Title: An Object-Oriented Approach to Site Characterization Decision Support

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Abstract:

An object-oriented approach to decision support for hazardous waste characterization is presented. Data generated during a site characterization are assigned to objects such as monitoring wells, soil cores, underground storage tanks, etc. Rules that are object-type dependent are used to control the way data can be graphically displayed. The object-oriented database acts as a data storage and display engine for statistical routines that guide sampling strategy selection. The object-oriented database gives interactive access to site data and a qualitative understanding of the nature and extent of contamination. Supporting statistical routines locate new sampling points, measure contamination extent, and provide stopping criteria for sampling programs. A case study where this approach was used is discussed.

Key-Word List:

geographical information system, object-oriented database, site characterization, decision support, sampling strategies

DISCLAIMER

INTRODUCTION

Effective decision support for site characterization is key to determining the nature and extent of contamination and the associated human and environmental risks. Site characterization data, however, present particular problems to technical analysts and decision-makers. Such data are four dimensional, incorporating temporal and spatial components. Their sheer volume can be daunting---sites with hundreds of monitoring wells and thousands of samples sent for laboratory analyses are not uncommon. Data are derived from a variety of sources including laboratory analyses, non-intrusive geophysical surveys, historical information, bore logs, in-field estimates of key physical parameters such as aquifer transmissivity, soil moisture content, depth-to-water table, etc.

Ultimately, decisions have to be made based on data that are always incomplete, often confusing, inaccurate, or inappropriate, and occasionally wrong. In response to this challenge, two approaches to environmental decision support have arisen, Data Quality Objectives[2] (DQOs) and the Observational Approach[3] (OA). DQOs establish criteria for data collection by clearly defining the decisions that need to be made, the uncertainty that can be tolerated, and the type and amount of data that needs to be collected to satisfy the uncertainty requirements. In practice, DQOs are typically based on statistical measures. The OA accepts the fact that the process of characterizing and remediating contaminated sites is always uncertain. Decision-making with the OA is based on what is known about a site, with contingencies developed for potential future deviations from the original assumptions about contamination nature, extent, and risks posed.

The two approaches are not mutually exclusive---in fact, they are highly complementary. The OA provides a basic approach to decision-making, while DQOs provide a defensible means for bringing each decision-making step to closure. Key to their successful implementation, however, is placing data in the hands of technical analysts and decision-makers. Such people need data that are immediately available and easily accessible, that can be massaged and manipulated, and that are visually informative.

The majority of insights about the nature, extent, and risks posed by a contamination event come from an intimate understanding of the site. The most effective way of assimilating, integrating and conveying information is via visual displays. The presentation and analysis of spatial data have spawned a growing discipline, commonly known as Geographic Information Systems (GIS). However, for several reasons, traditional GIS systems are not well suited to data generated during a site characterization. Raster-based GIS systems are ideal for data that is rich in location, but sparse in data available at each location (such as satellite imagery). Site assessment data are typically sparse in location, but rich in information at each location. For example, a particular site may have only a handful of monitoring wells, but each well may incorporate stratigraphic data, bore log data, soil sample information collected when the well was installed, and temporal water quality and depth-to-water table data. Site characterization data are typically three dimensional in spatial location. Raster and vector-based GIS systems treat information as two-dimensional layers. Traditional GIS systems were intended for data display purposes, and were not designed to function as databases themselves. Consequently, most GIS systems have very limited inherent data management facilities. Finally, site characterization demands specialized data displays that traditional GIS systems do not provide.

Traditional data archiving systems are also of little help to technical decision-makers. Data archiving systems for sites undergoing characterization are meant to preserve information. They guarantee data integrity, security, and quality. In this role, data archiving systems require lengthy quality assurance and quality control procedures before new data can be included in the database and controlled access to information after data has been archived. Environmental data archiving systems seldom provide anything more than tabular aggregates of data for analysis.

The best decision support approach for environmental site characterization decision-making is one that provides decision-makers with interactive, dynamic, visual access to site data, and that links this data with quantitative models that can be used for more thorough data analysis. The first half of this approach guarantees that decision makers following the OA have as good an understanding of their site as possible, while the second provides them with the analytical tools they need to implement DQOs for each decision that needs to be made.

AN OBJECT-ORIENTED APPROACH TO ENVIRONMENTAL DECISION SUPPORT

A promising approach to site characterization decision support uses a customized GIS developed around an object-oriented database[1] (OOD). The resulting GIS/OOD is

object-oriented, interactive, dynamic, and **graphically-based,** with sockets for attaching analytical routines. In an **object-oriented** database, information is stored by object rather than by table. Object classes are defined in an object dictionary. Each object class is assigned to an object proto-class. Proto-classes are predefined by the GIS/OOD, and include default representations for their object classes in graphical displays, intrinsic information fields, and definitions of applicable graphical displays and procedures. A GIS/OOD that is specifically designed for site characterization incorporates proto-classes meaningful for site assessment work. For example, object classes such as monitoring wells, soil cores, production wells, and cone penetrometer bores might all be classified under a boring proto-class. Each object class can also have additional information fields assigned in the object dictionary. As data is added to the GIS/OOD, new instances of the various object classes are created and their information fields completed. Each new instance inherits both the predefined characteristics associated with its proto-class, and any additional characteristics defined for its specific class within the object dictionary.

