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An Iterative, Probabilistic Environmental Decision Analysis Approach

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Abstract

In order to provide a more cost-effective and a more open decision making process for evaluating the safety of contaminated sites or proposed waste-management facilities, selecting appropriate remedial activities, as well as optimizing data collection and monitoring, Sandia National Laboratories is promoting a decision framework based on a form of probabilistic performance assessment. This framework is iterative and probabilistic allowing a connection between performance analysis and data collection. Additionally, the framework focuses all activities (regulatory analysis, technical analysis, information management, and data collection) on addressing the specified performance criteria, quantifies uncertainty in the decision, uses process based simulation techniques, and most importantly provides a platform where the process of assessing decision alternatives is transparent to all, and thus supports multi-party decision making (i.e., inclusive of all stake holders). The framework consists of a logical sequence of nine steps. Within the framework, decisions can be made based on acceptable levels of uncertainty in the decision or acceptable costs or both. The framework has been applied to a suite of different tasks with development, test application, and acceptance being supported by the Environmental Protection Agency (EPA), the Nuclear Regulatory Commission (NRC), and the Department of Energy (DOE). This paper discusses the basic framework and gives three examples of its implementation including: 1) development of a computer software system known as SEDSS, 2) evaluation of the performance of facility called the Greater Confinement Disposal (GCD) site in Nevada, and 3) development of a data collection optimization approach for remediating Dense Non-Aqueous Phase Liquids (DNAPLs) contamination. In all cases the general framework and underlying philosophical approach has been robust. Consequently, this approach is proposed as a generalized framework for environmental decision analysis.

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Introduction

The environmental industry is driven by the need to minimize costs while assuring regulatory compliance. However, for many environmental problems, we lack an understanding of both earth system and human health processes, or we have very poor information on how those processes operate at a particular place and time. To account for this uncertainty or lack of understanding, the various levels of environmental regulations are both intentionally and unintentionally designed to provide room for negotiation. Thus, gaining regulatory acceptance becomes a rather subjective process involving negotiation by regulators, responsible organizations, and other interested parties often supported by a suite of technical consultants. Magnifying the normal difficulties associated with such a negotiation are other problems such as an aversion on the part of the regulators to accept any risk of failure, poor communication, and inconsistent enforcement. The consequences of this complicated set of interpersonal and inter-organizational relationships often includes inequitable distribution of costs, an over-emphasis on legal issues rather than environmental clean-up solutions, and great effort expended toward very small environmental improvement.

Approaches for solving these problems have focused on bringing consistency to the documentation process (e.g., quality assurance for data, documentation steps for the Remedial Investigation / Feasibility Study process) and refining what is meant by regulatory compliance by establishing simple representative metrics (e.g., maximum concentration limits, dose limits).

Given that the physical/environmental conditions and the values of the various parties to one of these negotiations vary from site to site, the combination of documentation and simple blanket standards is inadequate. The missing component is a consistent process for performing the underlying technical analysis. Such a process must be *flexible* to accommodate varying perceptions of the uncertain environmental processes, *open* to allow all interested parties to view the details of the analysis, while at the same time being *rigid enough* to provide a consistent structure across multiple problems. We propose that such a method, founded on "probabilistic performance assessment," (Davis et al., 1990) exists and can be used to address a broad range of environmental problems.

Method

General Attributes

This approach provides several benefits. It: 1) minimizes the total cost of characterization and remediation by using probabilistic techniques to explicitly account for uncertainty, and by iterating between analysis and data collection; 2) incorporates a fundamental understanding of physical, biological and chemical processes through numerical simulation to minimize the need for monitoring data in order to estimate the extent of contamination and associated risks; and 3) supports the negotiation process, by providing a framework for evaluating different conceptualizations of the physical system and alternatives for action as well as making the assumptions, costs and conditions of each alternative explicit to all participants.

Framework

The methodology consists of nine steps (Figure 1) organized in a decision framework. The framework's goal is to define the type of information that must be generated and passed between steps. Any number of specific tools (conceptual or computer based) can be used to accomplish the tasks described for each step based on the question to be addressed and the physical system to be represented.

