRI and technical team results, the surface area in which the estimated contamination exceeded the minimum threshold concentration was evaluated. The ESRI analysis combined the areas for the three contaminants to determine the total site area requiring remediation and calculated that a surface area of 498,300 ft^2 contained contamination above the minimum threshold concentration. This was 50% larger than the area calculated in the baseline analysis generated by the technical team (330,217 ft^2). Two reasons were found for the difference. First, as previously discussed, the boundary defined in the ESRI analysis was 40% larger than that in the baseline analysis. This fact accounted for most of the difference between the two analyses. Second, the technical team confirmed that the IDW interpolations used by ESRI predicted a larger area of contamination than kriging. The technical team attempted to reproduce the ESRI analysis using IDW interpolation and the boundary defined by the technical team. In this case, the area estimate obtained using IDW was 381,000 ft^2. Next, the technical team performed a comparison of kriging and IDW for each contaminant at each threshold concentration using Surfer and concluded that IDW consistently predicts a larger area of contamination. Table 4 lists the area estimates and the percentage difference between the two interpolation routines for each contaminant and threshold concentration. For the higher

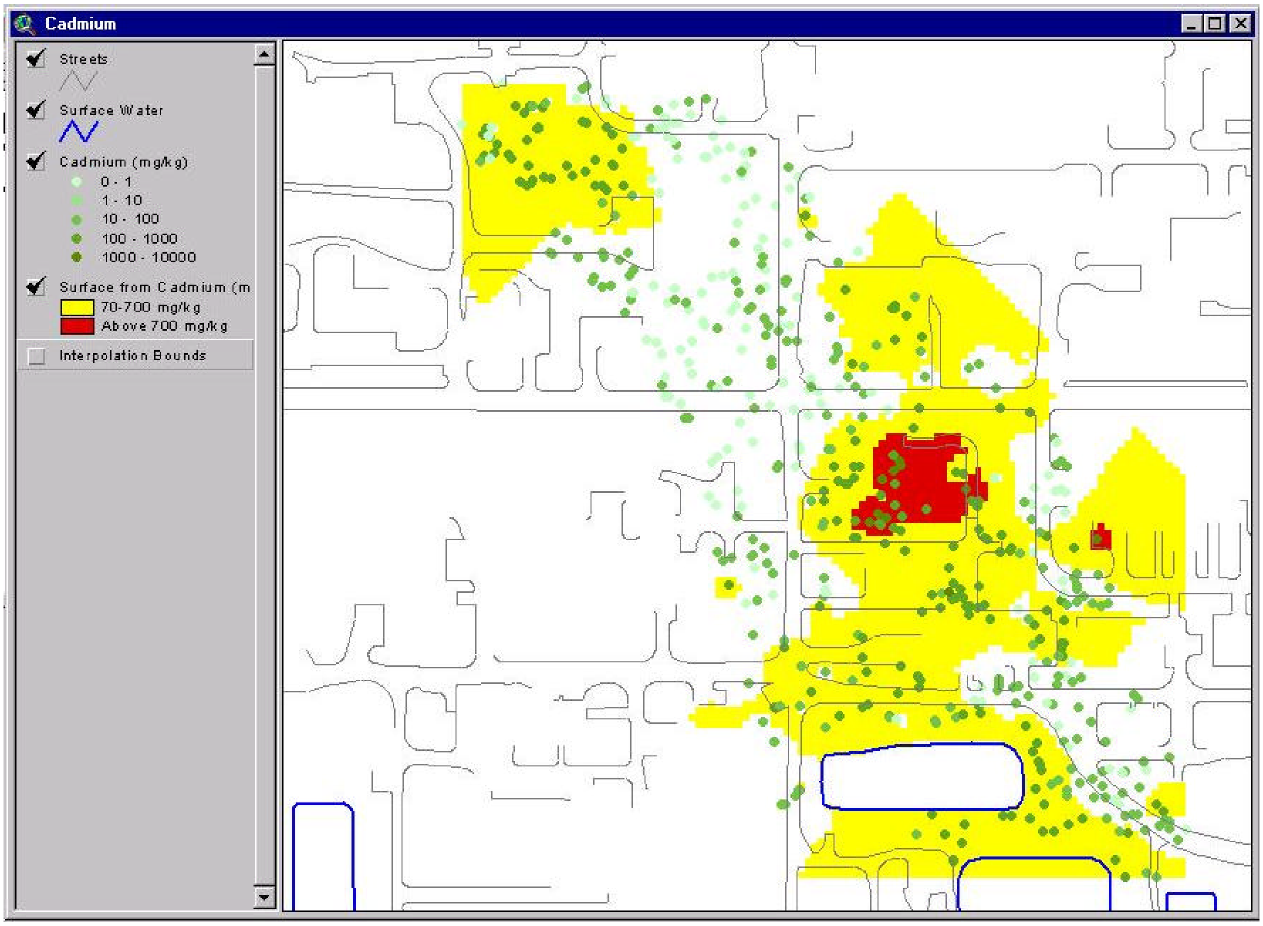


Figure 5. ArcView with Spatial Analyst cadmium contamination map at 70 and 700 mg/kg thresholds**.**

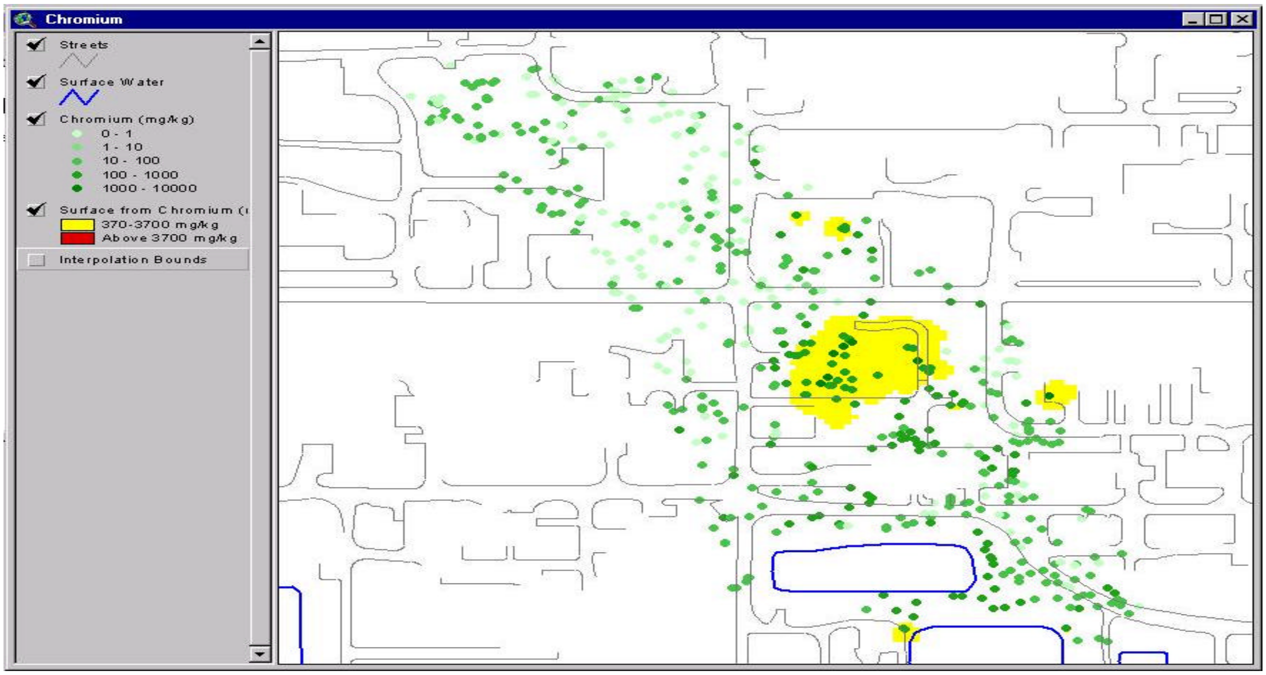


Figure 6. ArcView with Spatial Analyst chromium contamination map at 370 and 3700 mg/kg thresholds.

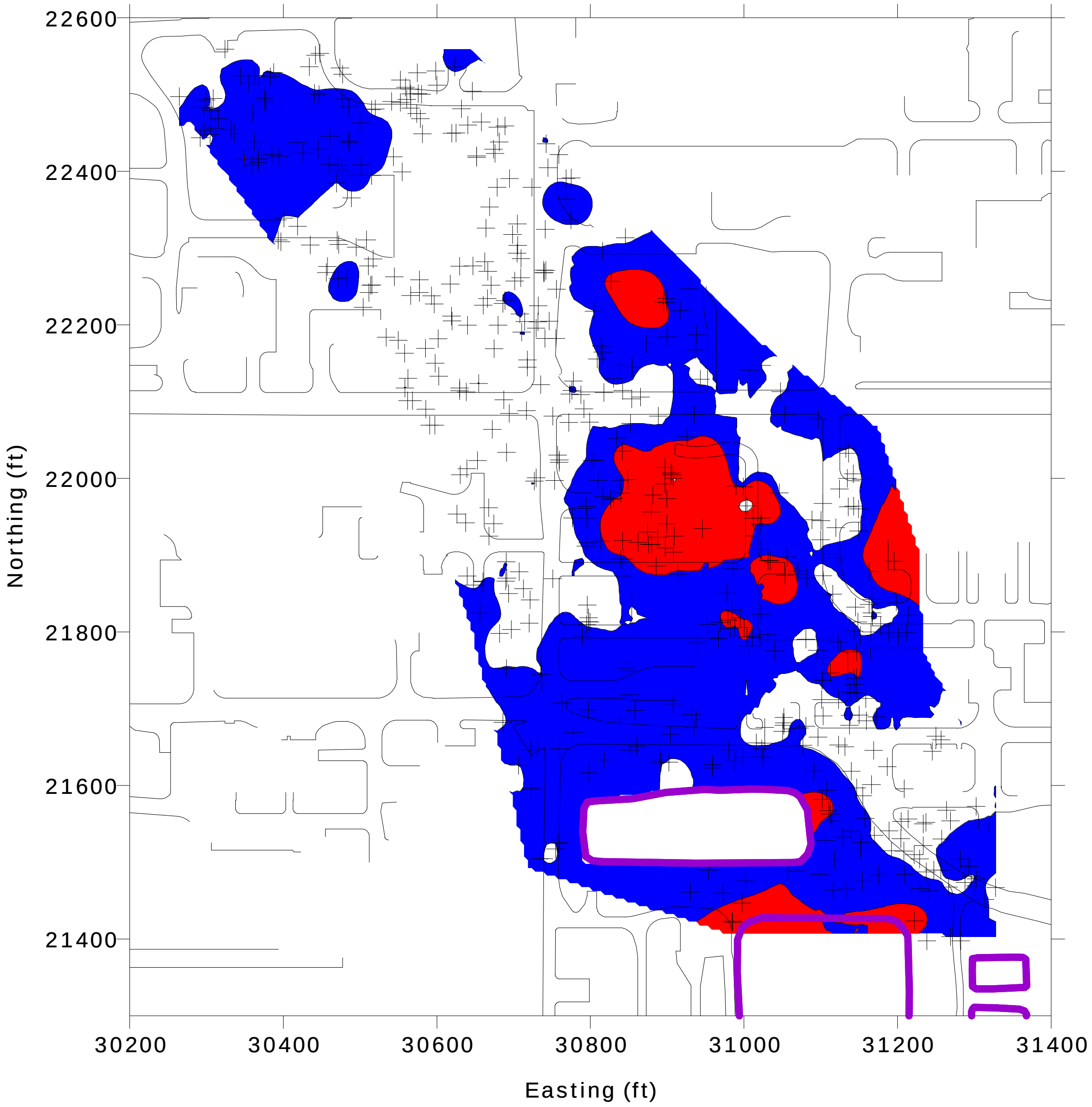


Figure 7. Baseline analysis contamination map for arsenic at 75 (blue) and 500 (red) mg/kg thresholds generated by DSS technical team using Surfer.