Graphically-based means that all data is displayed and accessible in some visually meaningful way. These graphics might take the form of plan views of the site, cross-sectional views showing subsurface characteristics, bore logs, fence diagrams, time views, or whatever was pertinent to the characterization. Within each graphic, data objects are identified by icons that can be selected and their data displayed. The type of view pertinent to a set of objects is based on display rules attached to each object's proto-class. For example, a bore log could be constructed and displayed for a monitoring well or a soil bore, but not for a buried drum. A time view might be constructed for a set of monthly depth-to-water table measures, but not for a collection of soil bores.

Dynamic means that all graphical displays generated by the GIS/OOD are dynamically tied to the underlying database. Changes in the underlying database are propagated to all graphical displays. For example, altering the coordinates of a soil bore would automatically change its location in all pertinent displays. **Interactive** means that the GIS/OOD user has easy access to data contained in displays, and that new graphical displays are simple to create. Implied in interactive is a menu, mouse and icon driven system based on a standard graphical user interface.

Finally, the availability of sockets allows technical decision-makers to easily "attach" their favorite analysis code---a simple statistics package, some specialized interpolation routine, a groundwater flow and transport model, or a risk assessment methodology---to the GIS/OOD and perform quantitative analyses on the stored data, using the GIS/OOD both as a source of data and a repository for saving and visualizing analysis results.

DECISION SUPPORT FOR SAMPLING STRATEGY SELECTION: A CASE STUDY

The most expensive and time-consuming component of site characterization is the collection and analysis of liquid, gas, and soil samples for hazardous chemical constituents to determine the nature and extent of contamination. The key decisions that need to be made are how many samples to take, where they should be located, and when enough data has been collected. Within every sampling program, evetually there are decreasing returns to data collection. Fig. 1 shows schematically the relationship between sampling costs, additional information gained, and the number of samples taken. Ideally, sampling should stop when the value of additional information is less than the cost of an additional sample---in the case of Fig. 1, when N samples have been taken.

The U.S. Department of Energy (DOE), through its Office of Technology Development (OTD), supports the development and demonstration of emerging technologies. One program, the Mixed Waste Landfill Integrated Demonstration (MWLID), demonstrates in-situ characterization technologies for landfills in arid environments that contain complex mixtures of metal, organic and radioactive wastes. The ultimate purpose of the MWLID is to transfer promising technologies to DOE's Environmental Restoration Program. In 1992, the MWLID demonstrated a suite of technologies at a chemical waste landfill operated by Sandia National Laboratory. One of the technologies was a decision support system designed to assist in sampling strategy selection.

The decision support system used for the MWLID was built around a GIS/OOD designed for site assessment, and a set of statistical routines developed at Argonne National Laboratory to assist in sample location selection. The GIS/OOD used a workstation as its platform, and an X-windowing system as the basis for its graphical user interface. The GIS/OOD provided data storage, management and visualization capabilities. The statistical routines combined Bayesian analyses with geostatistics, integrating "soft" information on contaminant location with "hard" sampling data to locate the most promising new sample positions. The statistical routines also provided measures of the level of contaminant delineation, allowing the formulation of stopping criteria to support DQOs. The statistical routines operated as a process separate from the GIS/OOD, also using an X-windows user interface. Data exchange between the GIS/OOD and the statistical routines was accomplished primarily through standard UNIX pipes.

The specific contamination event targeted was a chromium plume in the unsaturated zone underlying an unlined chromic acid pit within the chemical waste landfill. Fig. 2 shows the relative location of the unlined chromic acid pit within the chemical waste landfill, while Fig. 3 shows the unlined pit's immediate vicinity. The labeled soil bores in Fig. 3 denote seven borings completed during a 1987 boring program that formed an east-west transect of the pit. Fig. 4 is a cross-section of the unlined chromic acid pit showing the location of the plume in 1987 based on the data from these seven bores. When the MWLID began work in 1992, there was no information about the north-south extent of contamination, or its current depth of penetration.

At the time the MWLID began, a base map for the chemical waste landfill area already existed in ArcInfo format. This base map included the position of the landfill fence, as well as the locations of some of the burial pits within the landfill. It was imported into the GIS/OOD as dxf layer objects, and served as the backdrop for all plan view displays. A data dictionary was then constructed for the site that included, among other data objects, soil bores, directionally drilled bores, fence boundaries, disposal pits, monitoring wells, soil samples, and stratigraphic samples. These objects were divided into two fundamental classes---independent objects, or objects that possessed their own coordinate information, and dependent objects, or objects that derived their coordinate information from an independent object. Examples of the former were the various types of wells and bores defined for the site, while examples of the latter included soil and stratigraphic samples. Each object, in turn, was assigned a set of information fields that could contain information. For example, soil bores included fields for the contractor who installed the bore, its date of installation, and the finished depth. Soil samples included fields for all the different types of chemistry analyses performed.

Once the object dictionary was defined, historical data was brought into the GIS/OOD, along with new information being generated by the MWLID. Fig. 5 shows the GIS/OOD in operation as a database. Here soil bore UCAP-3 has been selected and its data displayed. From the scrolling list of dependent objects attached to this bore, soil sample 10073 has been selected and its data retrieved, including both locational information and chemical results. Fig. 6 shows a GIS/OOD session with various views opened. The plan view provides a bird's eye view of the unlined chromic acid pit, while the bore log and the cross-section provide a subsurface view of the site for an individual bore, and a set of bores, respectively. In every view, the icons displayed represent objects with data attached. For example, in both the bore log and the cross-section views the icons along the length of the bores indicate the locations of soil samples.

Many of the technologies being demonstrated by the MWLID focused on real-time generation of chemistry analytical results, either through in-situ sensors or via a field laboratory established at the site. The GIS/OOD provided the potential for integrating information as it was being generated with past data, and incorporating the new data dynamically in various graphical representations of the site. For example, in Fig. 6 the bore log for UCAP-3 shows analytical results for total chromium content in soil samples from UCAP-3. Each vertical graph represents the results from a different type of analytical procedure, the first showing laboratory results from EPA specified procedures, and the second two displaying results for the same samples from two field laboratory screening techniques. Dynamically displaying analytical results from field screening techniques offers the potential for interactive sampling programs---sampling programs whose progress and direction are dictated in "real-time" by data generated in the field.

The GIS/OOD also operated as the database and visualization tool for the statistical routines used to search for new sampling locations. The initial goal of the MWLID sampling strategy was to determine the best new vertical bore locations for delineating the extent of the chromium contamination, and the position of sampling points along these new bores. Fig. 7 shows the results of the statistical routines as they searched for the best new bore locations, using data from the 1987 boring program. The contoured area superimposed on the plan view of the unlined chromic acid pit denotes the potential impact of new bores on plume delineation. The best locations for new bores are shown in the plan view.

In the summer of 1992, two sets of new bores were installed and soil samples obtained. Fig. 8 shows the locations of the new bores. Fig. 9 shows the amount of estimated contaminated soil as a function of each sampling program. The two TEVES bores were close to the recommended boring location north of the unlined chromic acid pit shown in Fig. 7. The results from the two TEVES bores had a significant impact on the amount of soil classified as contaminated. Additional statistical analysis of the data indicated that only one additional bore near the southwest corner of RMMA-1 was required to quantify the extent of contamination. Because of radiation concerns and boring hardware demands, however, the UCAP bores avoided RMMA-1, a pit where suspected radioactive wastes were disposed, and instead focused on the western area of the unlined chromic acid pit. As is obvious from Fig. 9, the UCAP bores had little impact on the volume of soil considered contaminated because of their location.

CONCLUSIONS

For emerging site characterization methodologies such as DQOs and the OA to be effective, data analysts and decision-makers require easy, immediate, dynamic, and interactive access to data with graphics that are visually meaningful. In addition, technical analysts must be able to easily link their site data with analytical routines required for data analysis. For a variety of reasons traditional GIS systems are ill-suited for the data storage and display requirements of environmental characterization decision support. Standard data archiving systems also have serious shortcomings in this area. An object-oriented database with display graphics customized to the needs of site characterization is the ideal data storage and visualization engine. Within the last year, significant advances in both proprietary and public domain software have broadened the scope of such tools available to technical staff responsible for environmental site characterizations.

As the case study in this paper illustrates, a GIS/OOD system can effectively support environmental decision-making methodologies such as DQOs and the OA. A GIS/OOD can provide technical staff with as complete an understanding of a site's characteristics as possible as quickly as possible. Coupled with analysis tools such as the smart sampling strategy techniques described in the case study, the number of samples required to characterize a site can be minimized, and those samples that are taken can be placed so as to maximize the information obtained. Real-time data generation via field screening technologies, real-time data storage, integration and visualization, and real-time data analysis can lead to interactive sampling programs, whose progress is constantly modified to reflect data as they are being generated. The end result is an enormous potential for reducing the cost and time required for characterization programs.

ACKNOWLEDGMENTS

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REFERENCES

1. Baecher, G. B., & J. H. Hetrick, Computer-aided observational approaches to site assessment, *Air and Waste Management Association Annual Meeting*, Kansas City, June 22-26, 1992.

2. Neptune, D., E. P. Brantly, M. J. Messner, & D. I. Michael, Making in Superfund: A Data Quality Objectives Case Study, *HMC*, May/June, 1990, 19-27.

3. Peck, R.B., Advantages and limitations of the observational method in applied soil mechanics, *Geotechnique*, **19**, (1969), 171-187.