Table 4. Comparison of area estimates based on kriging and IDW interpolation routines

Contaminant	Threshold concentration (mg/kg)	Kriging area estimate (ft^2)	IDW area estimate (ft^2)	Difference (%)
As	75	330217	381452	!15.5
As	500	56981	58894	!3.4
Cd	70	270876	319023	!17.8
Cd	700	18207	18513	!1.7
Cr	370	37095	39301	!6.0
Cr	3700	0	0	0

threshold concentration of each contaminant, area estimates are within 5%. For the lower threshold concentration, area estimates differed by as much as 17.8%. The variations between the area estimate generated using kriging and the area estimate using IDW are the result of the different contouring algorithms. For this test problem, both approaches were consistent with the data, and one cannot make a scientific judgement as to which approach is more nearly correct. To check the IDW interpolation routines used in ArcView Spatial Analyst, ESRI staff supplied data at six arbitrary interpolation points for each contaminant for the Site N test problem. The technical team compared these predicted values with those generated by other interpolation routines (kriging) and the measured data (nearest neighbors) and found consistency among all interpretations of the data. In most instances, the difference between any two estimates was within 50%. This is expected due to the variability in the measured data. At locations with more than 50% variation, large changes in measured concentrations occurred around the interpolation point. For example, the ESRI prediction for chromium at one sample location was 1031 mg/kg, while the nearest measured concentration, which was 41 ft from the ESRI location, was 198 mg/kg. However, the next-nearest point, which was 44 ft away in another direction, had a measured concentration of 2613 mg/kg. Therefore, the estimate generated by the Spatial Analyst extension of ArcView was consistent with the data.

Site A Cost-Benefit Problem

ESRI staff used ArcView with the 3D Analyst extension to analyze groundwater contamination due to PCE and TCA at this site. To illustrate the software's capabilities in generating three-dimensional visualization of the data, ESRI staff generated a number of output files showing various aspects of the site and the contamination. The three-dimensional maps shown in this document (Figures 8–15) are a small subset of all of the views generated during the demonstration and are meant to provide an overview of the types of capabilities in ArcView and 3D Analyst.

Site A Bedrock and Groundwater Level Analysis

The initial analyses performed by ESRI staff involved integrating the surface feature data with information on bedrock location, surface elevation, and groundwater level. Figure 8 displays the Site A bedrock surface (brown region at the bottom of the figure) overlaid with a map of the groundwater levels (blue and green regions at the top of the figure). The water level contour key is found in the left part of the figure. In the foreground, the axis represents the northing for the site. The wells had contaminant concentrations measured every 5 ft from the water table to the bedrock. The measured contaminant concentrations at various wells are represented in the figure by circles. Note that the diameter of each circle is a function of contamination concentration, providing a visual reference for contaminant concentrations. Other figures demonstrated the capability to include surface features such as water bodies and buildings directly on the map. At the demonstration, it was shown that this view could be rotated to any angle to obtain a different perspective of the data. This is an important and powerful feature for interpreting the data. Figure 9 shows the interpolated bedrock surface (reddish-brown region at the bottom of the figure) with a direct comparison with the measured data. The depths to the bedrock are represented as lines extending from the surface to their termination depth, which is denoted by a circle at the bottom. The elevation scale is on the left of the diagram. Buildings on the surface are shown as extruded boxes. The bedrock surface between measured data was interpolated using kriging. Examination of the figure shows that most points on the interpolated surface are within a few feet of the measured surface. However, some points are separated from the measured bedrock data by several feet. In these instances, the interpolation routines had difficulty because of a rapid change in bedrock elevation over a short distance. Based on the figure, approximately half of the measured bedrock elevations are above the interpolated surface, and half are below. This capability permits the analyst to visually judge the quality of the interpolated surface compared with the measured data.

The technical team evaluated the accuracy of the interpolated bedrock surface and groundwater levels by comparing the ArcView and 3D Analyst results with the measured data and with interpolated surfaces generated using Surfer. The evaluation indicated that the surfaces generated using ArcView and 3D Analyst were consistent with the measured data and baseline analysis. Differences that occurred between the baseline analysis and the ArcView analysis were attributed to the

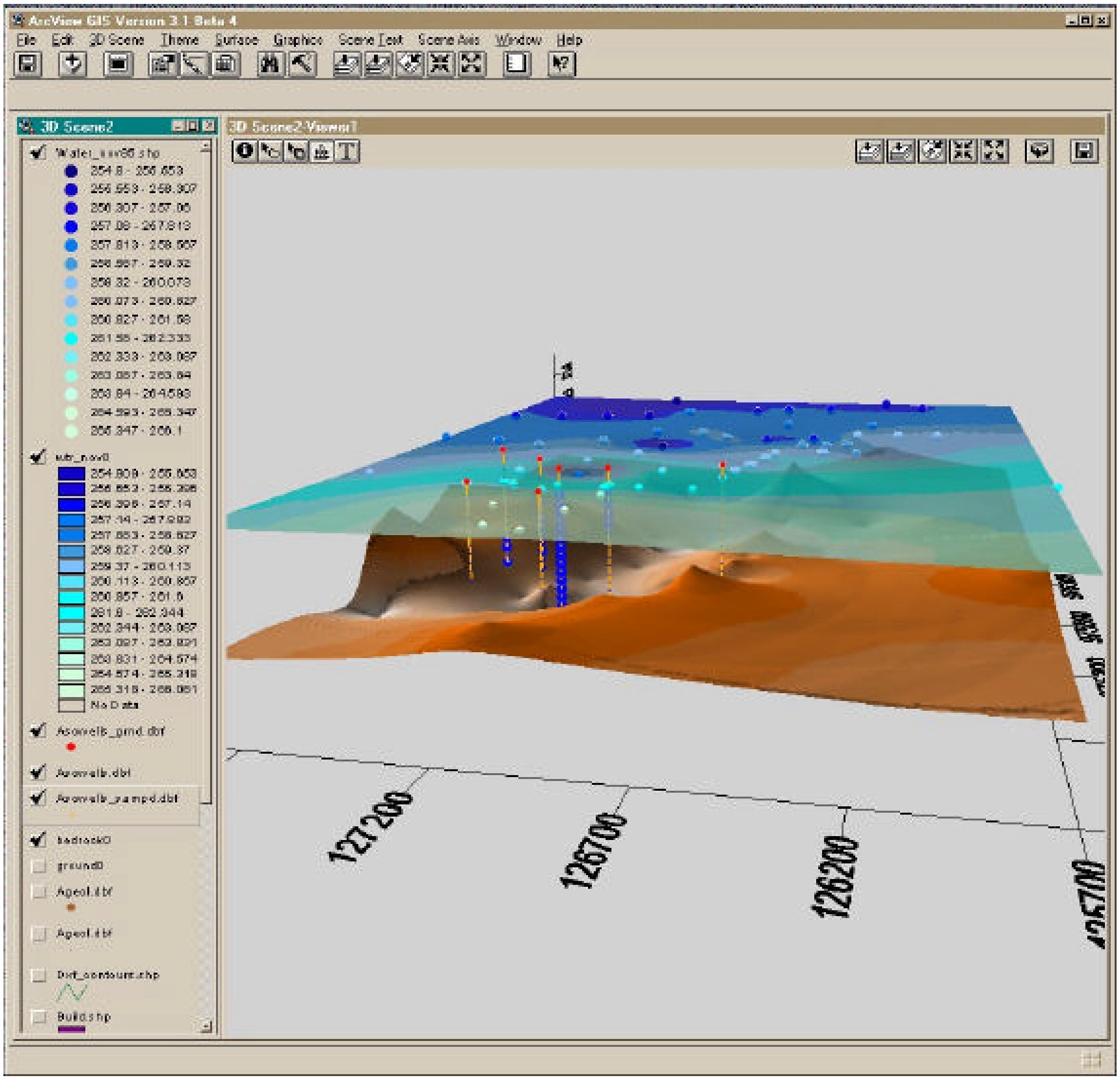


Figure 8. ArcView Site A view of bedrock, groundwater levels, and measured contaminant concentrations.

differences in contouring algorithms. The technical team attempted to reproduce the 3D Analyst results using Surfer and the same contouring algorithms used by ESRI; they generated results similar to those ESRI obtained using 3D Analyst.

Site A Contaminant Analysis

ArcView and 3D Analyst were used to visualize the concentration data for the two contaminants (TCA and PCE) in the cost-benefit test problem for Site A. Because this is a three-dimensional groundwater contamination problem, ESRI staff approached the problem by using their product's query capabilities to divide the contaminant data into vertical strata 10 ft thick. Within a vertical stratum, if more than one measured contaminant concentration was present in a well, the maximum value was used to generate interpolated surfaces. The test problem asked that the region of contamination be defined at two threshold concentrations for each contaminant. For TCA, the values were 5 and 50 µg/L; for PCE, the values were 100 and 500 µg/L.

Figure 10 shows an overview of the TCA contamination in groundwater generated using ArcView and 3D Analyst. In this figure, the

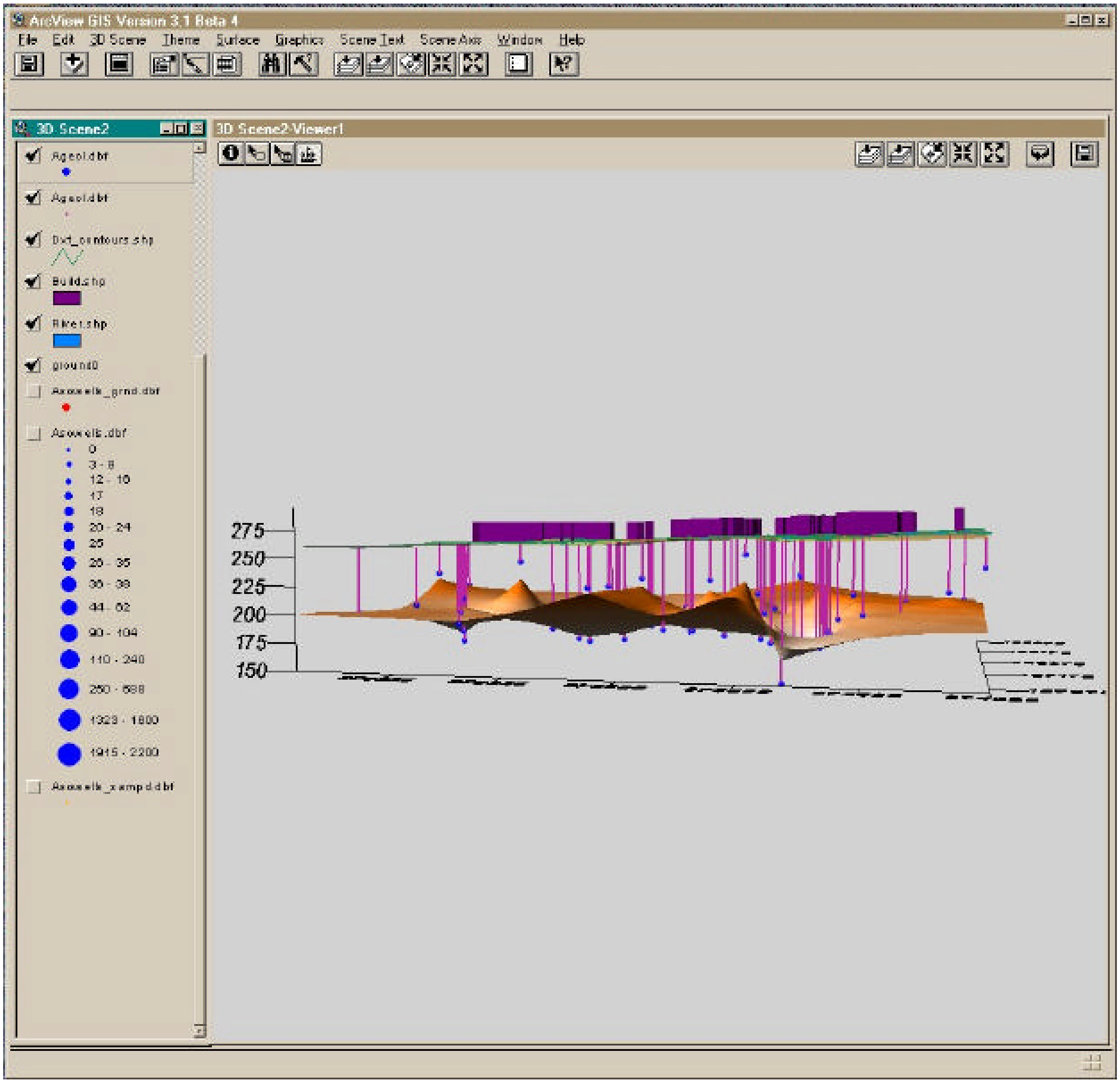


Figure 9. ArcView representation of the bedrock surface compared with the measured bedrock depth at fixed locations.

buildings, the river, and the well locations were included on the ground surface as points of reference. The ground surface corresponds to the elevation data supplied with the test problem and accurately slopes downward from west to east. The ground elevation contour key is found to the left of the map, with brown representing the highest and green the lowest elevation. Vertical exaggeration was used to highlight this feature. A brown circle was used to represent groundwater sample locations below the ground surface. The diameter of each circle corresponds to the magnitude of the TCA concentration. When 3D Analyst is used, this view can be rotated to obtain other perspectives on the measured data.