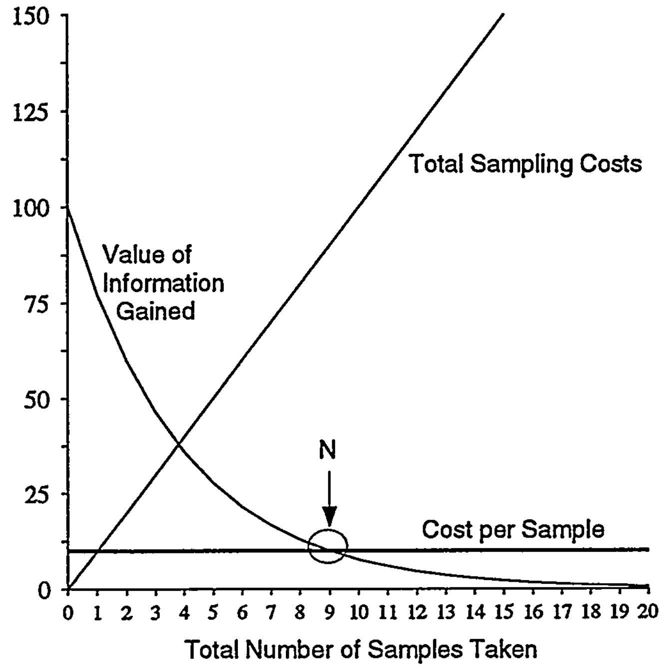
150
125
100
75
50
25
0
Total Sampling Costs
Value of Information Gained
N
Cost per Sample
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Total Number of Samples Taken

Figure 1

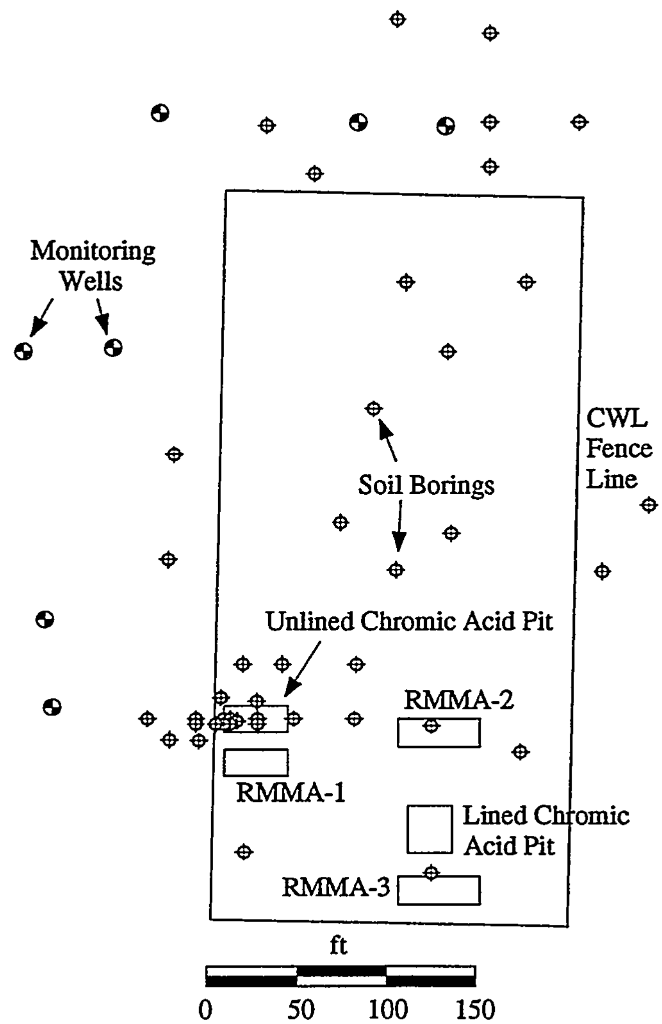
Monitoring
Wells
CWL
Fence
Line
Soil Borings
Unlined Chromic Acid Pit
RMMA-2
RMMA-1
Lined Chromic
Acid Pit
RMMA-3
ft
0
50
100
150

Figure 2

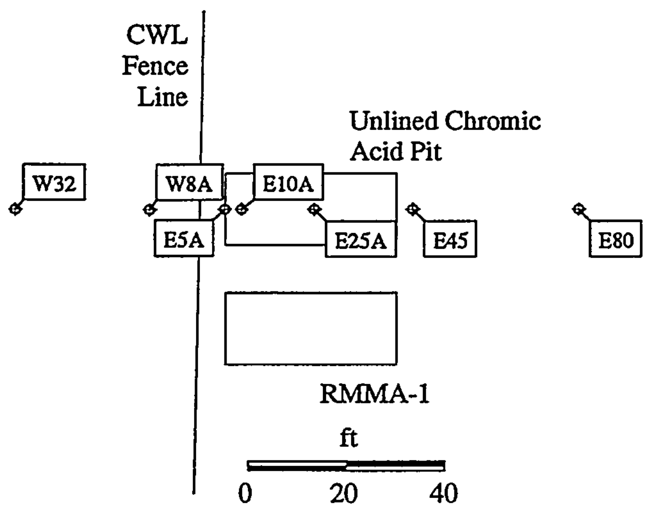
CWL
Fence
Line
Unlined Chromic
Acid Pit
W32
W8A
E10A
E5A
E25A
E45
E80
RMMA-1
ft
0
20
40