ESRI staff began interpolation of contaminant data during the DSS demonstration by applying trend and spline interpolation methods. However, both of those were rejected because the wide range in concentration values in neighboring wells caused both of these methods to over- and underestimate interpolated values by large margins. Kriging interpolators were investigated next but were not used because of the great variance in contaminant concentrations among data points close together. Initial IDW interpolators were tested using an exponent of 2 in the IDW interpolator. These initial studies were rejected because this approach tended to expand the area of the plume to regions with no measured data. To overcome this problem,

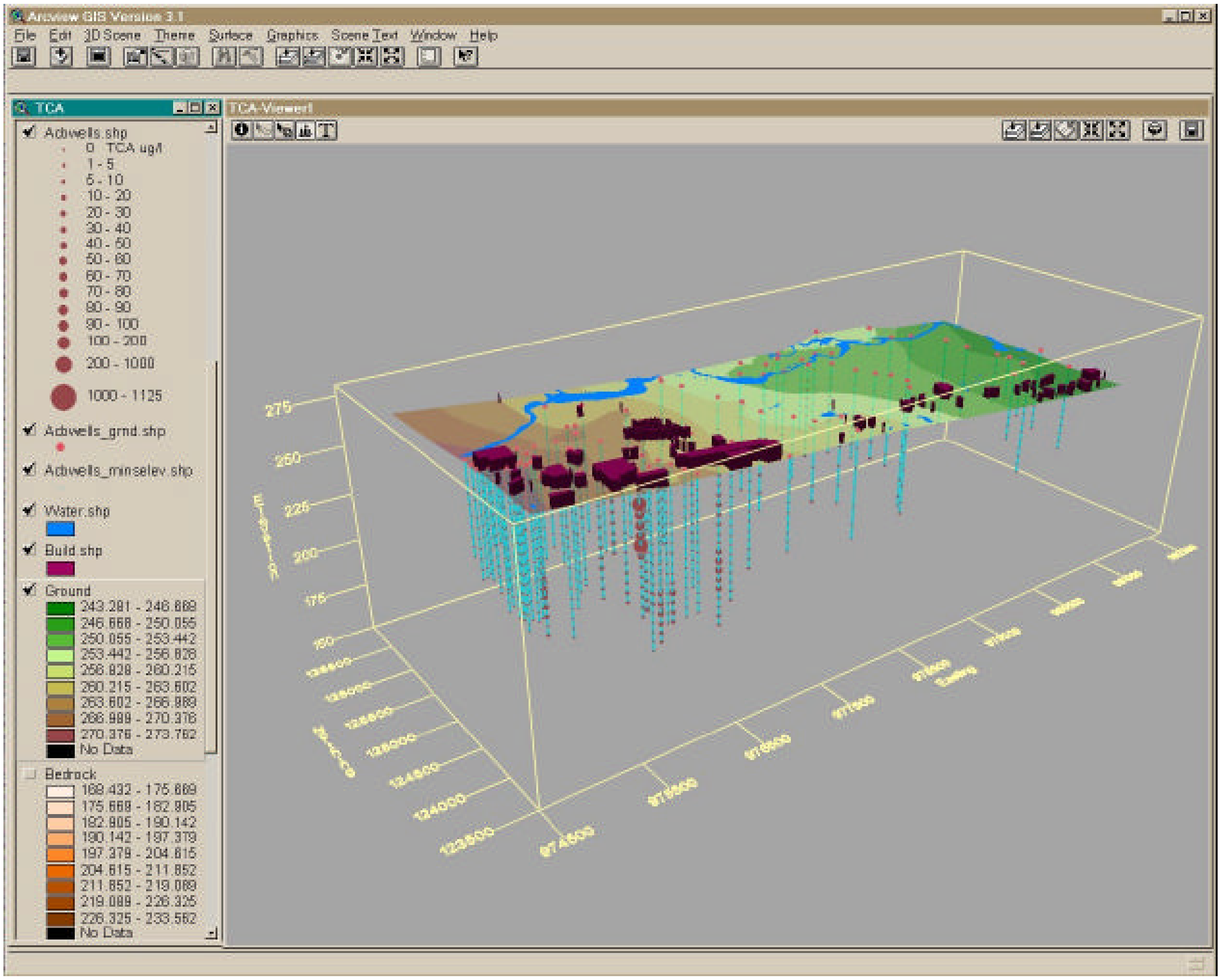


Figure 10. ArcView and 3D Analyst overview of the Site A TCA contamination problem.

several exponents were tried in the IDW interpolator before the exponent was selected for the final analysis (7 for the TCA and 9 for the PCE analysis). Also, the scale of the analysis was varied by ESRI analysts (i.e., small sampling radius and a small number of neighboring points) to better refine the interpolations. Each of these parameter choices helped to define the location of contamination more accurately. The use of multiple interpolation schemes and multiple lines of reasoning provides various views of the data, thereby assisting the analyst in data interpretation.

Upon selection of the IDW interpolation routine with an exponent of 7, the TCA contaminant analysis proceeded. ESRI staff generated interpolations of TCA data for vertical strata that were 10 ft thick. The technical team compared the ArcView outputs with the measured TCA concentrations. Figure 11 shows an example of TCA interpolations for the stratum defined between –7 and –17 ft below ground surface. ArcView was used to depict the well and groundwater sample locations as circles. For wells with a maximum concentration of less than 5 µg/L, the circle is light blue; for concentrations of greater than 5 µg/L, the circle is red. The diameter of the circle corresponds to the magnitude of the TCA concentration at that sample location. The technical team verified that all wells were labeled correctly in terms of their location and of having a TCA concentration greater than 5µg/L. From the visualization, it was not possible to determine if the size of the circle corresponded exactly with the TCA concentrations. However, wells with high concentrations were displayed with larger circles than wells with lower concentrations. Although it is not shown

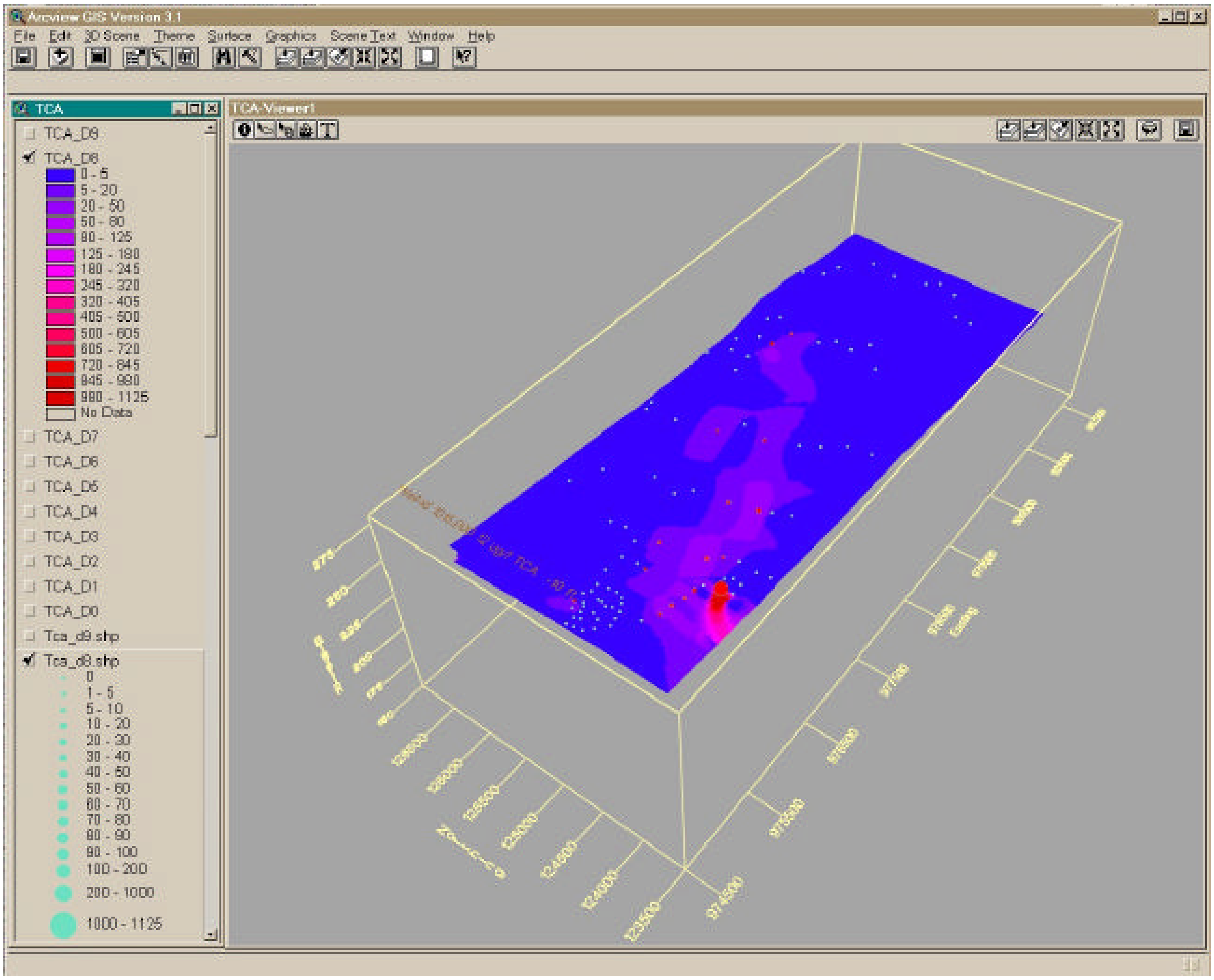


Figure 11. ArcView and 3D Analyst TCA concentration contours in the stratum defined by –7 to –17 ft below ground surface.

in Figure 11, ArcView has the capability to post the well identifier on the image. Also, with ArcView it is possible to select a well using the computer mouse and obtain all of the data for that well. These ArcView features assist the analyst in data interpretation and analysis. Figure 12 shows the same contour information as Figure 11 from a top view, with the ground surface and surface features overlaid on the map. In Figure 12, wells with a TCA concentration of greater than 5 µg/L are color coded in orange with the size proportional to concentration. Figure 13 shows a three-dimensional layered view of the TCA contamination for the five layers between –7 and –57 ft and TCA concentrations above 20 µg/L. Figure 14 shows the top view from Figure 13 with buildings and the river overlaid on the contamination contour to provide a spatial frame of reference.

ESRI staff performed a similar analysis for PCE contamination at Site A. Figure 15 shows a top view of the PCE contours generated for samples between –7 and – 57 ft below ground surface. The blue region around the edge of the contours represents the region in which the concentration is less than the lower threshold of Table 3 (100 µg/L). The purple region defines the region in which the concentration exceeds the 100 µg/L threshold level. Regions above the maximum threshold of 500 µg/L cannot be determined from this map. The map also contains buildings, the river, and ground surface elevation contours. A

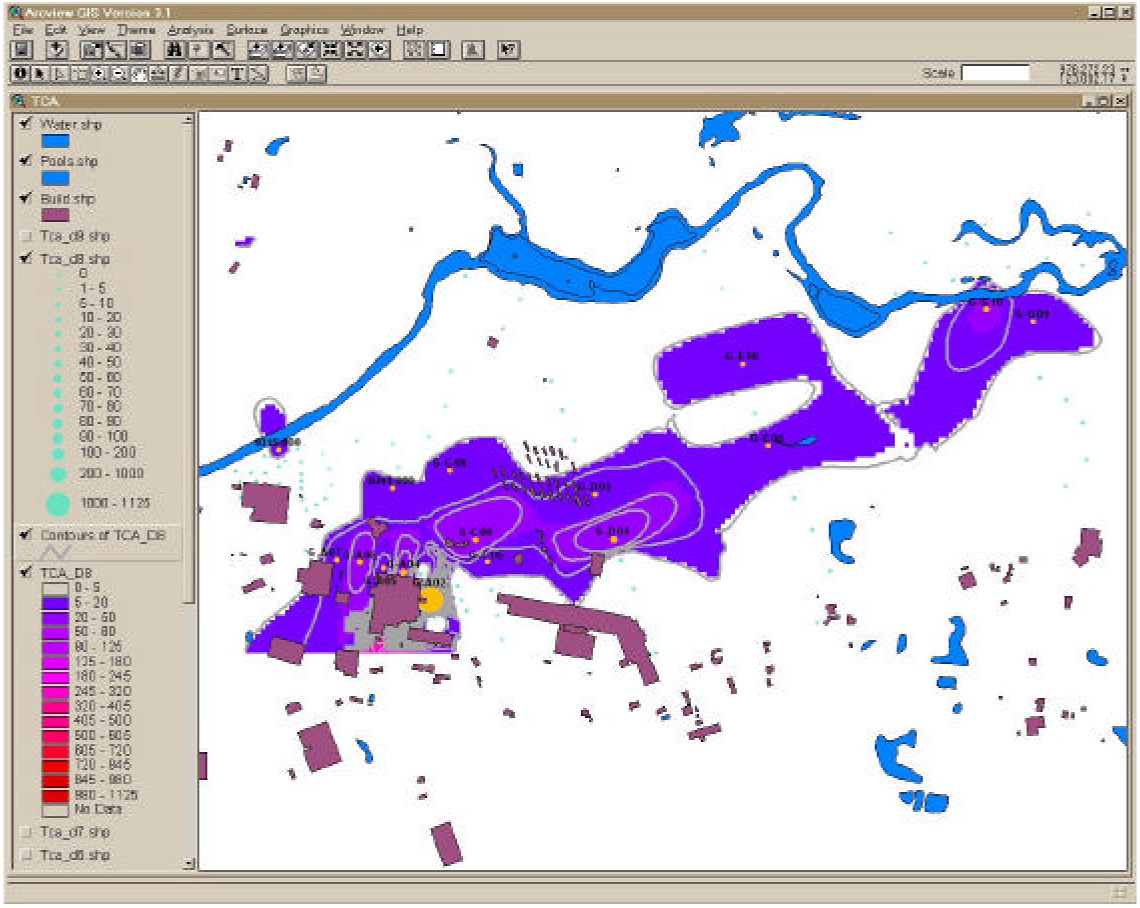


Figure 12. ArcView and 3D Analyst top view, containing surface features, of the TCA contours in the stratum defined by –7 to –17 ft below ground surface containing surface features.

comparison of Figure 14, the TCA plume, and Figure 15, the PCE plume, shows that the PCE plume originates from a different area than the main TCA plume. ESRI staff also provided maps of PCE concentrations for each 10-ft stratum.

The technical team compared the ArcView and 3D Analyst interpolations of the TCA- and PCE -contaminated regions with the baseline analysis. The Surfer baseline analysis, generated by the technical team, also segregated the data into ten-ft intervals and used the same vertical discretization and data treatment (maximum value in the stratum for each well) as the ArcView analysis. However, the Surfer analysis used kriging with an anisotropy ratio of 0.3 and a direction of !70 degrees with respect to vertical for the TCA contours and –80 degrees with respect to vertical for the PCE contours. These parameters were selected by the technical team based on the direction of groundwater flow and the ratio of the width to the length of the plume. Several different sets of parameters (anisotropy ratio and angle) were evaluated by the technical team for each stratum to define the best fit for that stratum.

Comparing the kriging baseline analysis of the TCA threshold concentration contours with the ArcView and 3D Analyst results was difficult. As previously noted, Figure 11 provides an example of the ArcView output received for each vertical stratum. The slight change in colors between TCA contour levels does not allow an accurate analysis of the location of the 50-µg/L TCA threshold contour. The lower TCA threshold contour, 5 µg/L, can be discerned from the figure as the outermost outline of the contours. Similar color figures were provided for each of the ten strata for TCA and PCE contours. Figure 12 shows a top view of Figure 11 with buildings and rivers overlaid on the map. From Figure 12, the extent of the 5-µg/L TCA contour can be clearly seen; however, the 50-µg/L contour is difficult to determine. In all of the top views provided by ESRI, the 5-µg/L TCA contour corresponded with the baseline analysis. The location of the 50-µg/L contour was difficult to establish because of the color scheme chosen to represent the contours. Similarly for PCE, the minimum threshold, 100 µg/L could

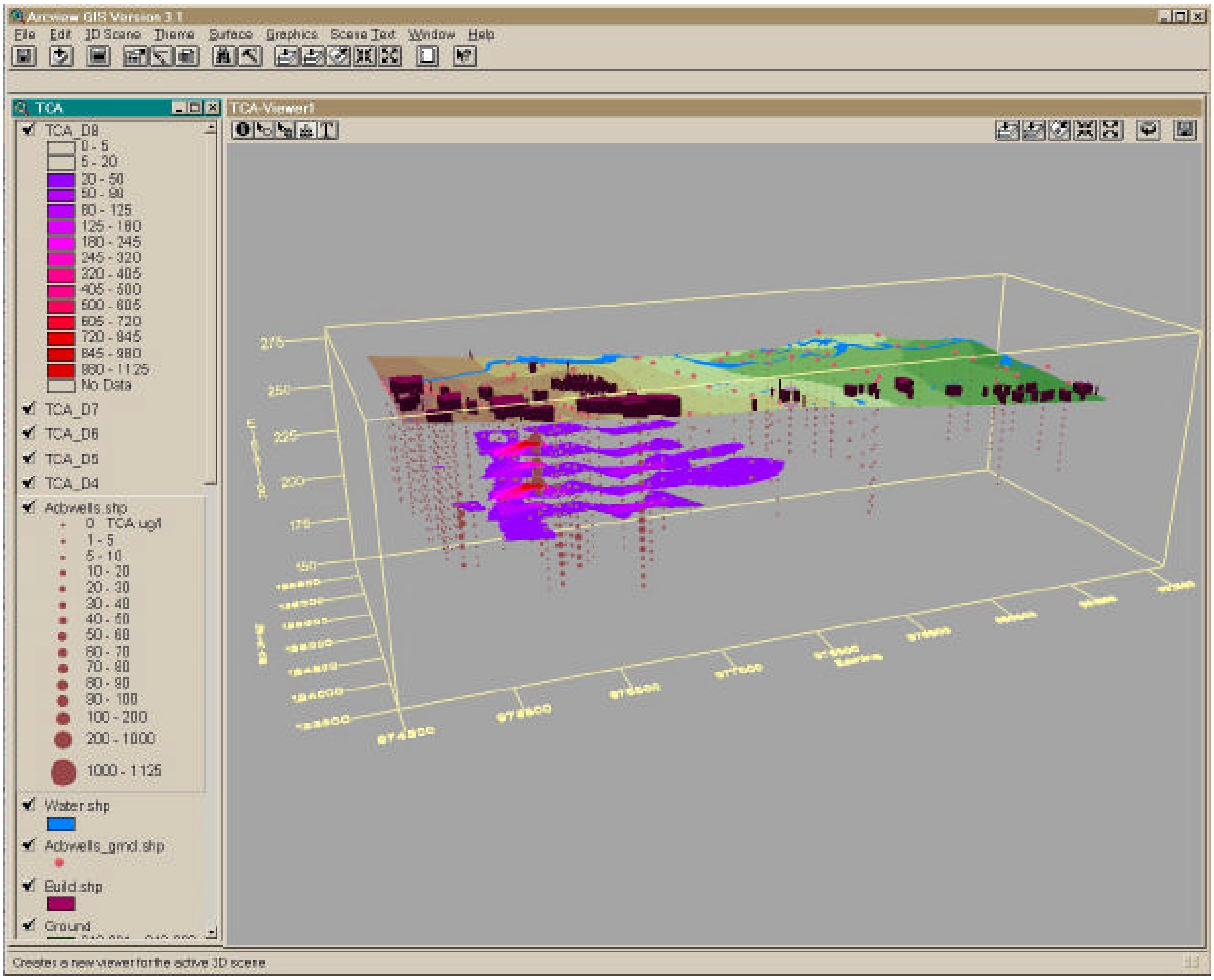


Figure 13. ArcView and 3D Analyst side view of the regions with TCA contamination levels greater than 20 µg/L in the strata containing data from –7 to –57 ft below ground.

be determined with reasonable accuracy from the maps supplied; however, the maximum threshold, 500 µg/L, could not. For this reason, the agreement between the ESRI and the baseline analysis for the maximum threshold level for TCA and PCE could not be evaluated.

The technical team took two approaches to determine the accuracy with which the 3D Analyst contaminant concentration contours matched the measured contaminant data and the baseline analysis generated by Surfer. First, for each stratum, a visual comparison was made between the 3D Analyst and the Surfer-generated contours. The comparison for these 20 contours showed reasonable agreement at the minimum threshold concentrations for both TCA and PCE. As expected, agreement was greatest in the vicinity of sampled locations. Any disagreement between the analyses occurred in the regions between sample locations. Comparison at the maximum threshold concentrations was difficult because of the color coding of the contours selected by ESRI.

The second approach to determine accuracy was to repeat the Surfer baseline analysis using the interpolation routines selected by ESRI staff for use in 3D Analyst (i.e., IDW with an exponent of 7 for TCA). The Surfer IDW contours were visually compared with the 3D Analyst contours; the results were similar, but it was not possible to determine if they matched exactly.

Finally, to illustrate the difference between the kriging and IDW contouring algorithms, the technical team used Surfer to generate 20-µg/L TCA contours using the maximum measured value in all wells. This example illustrates a number of the difficulties in contouring measured data, highlights the differences between the two contouring approaches, and is representative of the findings in the ESRI results for each stratum. As a starting

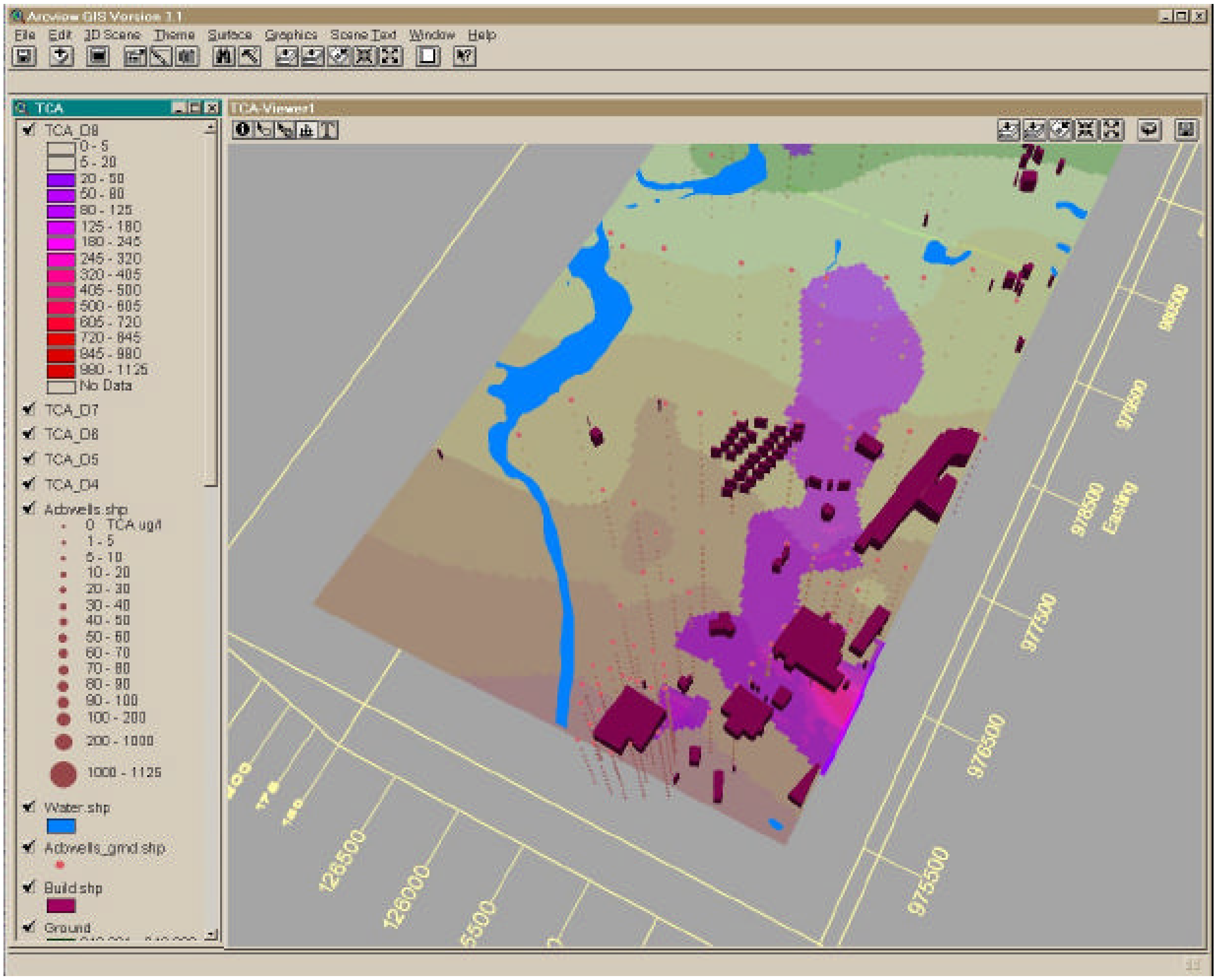


Figure 14. ArcView and 3D Analyst top view of the region with TCA contamination levels greater than 20 µg/L at depths between –7 and –57 ft below ground surface.