Figure 3

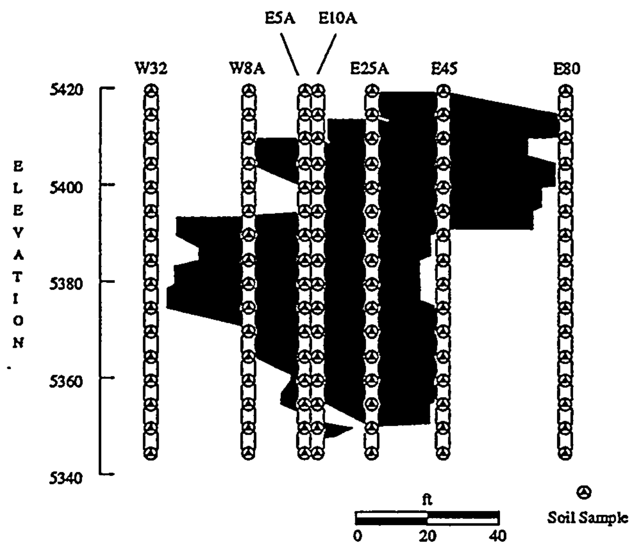
E5A
E10A
W32
W8A
E25A
E45
E80
5420
5400
5380
5360
5340
ELEVATION
ft
0
20
40
Soil Sample

Figure 4

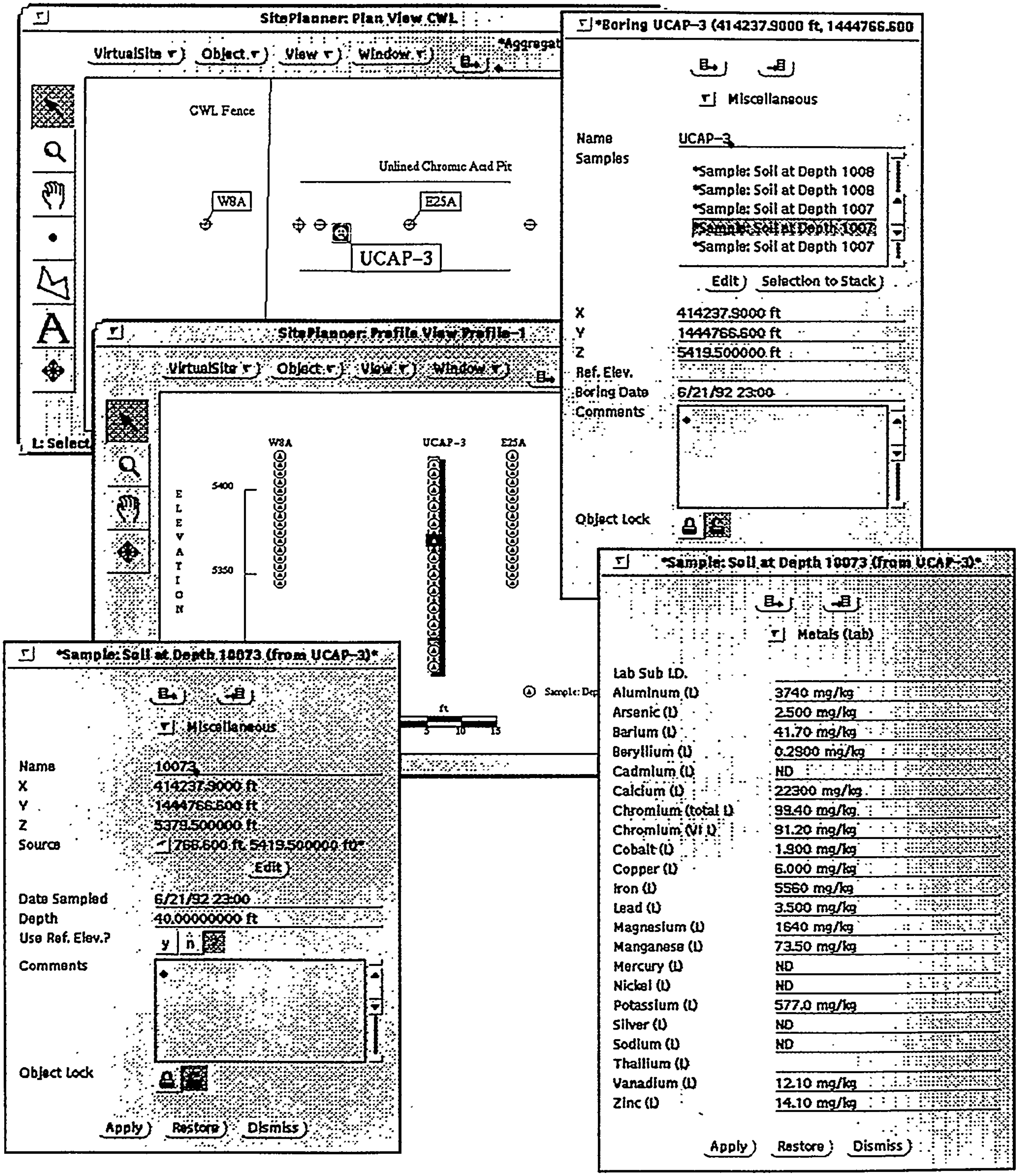
SitePlanner: Plan View CWL
VirtualSite
Object
View
Window
CWL Fence
Unlined Chromic Acid Pit
W8A
E25A
UCAP-3
L: Select
SitePlanner: Profile View Profile-1
ELEVATION
5400
5350
UCAP-3
*Boring UCAP-3 (414237.9000 ft, 1444766.600
Miscellaneous
Name
UCAP-3
Samples
*Sample: Soil at Depth 1008
*Sample: Soil at Depth 1008
*Sample: Soil at Depth 1007
*Sample: Soil at Depth 1007
Edit
Selection to Stack
X
414237.9000 ft
Y
1444766.600 ft
Z
5419.500000 ft
Ref. Elev.
Boring Date
6/21/92 23:00
Comments
Object Lock
Sample: Soil at Depth 10073 (from UCAP-3)
Miscellaneous
Name
10073
X
414237.9000 ft
Y
1444766.600 ft
Z
5379.500000 ft
Source
766.600 ft, 5419.500000 ft)*
Edit
Date Sampled
6/21/92 23:00
Depth
40.00000000 ft
Use Ref. Elev.?
y
n
Comments
Object Lock
Apply
Restore
Dismiss
Sample: Soil at Depth 10073 (from UCAP-3)
Metals (lab)
Lab Sub I.D.
Aluminum (l) 3740 mg/kg
Arsenic (l) 2.500 mg/kg
Barium (l) 41.70 mg/kg
Beryllium (l) 0.2900 mg/kg
Cadmium (l) ND
Calcium (l) 22300 mg/kg
Chromium (total l) 99.40 mg/kg
Chromium (VI l) 91.20 mg/kg
Cobalt (l) 1.900 mg/kg
Copper (l) 6.000 mg/kg
Iron (l) 5560 mg/kg
Lead (l) 3.500 mg/kg
Magnesium (l) 1640 mg/kg
Manganese (l) 73.50 mg/kg
Mercury (l) ND
Nickel (l) ND
Potassium (l) 577.0 mg/kg
Silver (l) ND
Sodium (l) ND
Thallium (l)
Vanadium (l) 12.10 mg/kg
Zinc (l) 14.10 mg/kg
Apply
Restore
Dismiss