point, the ESRI analysis using ArcView and 3D Analyst and the measured TCA concentrations between –7 and –57 ft (presented in Figure 14) was repeated by the technical team using Surfer and IDW interpolations with a search radius of 1298 ft and a weight of 7 (the same parameters as used in the ESRI analysis). Also, for comparison, kriging using an anisotropy ratio of 0.3 and an angle of 80° with respect to the vertical was performed on the same TCA data using Surfer. Surfer generated a map containing the 20-µg/L contour for TCA using the maximum measured TCA concentration in each well and a base map including the river, buildings (irregularly shaped outlines), and well locations (black circles). Figure 16 shows that both IDW (cross-hatched region) and kriging (solid line) contours give essentially the same results. Both identify one plume originating from the building just south of the river (975000 easting, 124800 northing) and a second major plume originating from a building to the southeast from that point. As expected, both contouring algorithms agree closely at the location of the wells (sample locations) and differ slightly between wells.

Further examination of Figure 16 indicates two other isolated areas of contamination on the map. One appears south of the main plume at an easting of 978000. The other appears near the river at an easting of 979000. In both of these cases, the plume arises from one well with a measured TCA concentration slightly greater than the contour level of 20 µg/L. For example, near the river, the measured TCA concentration is 21 µg/L. In both of these isolated areas, the IDW contoured area is larger than the kriged area, indicating a larger zone of influence from that data point. This can also be seen in the main plume, where, between the rows of wells, the contaminated areas estimate obtained using the IDW method tends to spread wider than the kriging method. The main difference between the contours in terms of enclosing wells within the contours occurs at the series of wells that run

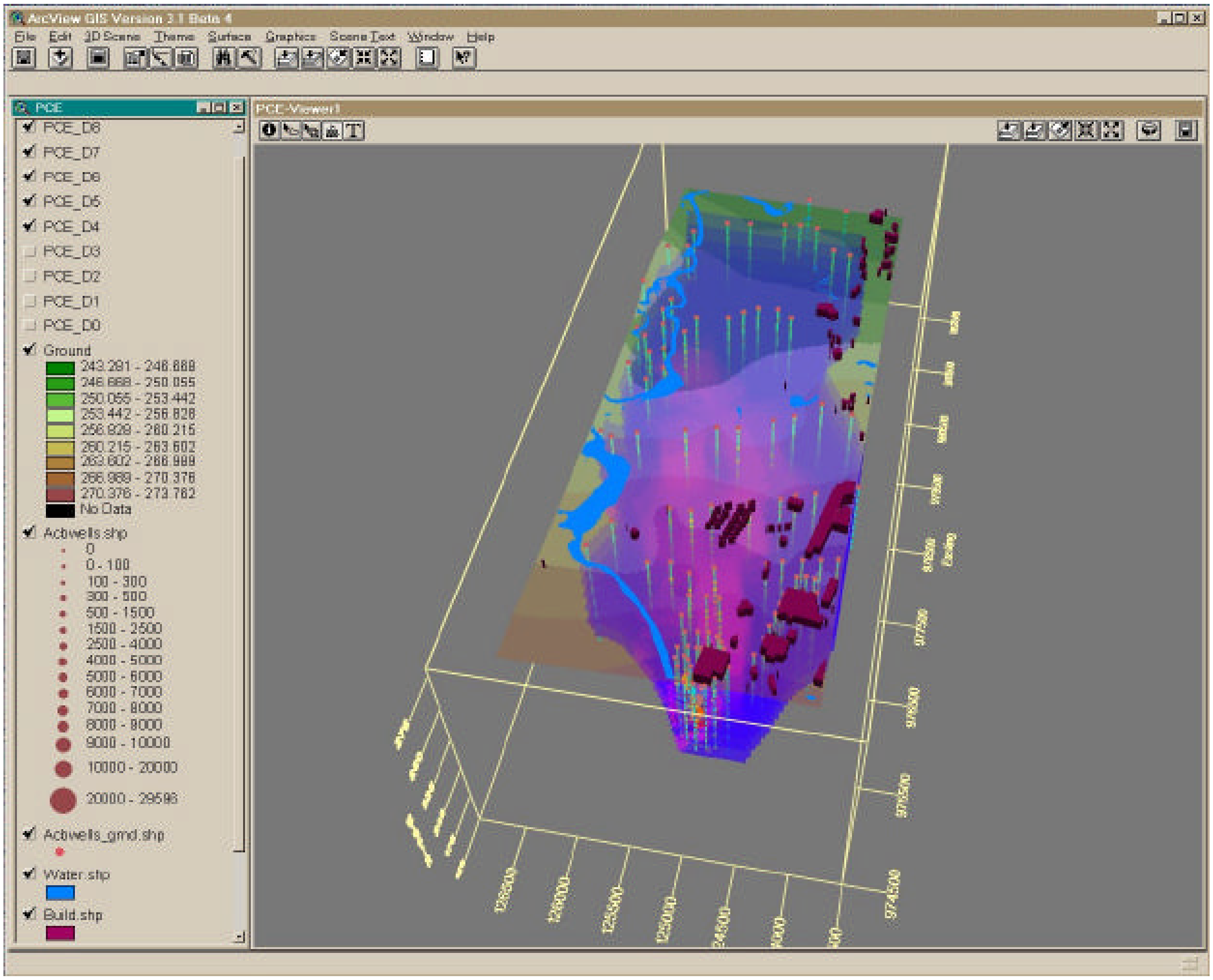
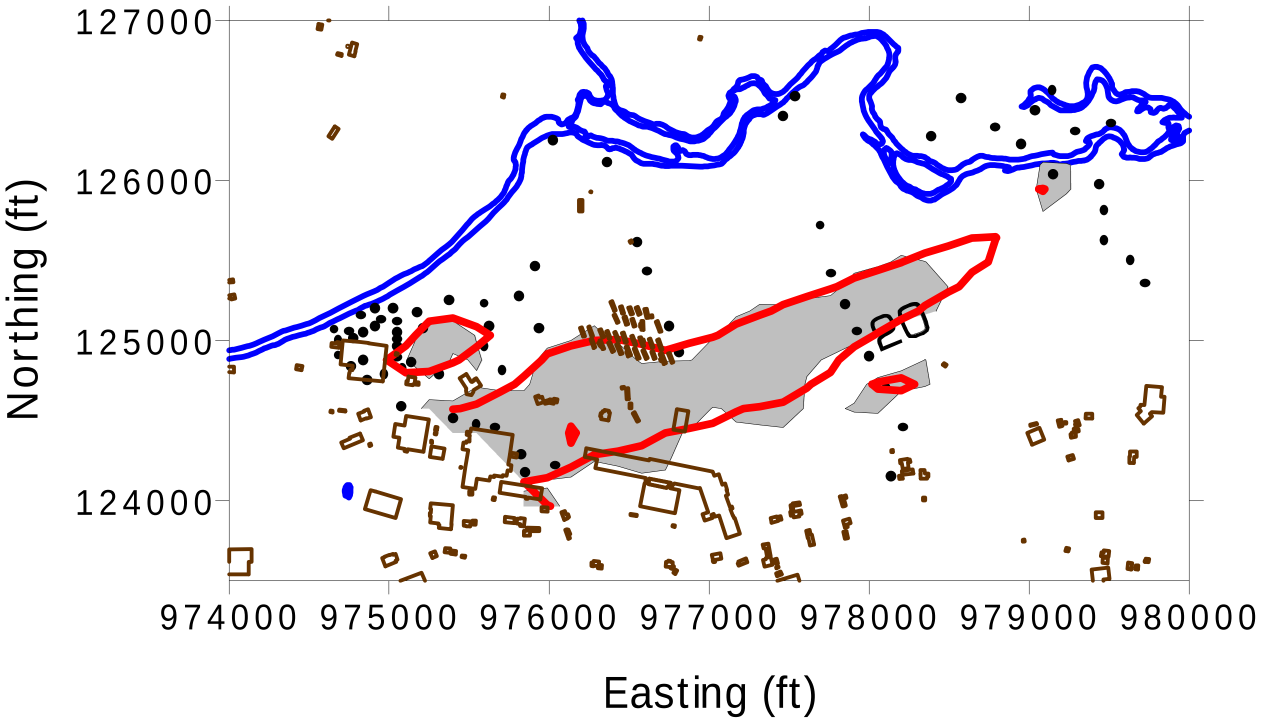


Figure 15. ArcView and 3D Analyst top view of the region with PCE contamination contours for the strata between –7 and –57 ft below ground surface.

primarily north to south just east of the large L-shaped building (easting 977000). In this series of wells, IDW places only one well inside the contour, while kriging places three inside. The measured TCA concentrations for these three wells are 11, 125, and 17 µg/L. Therefore, the kriging approach included two wells with measured TCA concentrations slightly less than the 20-µg/L contour level. However, overall, both contouring methods give a reasonable representation of the data that is suitable to assist in understanding the extent of contamination. From a technical perspective, there is no basis for claiming one approach is superior to the other. In fact, there is excellent agreement between the two approaches. This is due in part to having an adequately characterized site. However, it is also due to the fact that in each interpolation approach, kriging and IDW, the model parameters were optimized through examining many sets of parameters to obtain the best fit to the data. The ArcView and 3D Analyst software permit the analyst to conduct such a study; however, ultimately it is up to the analyst to optimize the treatment of the data.

For both the technical team and the ESRI staff analyses, the three-dimensional data were analyzed as a series of two-dimensional slices. This approach does not account for changes in bedrock elevations and can lead to incorrect contouring. A better technical approach would have been to contour only in regions that were above the bedrock. This can be done by drawing exclusion zones around the region, as demonstrated by



Site A TCA 20 ug/l contour. Contours generated from the maximum concentration in the well at elevations between –7 and – 57 feet. Comparison of IDW (hatched region) and kriging (solid line) interpolation routines.

Figure 16. Site A TCA 20-ug/L contour. Comparison between IDW (cross-hatched) and kriging (solid line).

ESRI staff on the Site N test problem. However, it would have required considerably more time and effort on the part of the analyst.

Multiple Lines of Reasoning

ESRI staff used ArcView, Spatial Analyst, and 3D Analyst to provide multiple interpretations of the data with different contouring algorithms and contouring parameters. The best fit to the data was provided for review. This flexibility permitted a better understanding of the extent of the contamination problem.

Secondary Evaluation Criteria

Ease of Use

During the demonstration, it was observed that ArcView and its extensions were easy to use. ArcView has a graphical user interface (GUI) with pull-down menus to permit use of the options in the software. ArcView imports database files with any user-defined structure, an important feature that removes the need to reformat data. ArcView also demonstrated the capability to import a wide range of image files (.dxf, .shp, and .jpg) and integrate them into the visualization of the problem. For example, during the demonstration, it was able to incorporate an aerial photograph (.jpg file) containing surface features and .dbf files containing data on contamination and hydrology. The GUI provided a platform to address problems efficiently and to tailor the analysis to the problem under study (for example, contours can be defined at any value; the number of layers in a three-dimensional analysis is user-defined; and, for multiple measurement values at a single location, ArcView can take the maximum, minimum, minimum non-zero, or average value for the analysis). The database structure permitted queries on any field (e.g., chemical name, date, concentration, well identifiers) and permitted filtering (e.g., include only data within a range of elevations, maximum concentration at a location over a range of dates).

ArcView can export text and graphics directly to standard word processing softwares. ArcView generated .jpg and text files that can be read by a large number of software products. It also was able to generate project files that contain information on all of the visualization and data files used in a single project. Thus the entire project can be moved to another machine with ArcView software. However, the technical review team using ArcView could not open the project files provided from the demonstration. The cause is believed to be that not all the files referenced by the project file were provided by ESRI.

During the demonstration, several members of the technical team received a 4-hour introduction to ArcView. The reviewers observed that ArcView was a large, feature-rich software program that had several tutorials to guide the novice user through the system and applications. The reviewers felt that with 1 or 2 days of training, they would be able to use the fundamental features found in ArcView. However, some of the reviewers were confused by the terminology used by ArcView (e.g., “scenes,” “views,” “themes,” “project files”). In addition, they all felt that regular use of the product would be needed to efficiently use all of the features found in the product. For example, ArcView contains a scripting language, Avenue, that permits automation of routine tasks, database manipulation, and customization of the pull-down menus. Learning to use this feature effectively would require much more extensive training.

Efficiency and Representativeness

During the demonstration, ESRI provided two technical staff members for 1 week and two marketing staff members for 1 day. Additional time was required to prepare the reports of the analyses. The marketing staff members were present for Visitors Day and handled the presentation for this meeting and some of the individual demonstration. ESRI estimated that the level of staff effort required to prepare the data, conduct the analysis, and write the report was approximately 1 day for the Site B and Site N problems and 10 days for the Site A problem. Therefore, a total of 12 person-days were needed to complete the three visualization problems along with the documentation, but one problem took substantially longer than the other two. Approximately half of the time was spent conducting the analyses, and half was spent preparing the report.

The software was able to handle a wide range of environmental contaminants and conditions. Based on the capabilities demonstrated, the technical team concludes that the software may be representative for a wide range of environmental problems. The capability to sort and query the database files permits efficient focusing of the analysis to the problem. Multiple contaminants can be evaluated in a single analysis. The capability to tailor the output to the threshold concentrations makes data interpretation easier. The capability to write instructions to ArcView through its Avenue scripting language permits the analysis to be very flexible.

Training and Technical Support

ESRI provides a number of options for ArcView training and technical support:

- There is an extensive on-line help manual.
- Tutorial case studies are provided with ArcView and are available at www.esri.com.
- Training courses are available at the ESRI headquarters, at regional ESRI offices, and at the customer’s site.
- Technical support is provided for 60 days with the purchase of any ESRI product. Additional technical support can be purchased.

ArcView GIS version 3.1, Spatial Analyst, and 3D Analyst each has a user manual that provides detailed instructions on how to operate the software.

Additional Information about the ArcView Software

To use ArcView efficiently, the operator should have a basic understanding of the use of computer software to analyze environmental problems. This understanding includes fundamental knowledge about GIS and relational database structures and knowledge of contouring environmental data sets.

ArcView was demonstrated on a Windows NT 4.0 operating system. It requires a minimum of 128 MB of RAM. During the demonstration, two machines were used. For Sites B and N, a 233-MHz Pentium II laptop with 128 MB of RAM, a 5-gigabyte hard drive, and standard 1024 H 768 video was used. The laptop was equipped with an internal CD drive, a 1-gigabyte Jazz drive, and a PCMCIA network adapter. The computer used for the Site A analysis contained a 300-MHz Pentium II processor with 128 MB of RAM and an Elsa Gloria XLM graphics card with 16 MB of video RAM and an Open GL chipset. This computer was equipped with an internal CD drive, a 1-gigabyte

Jazz drive, an internal network adapter, and a 19-inch monitor.

The price varies for single stand-alone systems through enterprise-wide systems. ESRI representatives assist customers in choosing the appropriate system configuration for their needs, and the software is available for purchase directly from ESRI or through authorized resellers. Several existing contracts also make purchasing software easy for the federal government, including the ESRI Government Services Administration (GSA) Schedule #GS-35F-5086H. Currently, the GSA price for the Windows version of a single stand-alone system of ArcView GIS version 3.1 is $996. For Spatial Analyst and 3D Analyst, the GSA price is $2342 each. Prices for these products for private industry or for use on Unix systems are slightly higher.

Summary of Performance

A summary of ArcView's, Spatial Analyst's, and 3D Analyst's performance is presented in Table 5. Overall, the main strength of ArcView GIS version 3.1 and its extensions is their ability to integrate data and maps easily in a single platform to allow spatial visualization of the data. The visualization output was clear and easy to understand. The GUI platform appeared to be easy to use and had pull-down menus and on-line help. ArcView supports a wide range of formats for importing and exporting data including computer-aided-design files (.dxf), GIS files (.shp), and data files (.dbf, ASCII text). The ability to sort and query data makes examination of a subset of the data easy to perform. ArcView's ability to manage data files from a wide range of sources make it suitable for managing complex environmental contamination problems. The ease of use makes ArcView and its extensions accessible for the occasional user who wants to view the spatial correlation between data. For the more advanced user, the scripting language, Avenue, makes the ArcView products extremely flexible and customizable for problem-specific applications. ArcView is a mature product with a large customer base.

The technical team concluded that for visualization of environmental data sets, there are no major limitations in the ArcView set of programs. Minor problems noticed by the technical team included the inability to open some of the project files provided at the demonstration and, for a new user, the need to learn the terminology to understand the operation of ArcView.(e.g., “scenes,” “themes,” “project files”).

Table 5. Performance summary for ArcView version 3.1 with Spatial Analyst and 3D Analyst extensions

Decision support	ArcView integrated data, aerial photos, and surface features into two-and three-dimensional spatial representations of the data. Query and sort capabilities permitted investigation of the data against threshold concentrations. Contour maps of contaminant concentration placed contamination regions in visual context.
Documentation of analysis	Documentation of the process and parameters was provided and assumptions explained. Model parameters, queries, and maps were exported to word processing files to document the analysis. Graphical output was prepared in .jpg format and incorporated directly into a MircroSoft Word file.
Comparison with baseline analysis and data	Two-dimensional contaminant concentration and hydraulic head contours were consistent with the measured data. Accurately mapped wells, buildings, and site features. Accurately posted data to sample locations. Hot-linked data to well locations. Contour map of bedrock surface was consistent with the data. Quasi–three-dimensional layered maps of contaminant concentration were consistent with the data.
Multiple lines of reasoning	Data contoured with different model parameters. Best fit to the data presented for visualization of the data.
Ease of use	Many features promote ease of use, including logical layout of pull-down menus, query capabilities, tutorials to guide novice users, and input and output in a wide range of formats. One or two days of training are needed to become familiar with the basic features of the software. More training is required to become proficient in the Avenue scripting language.
Efficiency	Three visualization problems were completed and documented with 12 person-days of effort.
Representativeness	ArcView GIS version 3.1 contains a database architecture that permits incorporation of a wide range of data sources into the analysis. Query capabilities permit flexibility in the analysis to handle a wide range of conditions. Avenue scripting language permits tailoring the analysis to the application.
Training and technical support	User manual On-line help Web-based help Many tutorials to teach different software features Training courses available through ESRI Technical support provided free for 60 days after purchase; may be purchased for longer times.
Operator skill base	Basic knowledge about environmental data and GIS, database files, and contouring
Platform	Windows NT 4.0. Minimum of 128 MB RAM, 233 or 300 MHz Pentium II processor and an Open GL video card for three-dimensional representations.
Cost	GSA costs for products that use Windows operating systems: ArcView GIS version 3.1 — $996 ArcView Spatial Analyst — $2342 ArcView 3D Analyst — $2342 Prices for commercial customers or for UNIX-based operating systems are slightly higher.

Section 5 — ArcView GIS Version 3.1, Spatial Analyst, and 3D Analyst Update and Representative Applications

Objective

The purpose of this section is to allow ESRI to provide information regarding new developments with its technology since the demonstration activities. In addition, the developer has provided a list of representative applications in which its technology has been or is currently being used.

Technology Update

Version 3.1 for ArcView was released in July 1998 and was used during the ETV demonstration period. Version 3.1 contains a large number of enhancements to Version 3.0. These include improved report generation capability, support for more input/output formats, and map annotation and presentation capabilities. A white paper detailing the enhancements is located at http://www.esri.com/library/whitepapers/pdfs/arcview.pdf.

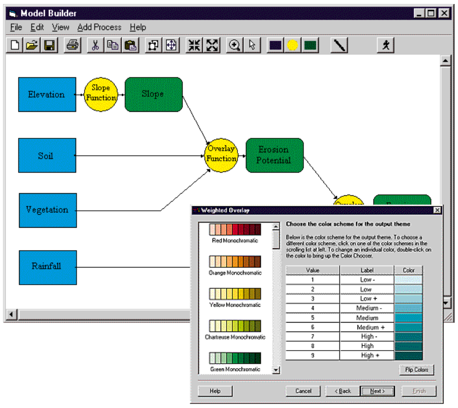
ArcView 3.2 was released in September 1999 ArcView GIS 3.2 provides numerous quality improvements as well as new features, including a projection utility for shapefiles; enhanced Spatial Database Engine and Open DataBase Connectivity database access; an update for the Report Writer extension, including Crystal Reports Version 7; new data readers and converters; and new and updated data for the *ESRI Data & Maps* CDs.

The 3D Analyst extension used in the demonstration was first released in mid-1998. A white paper detailing the functionality of the extension was released in December 1998. The white paper can be found at http://www.esri.com/library/whitepapers/pdfs/3danalys.pdf.

The Spatial Analyst extension has not received any major updates since the demonstration in September 1998. Spatial Analyst 2 is expected to be released in late 1999. ArcView Spatial Analyst 2 software will include the new ModelBuilder that enables users to quickly build and interact with spatial models. Users can construct models using process wizards or by dragging icons representing data (grid themes) and functions (such as slope, buffer, and overlay) into the model document and connecting them with lines to show how the data is processed.

The ModelBuilder provides both beginning and advanced users with a set of easy-to-use tools for building various types of spatial models within ArcView Spatial Analyst. The flow diagrams created in the model are a convenient way to build spatial models and are an excellent way to document and present one's models to others.

These new tools can be used to construct spatial models in any application area. For example, organizations can use Spatial Analyst's ModelBuilder to build land use suitability models, environmental sensitivity models, hazardous risk models, and social impact models. The user can also build models in which all of these spatial assessments are included in a single larger model.



Choose the color scheme for the output theme

Below is the color scheme for the output theme. To choose a different color scheme, click on one of the color schemes in the scrolling list at left. To change an individual color, double-click on the color to bring up the Color Chooser.

Value	Label	Color
1	Low -	🟦
2	Low	🟦
3	Low +	🟦
4	Medium -	🟦
5	Medium	🟦
6	Medium +	🟦
7	High -	🟦
8	High	🟦
9	High +	🟦

Figure 17 Screen capture of Spatial Analyst's ModelBuilder

Also in late 1999, ArcInfo 8 will be the most significant release of ArcInfo, ESRI's professional GIS. ArcInfo 8 has been completely redesigned and engineered to be an easy-to-use, fast, modern, and powerful GIS. A key feature of ArcInfo 8 is that it makes sophisticated GIS more usable. New applications like ArcMap and ArcCatalog accomplish this goal by approaching GIS from a new perspective. While the depth of functionality in ArcInfo is tremendous, new user interfaces and wizards make it easy by presenting users with what they need when they need it.

The Geostatistical Analyst—an extension to ArcInfo Version 8—is aimed at an emerging advanced spatial modeling audience. These tools were developed specifically for surface generation using geostatistical tools and analyzing the error of the resulting estimation (surface).

The generation of predictive surfaces, their accuracy, and their estimation of error are critical to modeling and analysis. The Geostatistical Analyst will help spatial scientists understand and use kriging and other advanced mathematical methods used for surface generation. It will provide control over the surface generation process and provide advanced tools for analysis of resulting surfaces.

Representative Applications

ESRI has many examples of ArcView technology used on a wide range of environmental-related projects in both the public and private sectors. Here are some examples.