Figure 5

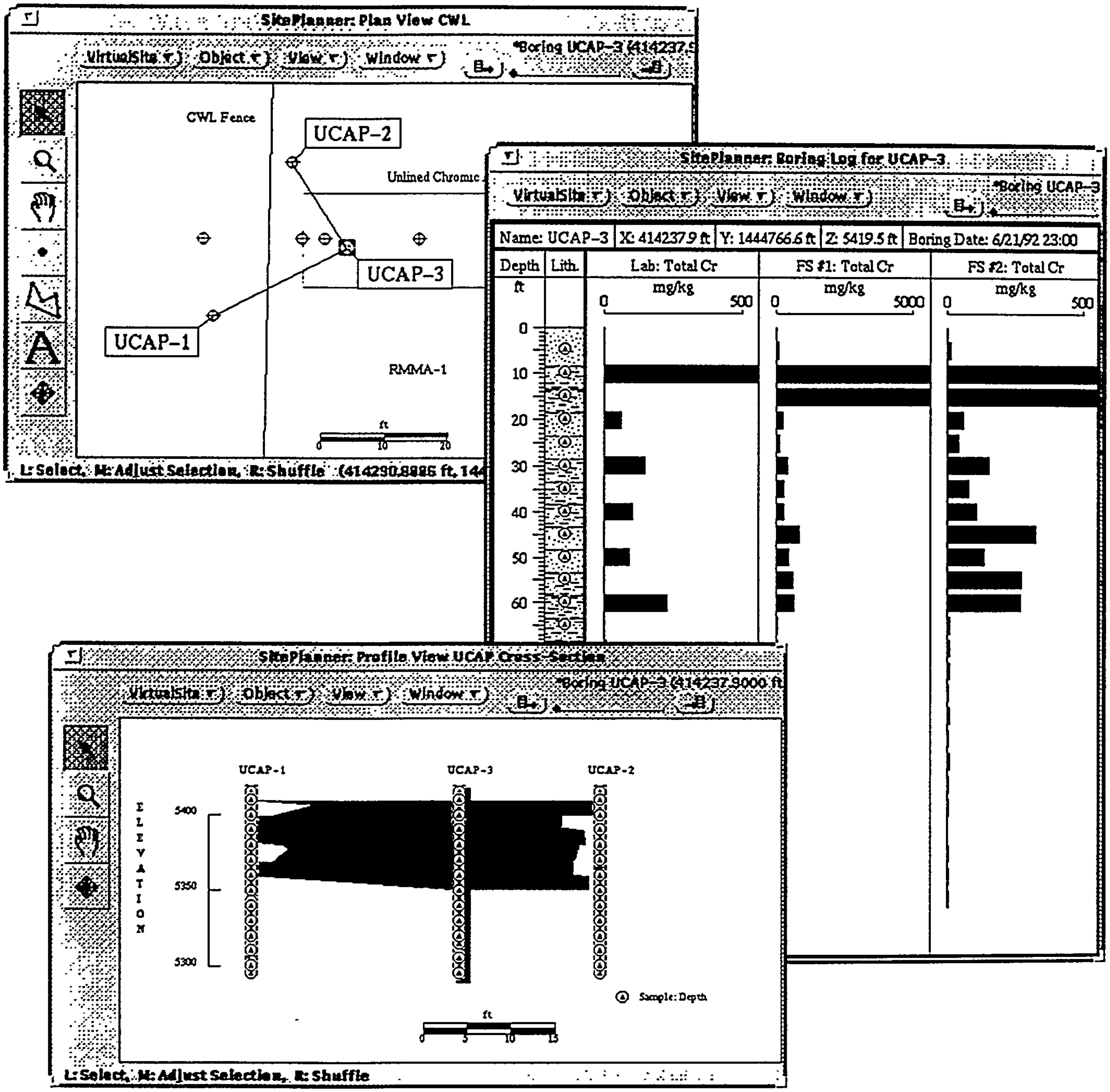
SitePlanner: Plan View CWL
VirtualSite
Object
View
Window
CWL Fence
UCAP-2
Unlined Chromic
UCAP-3
UCAP-1
RMMA-1
L: Select, M: Adjust Selection, R: Shuffle
SitePlanner: Boring Log for UCAP-3
Name: UCAP-3
X: 4142379 ft
Y: 1444766.6 ft
Z: 5419.5 ft
Boring Date: 6/21/92 23:00
Depth ft
Lith.
Lab: Total Cr
FS #1: Total Cr
FS #2: Total Cr
mg/kg
SitePlanner: Profile View UCAP Cross-Section
UCAP-1
UCAP-3
UCAP-2
ELEVATION
Sample: Depth
L: Select, M: Adjust Selection, R: Shuffle

Figure 6

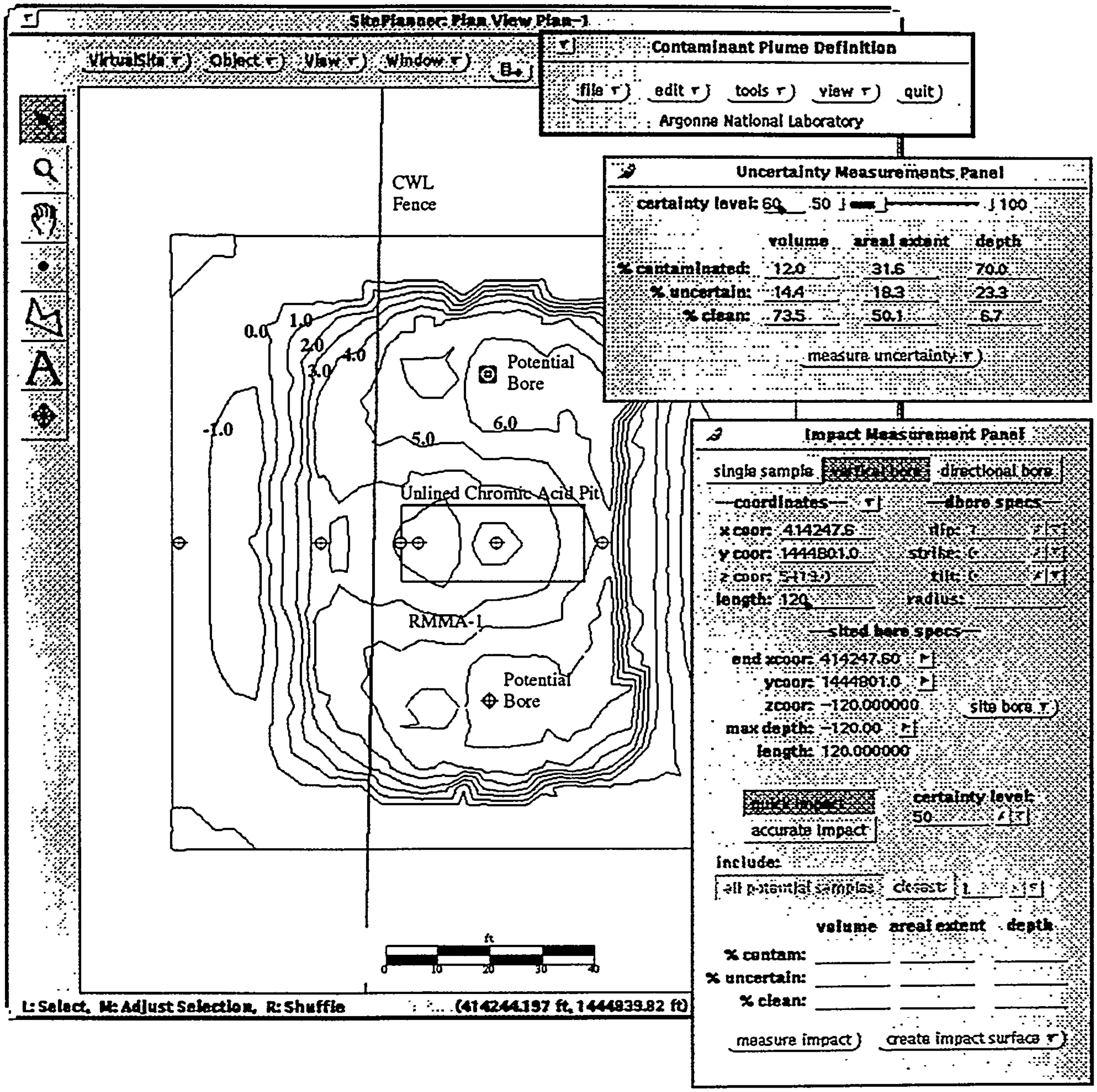
SitePlanner: Plan View Plan-1
VirtualSite
Object
View
Window
Contaminant Plume Definition
file
edit
tools
view
quit
Argonne National Laboratory
Uncertainty Measurements Panel
certainty level: 60
50
100
volume
areal extent
depth
% contaminated: 12.0 31.6 70.0
% uncertain: 14.4 18.3 23.3
% clean: 73.5 50.1 6.7
measure uncertainty
CWL
Fence
Potential
Bore
Unlined Chromic Acid Pit
RMMA-1
0.0
1.0
2.0
3.0
4.0
5.0
6.0
-1.0
ft
0
10
20
30
40
Impact Measurement Panel
single sample
vertical bore
directional bore
coordinates
bore specs
x coor: 414247.6
y coor: 1444801.0
length: 120
sited bore specs
end xcoor: 414247.60
ycoor: 1444801.0
zcoor: -120.000000
site bore
max depth: -120.00
length: 120.000000
quick impact
accurate impact
certainty level:
50
include:
volume
areal extent
depth
% contam:
% uncertain:
% clean:
measure impact
create impact surface
L: Select, M: Adjust Selection, R: Shuffle
(414244.197 ft, 1444939.82 ft)