- EPA's Superfund application, Fields, is an ArcView application from Region 5 in Chicago. Fields can be seen at http://www.epa.gov/r5water/fields/FIELDSITE/SHARED/PAGES/FLDHOME/HTM. The Fields program involves contamination of a stream by pesticides and is similar in nature to the problems solved in the ETV DSS project.

- ESRI, the Department of the Interior's Minerals Management Service, the state of Florida, and Louisiana State University collaborated to develop an ArcView Marine Spill Analysis System for the Gulf of Mexico coastal states. Although developed as an oil spill contingency planning tool, the database compiled can be used for other environmental and planning applications.

- The state of Florida's Department of Environmental Protection uses ArcView to analyze the environmental impact of issuing a permit for a project of any kind (e.g., building, destruction) anywhere in Florida. This generic permit analysis application will report many types of information about a site that would affect a decision about whether to issue a permit, including environmental sensitivity, cultural value, and environmental risk factors.
- New Jersey's Office of Water Monitoring Management uses Arc/Info and ArcView to analyze the water quality of New Jersey's 1200 lakes and 6000 miles of streams and rivers. One use of the system is to show impairment ratings for stream segments. The impairment rating is a measure of the health hazard posed to fish and human swimmers by high concentrations of nutrients, organics, and/or metals.

- The New York City Mayor's Office of Environmental Coordination uses ArcView in its efforts to redevelop land and revitalize local economies by reclaiming brownfields.

- Chevron Nigeria Ltd. has implemented ArcView GIS technology to locate oil in the Niger Delta and work with the Nigerian government on long-term agreements for oil extraction and resource protection. GIS technology is used to assess oil drilling and processing operations with the least possible disruption to Nigeria's plants and animals.

Additional examples can be found at www.esri.com/partners/gissolutions/.

In addition to ArcView, ESRI has developed other software tools for addressing environmental contamination issues. For example, see EPA's EnviroMapper (ESRI software MapObjects Internet mapping application for Superfund Sites) at http://maps.epa.gov:10008/enviro/html/mod/enviromapper/index.html. EnviroMapper is an extremely successful tool for delivering environmental data to the public; it received more than 200,000 Web hits last year. Also, ERSI–Germany created an Arc/Info application used across Europe for remedial action. COSIMA (Contaminated Sites Management) is currently being translated into English for a broader distribution.

Section 6 — References

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Appendix A — Summary of Test Problems

Site A: Sample Optimization Problem

Site A has been in operation since the late 1940s as an industrial machine plant that used solvents and degreasing agents. It overlies an important aquifer that supplies more than 2.7 million gal of water per day for industrial, commercial, and residential use. Site characterization and monitoring activities were initiated in the early 1980s, and it was determined that agricultural and industrial activities were sources of contamination. The industrial plant was shut down in 1985. The primary concern is volatile organic compounds (VOCs) in the aquifer and their potential migration to public water supplies. Source control is considered an important remediation objective to prevent further spreading of contamination.

The objective of this Site A problem was to challenge the software's capabilities as a sample optimization tool. The Site A test problem presents a three-dimensional (3-D) groundwater contamination scenario where two VOCs, dichloroethene (DCE) and trichloroethene (TCE), are present. The data that were supplied to the analysts included information on hydraulic head, subsurface geologic structure, and chemical concentrations from seven wells that covered an approximately 1000-ft square. Chemical analysis data were collected at 5-ft intervals from each well.

The design objective of this test problem was for the analyst to predict the optimum sample locations to define the depth and location of the plume at contamination levels exceeding the threshold concentration (either 10 or 100 µg/L). Because of the limited data set provided to the analysts and the variability found in natural systems, the analysts were asked to estimate the plume size and shape as well as the confidence in their prediction. A high level of confidence indicates that there is a high probability that the contaminant exceeds the threshold at that location. For example, at the 10-µg/L threshold, the 90% confidence level plume is defined as the region in which there is greater than a 90% chance that the contaminant concentration exceeds 10 µg/L. The analysts were asked to define the plume for three confidence levels—10% (maximum plume, low certainty, and larger region), 50% (nominal plume), and 90% (minimum plume, high certainty, and smaller region). The initial data set provided to the analyst was a subset of the available baseline data and intended to be insufficient for fully defining the extent of contamination in any dimension. The analyst used the initial data set to make a preliminary estimate of the dimensions of the plume and the level of confidence in the prediction. In order to improve the confidence and better define the plume boundaries, the analyst needed to determine where the next sample should be collected. The analyst conveyed this information to the demonstration technical team, which then provided the analyst with the contamination data from the specified location or locations. This iterative process continued until the analyst reached the test problem design objective.

Site A: Cost-Benefit Problem

The objectives of the Site A cost-benefit problem were (1) to determine the accuracy with which the software predicts plume boundaries to define the extent of a 3-D groundwater contamination problem on a large scale (the problem domain is approximately 1 square mile) and (2) to evaluate human health risk estimates resulting from exposure to contaminated groundwater. The VOC contaminants of concern for the cost-benefit problem were perchloroethene (PCE) and trichloroethane (TCA).

In this test problem analysts were to define the location and depth of the PCE plume at concentrations of 100 and 500 µg/L and TCA concentrations of 5 and 50 µg/L at confidence levels of 10 (maximum plume), 50 (nominal plume), and 90% (minimum plume). This information could be used in a cost-benefit analysis of remediation goals versus cost of remediation. The analysts were provided with geological information, borehole logs, hydraulic data, and an extensive chemical analysis data set consisting of more than 80 wells. Chemical analysis data were collected at 5-ft intervals from each well. Data from a few wells were withheld from the analysts to provide a reference to check interpolation routines. Once the analysts defined the PCE and TCA plumes, they were asked to calculate the human health risks associated with drinking 2 L/day of contaminated groundwater at two defined exposure points over the next 5 years. One exposure point was in the central region of the plume and one was at the outer edge. This information could be used in a cost-benefit analysis of reduction of human health risk as a function of remediation.

Site B: Sample Optimization and Cost-Benefit Problem

Site B is located in a sparsely populated area of the southern United States on a 1350-acre site about 3 miles south of a large river. The site is typical of many metal fabrication or industrial facilities because it has numerous potential sources of contamination (e.g., material storage areas, process activity areas, service facilities, and waste management areas). As with many large manufacturing facilities, accidental releases from laboratory activities and cleaning operations introduced solvents and other organic chemicals into the environment, contaminating soil, groundwater, and surface waters.

The objective of the Site B test problem was to challenge the software's capabilities as a sample optimization and cost-benefit tool. The test problem presents a two-dimensional (2-D) groundwater contamination scenario with three contaminants—vinyl chloride (VC), TCE, and technetium-99 (Tc-99). Chemical analysis data were collected at a series of groundwater monitoring wells on quarterly basis for more than 10 years along the direction of flow near the centerline of the plume. The analysts were supplied with data from one sampling period.

There were two design objectives for this test problem. First, the analyst was to predict the optimum sample location to define the depth and location of the plume at specified contaminant threshold concentrations with confidence levels of 50, 75, and 90%. The initial data set provided to the analyst was a subset of the available baseline data and was intended to be insufficient for fully defining the extent of contamination in two dimensions. The analyst used the initial data set to make a preliminary estimate of the dimensions of the plume and the level of confidence in the prediction. In order to improve the confidence in defining the plume boundaries, the analyst needed to determine the location for collecting the next sample. The analyst conveyed this information to the demonstration technical team, who then provided the analyst with the contamination data from the specified location or locations. This iterative process continued until the analyst reached the design objective.

Once the location and depth of the plume was defined, the second design objective was addressed. The second design objective was to estimate the volume of contamination at the specified threshold concentrations at confidence levels of 50, 75, and 90%. This information could be used in a cost-benefit analysis of remediation goals versus cost of remediation. Also, if possible, the analyst was asked to calculate health risks associated with drinking 2 L/day of contaminated groundwater from two exposure points in the plume. One exposure point was near the centerline of the plume, while the other was on the edge of the plume. This information could be used in a cost-benefit analysis of reduction of human health risk as a function of remediation.

Site D: Sample Optimization and Cost-Benefit Problem

Site D is located in the western United States and consists of about 3000 acres of land bounded by municipal areas on the west and southwest and unincorporated areas on northwest and east. The site has been an active industrial facility since it began operation in 1936. Operations have included maintenance and repair of aircraft and, recently, the maintenance and repair of communications equipment and electronics. The aquifer beneath the site is several hundred feet thick and consists of three or four different layers of sand or silty sand. The primary concern is VOC contamination of soil and groundwater as well as contamination of soil with metals.

The objective of the Site D problem was to test the software's capability as a tool for sample optimization and cost-benefit problems. This test problem was a 3-D groundwater sample optimization problem for four VOC contaminants—PCE, DCE, TCE, and TCA. The test problem required the developer to predict the optimum sample locations to define the region of the contamination that exceeded threshold concentrations for each contaminant. Contaminant data were supplied for a series of wells screened at different depths for four quarters in a 1-year time frame. This initial data set was insufficient to fully define the extent of contamination. The analyst used the initial data set to make a preliminary estimate of the dimensions of the plume and the level of confidence in the prediction. In order to improve the confidence in the prediction of the plume boundaries, the analyst needed to determine the location for collecting the next sample. The analyst conveyed this information to the demonstration technical team, who then provided the analyst with the contamination data from the specified location or locations. This iterative process was continued until the analyst determined that the data could support definition of the location and depth of the plume exceeding the threshold concentrations with confidence levels of 10, 50, and 90% for each contaminant.

After the analyst was satisfied that the sample optimization problem was complete and the plume was defined, he or she was given the option to continue and perform a cost-benefit analysis. At Site D, the cost-benefit problem required estimation of the volume of contamination at specified threshold concentrations with confidence levels of 10, 50, and 90%. This information could then be used in a cost-benefit analysis of remediation goals versus cost of remediation.

Site N: Sample Optimization Problem

Site N is located in a sparsely populated area of the southern United States and is typical of many metal fabrication or industrial facilities in that it has numerous potential sources of contamination (e.g., material storage areas, process activity areas, service facilities, and waste management areas). Industrial operations include feed and withdrawal of material from the primary process; recovery of heavy metals from various waste materials and treatment of industrial wastes. The primary concern is contamination of the surface soils by heavy metals.

The objective of the Site N sample optimization problem was to challenge the software's capability as a sample optimization tool to define the areal extent of contamination. The Site N data set contains the most extensive and reliable data for evaluating the accuracy of the analysis for a soil contamination problem. To focus only on the accuracy of the soil sample optimization analysis, the problem was simplified by removing information regarding groundwater contamination at this site, and it was limited to three contaminants. The Site N test problem involves surface soil contamination (a 2-D problem) for three contaminants—arsenic (As), cadmium (Cd), and chromium (Cr). Initial sampling indicated a small contaminated region on the site; however, the initial sampling was limited to only a small area (less than 5% of the site area).

The design objective of this test problem was for the analyst to develop a sampling plan that defines the extent of contamination on the 150-acre site based on exceedence of the specified threshold concentrations with confidence levels of 10, 50% and 90%. Budgetary constraints limited the total expenditure for sampling to $96,000. Sample costs were $1200 per sample, which included collecting and analyzing the surface soil sample for all three contaminants. Therefore, the number of additional samples had to be less than 80. The analyst used the initial data to define the areas of contamination and predict the location of additional samples. The analyst was then provided with additional data at these locations and could perform the sample optimization process again until the areal extent of contamination was defined or the maximum number of samples (80) was attained. If the analyst determined that 80 samples was insufficient to adequately characterize the entire 150-acre site, the analyst was asked to use the software to select the regions with the highest probability of containing contaminated soil.

Site N: Cost-Benefit Problem

The objective of the Site N cost-benefit problem was to challenge the software's ability to perform cost-benefit analysis as defined in terms of area of contaminated soil above threshold concentrations and/or estimates of human health risk from exposure to contaminated soil. This test problem considers surface soil contamination (2-D) for three contaminants—As, Cd, and Cr. The analysts were given an extensive data set for a small region of the site and asked to conduct a cost-benefit analysis to evaluate the cost for remediation to achieve specified threshold concentrations. If possible, an estimate of the confidence in the projected remediation areas was provided at the 50 and 90% confidence limits. For human health risk analysis, two scenarios were considered. The first was the case of an on-site worker who was assumed to have consumed 500 mg/day of soil for one year during excavation activities. The worker would have worked in all areas of the site during the excavation process. The second scenario considered a resident who was assumed to live on a 200- by 100-ft area at a specified location on the site and to have consumed 100 mg/day of soil for 30 years.