Figure 7

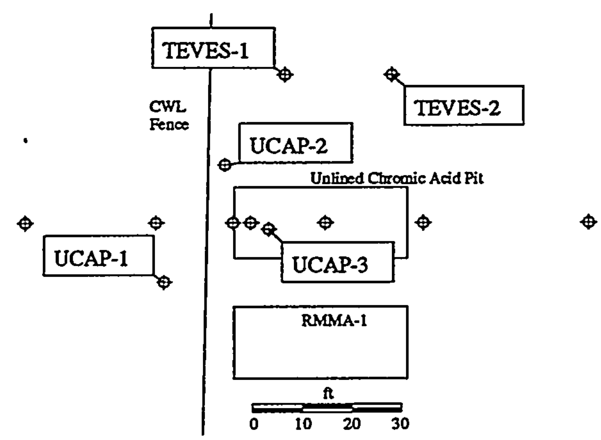
TEVES-1
TEVES-2
CWL
Fence
UCAP-2
Unlined Chromic Acid Pit
UCAP-1
UCAP-3
RMMA-1
ft
0
10
20
30

Figure 8

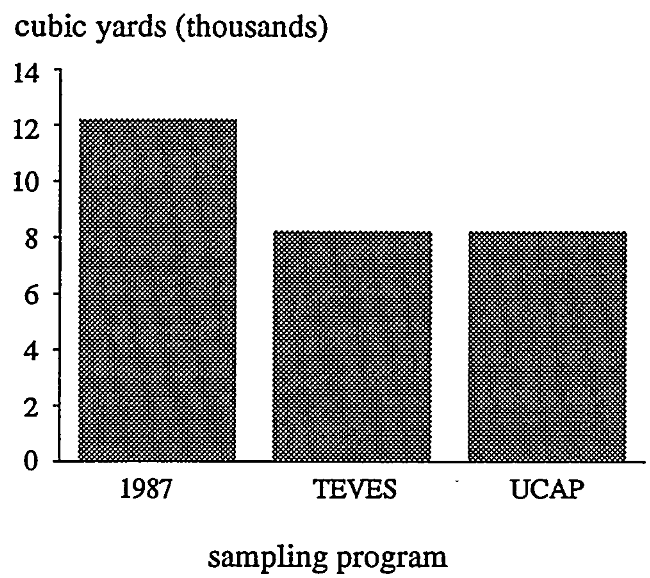
cubic yards (thousands)
14
12
10
8
6
4
2
0
1987
TEVES
UCAP
sampling program

Figure 9