This information could be used in a cost-benefit (i.e., reduction of human health risk) analysis as a function of remediation.

Site S: Sample Optimization Problem

Site S has been in operation since 1966. It was an industrial fertilizer plant producing pesticides and fertilizer and used industrial solvents such as carbon tetrachloride (CTC) to clean equipment. Recently, it was determined that routine process operations were causing a release of CTC onto the ground; the CTC was then leaching into the subsurface. Measurements of the CTC concentration in groundwater have been as high as 80 ppm a few hundred feet down-gradient from the source area. The site boundary is approximately 5000 ft from the facility where the release occurred. Sentinel wells at the boundary are not contaminated with CTC.

The objective of the Site S sample optimization problem was to challenge the software's capability as a sample optimization tool. The test problem involved a 3-D groundwater contamination scenario for a single contaminant, CTC. To focus only on the accuracy of the analysis, the problem was simplified. Information regarding surface structures (e.g., buildings and roads) was not supplied to the analysts. In addition, the data set was modified such that the contaminant concentrations were known exactly at each point (i.e., release and transport parameters were specified, and concentrations could be determined from an analytical solution). This analytical solution permitted a reliable benchmark for evaluating the accuracy of the software's predictions.

The design objective of this test problem was for the analyst to define the location and depth of the plume at CTC concentrations exceeding 5 and 500 μg/L with confidence levels of 10, 50, and 90%. The initial data set provided to the analysts was insufficient to define the plume accurately. The analyst used the initial data to make a preliminary estimate of the dimensions of the plume and the level of confidence in the prediction. In order to improve the confidence in the predicted plume boundaries, the analyst needed to determine where the next sample should be collected. The analyst conveyed this information to the demonstration technical team, who then provided the analyst with the contamination data from the specified location or locations. This iterative process continued until the analyst reached the design objective.

Site S: Cost-Benefit Problem

The objective of the Site S cost-benefit problem was to challenge the software's capability as a cost-benefit tool. The test problem involved a 3-D groundwater cost-benefit problem for a single contaminant, chlordane. Analysts were given an extensive data set consisting of data from 34 wells over an area that was 2000 ft long and 1000 ft wide. Vertical chlordane contamination concentrations were provided at 5-ft intervals from the water table to beneath the deepest observed contamination.

This test problem had three design objectives. The first was to define the region, mass, and volume of the plume at chlordane concentrations of 5 and 500 μg/L. The second objective was to extend the analysis to define the plume volumes as a function of three confidence levels—10, 50, and 90%. This information could be used in a cost-benefit analysis of remediation goals versus cost of remediation. The third objective was to evaluate the human health risk at three drinking-water wells near the site, assuming that a resident drinks 2 L/day of water from a well screened over a 10-ft interval across the maximum chlordane concentration in the plume. The analysts were asked to estimate the health risks at two locations at times of 1, 5 and 10 years in the future. For the health risk analysis, the analysts were told to assume source control preventing further release of chlordane to the aquifer. This information could be used in a cost-benefit analysis of reduction of human health risk as a function of remediation.

Site T: Sample Optimization Problem

Site T was developed in the 1950s as an area to store agricultural equipment as well as fertilizers, pesticides, herbicides, and insecticides. The site consists of 18 acres in an undeveloped area of the western United States, with the nearest residence being approximately 0.5 miles north of the site. Mixing operations (fertilizers and pesticides or herbicides and insecticides) were discontinued or replaced in the 1980s when concentrations of pesticides and herbicides in soil and wastewater were determined to be of concern.

The objective of the Site T sample optimization problem was to challenge the software's capability as a sample optimization tool. The test problem presents a surface and subsurface soil contamination scenario for four VOCs: ethylene dibromide (EDB), dichloropropane (DCP), dibromochloropropane (DBCP), and CTC. This sample optimization problem had two stages. In the first stage, the analysts were asked to prepare a sampling strategy to define the areal extent of surface soil contamination that exceeded the threshold concentrations listed in Table A-1 with confidence levels of 10, 50 and 90% on a 50- by 50-ft grid. This was done in an iterative fashion in which the analysts would request data at additional locations and repeat the analysis until they could determine, with the aid of their software, that the plume was adequately defined.

The stage two design objective addressed subsurface contamination. After defining the region of surface contamination, the analysts were asked to define subsurface contamination in the regions found to have surface contamination above the 90% confidence limit. In stage two, the analysts were asked to suggest subsurface sampling locations on a 10-ft vertical scale to fully characterize the soil contamination at depths from 0 to 30 ft below ground surface (the approximate location of the aquifer).

Table A-1. Site T soil contamination threshold concentrations

Contaminant	Threshold concentration (:g/kg)
Ethylene dibromide	21
Dichloropropane	500
Dibromochloropropane	50
Carbon tetrachloride	5

Site T: Cost-Benefit Problem

The objective of the Site T cost-benefit problem was to challenge the software's capability as a cost-benefit tool. The test problem involved a 3-D groundwater contamination scenario with four VOCs (EDB, DCB, DBCP, and CTC). The analysts were given an extensive data set and asked to estimate the volume, mass, and location of the plumes at specified threshold concentrations for each VOC. If possible, the analysts were asked to estimate the 50 and 90% confidence plumes at the specified concentrations. This information could be used in a cost-benefit analysis of various remediation goals versus the cost of remediation. For health risk cost-benefit analysis, the analysts were asked to evaluate the risks to a residential receptor (with location and well screen depth specified) and an on-site receptor over the next 10 years. For the residential receptor, consumption of 2 L/day of groundwater was the exposure pathway. For the on-site receptor, groundwater consumption of 1 L/day was the exposure pathway. For both human health risk estimates, the analysts were told to assume removal of any and all future sources that may impact the groundwater. This information could be used in a cost-benefit analysis of various remediation goals versus the cost of remediation.

Appendix B — Description of Interpolation Methods

A major component of the analysis of environmental data sets involves predicting physical or chemical properties (contaminant concentrations, hydraulic head, thickness of a geologic layer, etc.) at locations between measured data. This process, called interpolation, is often critical in developing an understanding of the nature and extent of the environmental problem. The premise of interpolation is that the estimated value of a parameter is a weighted average of measured values around it. Different interpolation routines use different criteria to select the weights. Because of the importance of obtaining estimates of data between measured data points in many fields of science, a wide number of interpolation routines exist.

Three classes of interpolation routines commonly used in environmental analysis are nearest neighbor, inverse distance, and kriging. These three classes cover the range found in the software used in the demonstration and use increasingly complex models to select their weighting functions.

Nearest neighbor is the simplest interpolation routine. In this approach, the estimated value of a parameter is set to the value of the spatially nearest neighbor. This routine is most useful when the analyst has a lot of data and is estimating parameters at only a few locations. Another simple interpolation scheme is averaging of nearby data points. This scheme is an extension of the nearest neighbor approach and interpolates parameter values as an average of the measured values within the neighborhood (specified distance). The weights for averaging interpolation are all equal to $1/n$, where n is the number of data points used in the average. The nearest neighbor and averaging interpolation routines do not use any information about the location of the data values.

Inverse distance weighting (IDW) interpolation is another simple interpolation routine that is widely used. It does account for the spatial distance between data values and the interpolation location. Estimates of the parameter are obtained from a weighted average of neighboring measured values. The weights of IDW interpolation are proportional to the inverse of these distances raised to a power. The assigned weights are fractions that are normalized such that the sum of all the weights is equal to 1.0. In environmental problems, contaminant concentrations typically vary by several orders of magnitude. For example, the concentration may be a few thousand micrograms per liter near the source and tens of micrograms per liter away from the source. With IDW, the extremely high concentrations tend to have influence over large distances, causing smearing of the estimated area of contamination. For example, for a location that is 100 m from a measured value of 5 μg/L and 1000 m from a measured value of 5000 μg/L, using a distance weighting factor of 1 in IDW yields a weight of 5000/1000 for the high-concentration data point and 5/100 for the low-concentration data point. Thus, the predicted value is much more heavily influenced by the large measured value that is physically farther from the location at which an estimate is desired. To minimize this problem, the inverted distance weight can be increased to further reduce the effect of data points located farther away. IDW does not directly account for spatial correlation that often exists in the data. The choice of the power used to obtain the interpolation weights is dependent on the skills of the analyst and is often obtained through trial and error.

The third class of interpolation schemes is kriging. Kriging attempts to develop an estimate of the spatial correlation in the data to assist in interpolation. Spatial correlation represents the correlation between two measurements as a function of the distance and direction between their locations. Ordinary kriging interpolation methods assume that the spatial correlation function is based on the assumption that the measured data points are normally distributed. This kriging method is often used in environmental contamination problems and was used by some decision support software (DSS) products in the demonstration and in the baseline analysis. If the data are neither lognormal nor normally distributed, interpolations can be handled with indicator kriging. Some of the DSS products in this demonstration used this approach. Indicator kriging differs from ordinary kriging in that it makes no assumption on the distribution of data and is essentially a nonparametric counterpart to ordinary kriging.

Both kriging approaches involve two steps. In the first step, the measured data are examined to determine the spatial correlation structure that exists in the data. The parameters that describe the correlation structure are calculated as a variogram. The variogram merely describes the spatial relationship between data points. Fitting a model to the variogram is the most important and technically challenging step. In the second step, the kriging process interpolates data values at unsampled locations by a moving-average technique that uses the results from the variogram to calculate the weighting factors. In kriging, the spatial correlation structure is quantitatively evaluated and used to calculate the interpolation weights.

Although geostatistical-based interpolation approaches are more mathematically rigorous than the simple interpolation approaches using nearest neighbor or IDW, they are not necessarily better representations of the data. Statistical and geostatistical approaches attempt to minimize a mathematical constraint, similar to a least squares minimization used in curve-fitting of data. While the solution provided is the "best" answer within the mathematical constraints applied to the problem, it is not necessarily the best fit of the data. There are two reasons for this.

First, in most environmental problems, the data are insufficient to determine the optimum model to use to assess the data. Typically, there are several different models that can provide a defensible assessment of the spatial correlation in the data. Each of these models has its own strengths and limitations, and the model choice is subjective. In principle, selection of a geostatistical model is equivalent to picking the functional form of the equation when curve-fitting. For example, given three pairs of data points, (1,1), (2,4) and (3,9), the analyst may choose to determine the best-fit line. Doing so gives the expression $y = 4x – 3.33$, where y is the dependent variable and x is the independent variable. This has a goodness of fit correlation of 0.97, which most would consider to be a good fit of the data. This equation is the "best" linear fit of the data constrained to minimization of the sum of the squares of the residuals (difference between measured value and predicted value at the locations of measured values). Other functional forms (e.g., exponential, trigonometric, and polynomial) could be used to assess the data. Each of these would give a different "best" estimate for interpolation of the data. In this example, the data match exactly with $y = x^2$, and this is the best match of this data. However, that this is the best match cannot be known with any high degree of confidence.

This conundrum leads to the second reason for the difficulty, if not impossibility, of finding the most appropriate model to use for interpolation—which is that unless the analyst is extremely fortunate, the measured data will not conform to the mathematical model used to represent the data. This difficulty is often attributed to the variability found in natural systems, but is in fact a measure of the difference between the model and the real-world data. To continue with the previous example, assume that another data point is collected at $x = 2.5$ and the value is $y = 6.67$. This latest value falls on the previous linear best-fit line, and the correlation coefficient increases to 0.98. Further, it does not fall on the curve $y = x^2$. The best-fit 2nd-order polynomial now changes from $y = x^2$ to become $y = 0.85x^2 + 0.67x – 0.55$. The one data point dramatically changed the "best"-fit parameters for the polynomial and therefore the estimated value at locations that do not have measured values.

Lack of any clear basis for choosing one mathematical model over another and the fact that the data are not distributed in a manner consistent with the simple mathematical functions in the model also apply to the statistical and geostatistical approaches, albeit in a more complicated manner. In natural systems, the complexity increases over the above example because of the multidimensional spatial characteristics of environmental problems. This example highlighted the difficulty in concluding that one data representation is better than another. At best, the interpolation can be reviewed to determine if it is consistent with the data. The example also highlights the need for multiple lines of reasoning when assessing environmental data sets. Examining the data through use of different contouring algorithms and model parameters often helps lead to a more consistent understanding of the data and helps eliminate poor choices for interpolation parameters.