The steps of the framework include definition of the objective of the analysis and associated metrics (performance measures) to be used in assessing appropriateness of the proposed alternatives (step 1); compilation and review of existing data (step 2); development of a description, in the form of site assumptions or interpretations and their relationship to site data, for contamination sources, transport pathways, exposure pathways and human health or ecological consequences (also termed a conceptual model), selection of a numerical analysis technique and tools, and definition of probabilistic input parameters necessary to propagate uncertainty and perform the analysis (step 3); numerical analysis using the simulation techniques defined in step three and compilation of the results into a probabilistic answer (histogram, probability map, etc.)(step 4); comparison of the analysis from step four with the original performance measures (step 5). If the user is faced with an ambiguous answer the methodology continues, allowing the user to define a sensible course of action using tools to perform sensitivity analysis (step 6), and data worth (cost/benefit) functions to determine the value of additional data (step 7). If the user decides to characterize the site further (step 8), then additional information is gathered (as specified in the data worth step 7) (step 9). The act of collecting more data brings the user back through the iterative loop to the site conceptualization stage, where the new data is used to reduce the uncertainty in conceptual model assumptions or parameter values.

Description of the Framework Components

Performance Objectives

The performance objectives step includes three tasks. In the first step, one must specify the type of analysis, the decision options, and the criteria that will be used to select between options. For example, the U.S. Environmental Protection Agency (EPA) Superfund program (in dealing with abandoned hazardous contaminant sites) addresses three high end questions:

- Is the site safe ?
- If the site is not safe, what action should we take ?
- Once action is taken, when is it complete ?

Under Superfund regulations, one would perform several steps that effectively ask the first question. These include Hazard Indexing, Preliminary Analysis, and Baseline Risk Assessment. For each, the metric of safety is different and the analysis approaches vary. Thus, if we were performing the Baseline Risk Assessment within the EPA Superfund program, the type of analysis is a *safety or risk assessment*, the decision options are *safe* or *proceed to remediation*, and the metric, as defined by the EPA regulations, might be a threshold of *one in a million excess cancer deaths*. In a probabilistic approach, one must also define the level of probability of failure that is acceptable. Thus the metric might be stated as: *a site is unsafe if it has a 5% probability of exceeding the threshold of one in a million excess cancer deaths.*

Site Information

The initial analysis is always performed using existing information. In many cases this information includes not only previous field sampling, but also descriptions of previous site activities and chemical use, geologic/hydrologic data, detections of contamination, etc. This information may need to be compiled and the quality of the information evaluated. The compilation of data may include the use of electronic data bases and geographic information systems (GIS).

Conceptual Model Development

Conceptual model development requires an interpretation of data or development of a set of assumptions about contaminant sources, transport processes and pathways, exposure pathways, and the resulting consequences to human or ecological health. The uncertainty about pathways and processes (conceptual model uncertainty) as well as their controlling factors (parameter uncertainty) must also be defined. Thus, if more than one conceptual model is plausible or presented by an interested party, then each must be defined and evaluated through all steps of the decision framework to determine its validity and significance to evaluate conceptual model uncertainty. Once these descriptive models have been developed, and documented, a probabilistic numerical simulation technique must be selected that represents the suite of specified assumptions. Then, the necessary input parameters and their associated uncertainties to perform each analysis must be defined. To do this, each parameter is defined as a distribution from which individual values are extracted for each probabilistic simulation (parameter uncertainty).

Numerical Consequence Analysis

Numerical consequence analysis involves selecting input parameters values from the specified distributions, executing the simulation analysis multiple times, and compiling the resulting estimates of concentration, risk, or dose into some type of representative, empirical distribution. The definition of the conceptual model and selection of numerical techniques determines whether this requires a short or extremely long time and computational effort.

Uncertainty Decision Point

The fifth step, termed an uncertainty decision point, is simply an explicit comparison of the probabilistically defined performance measure with the results of the consequence analysis. Graphically this might be displayed as a histogram of simulation output compared with a performance measure threshold and a measure of the frequency with which the system exceeds that threshold. If the user or user group finds that the simulation results either greatly exceed the performance measure (site is unsafe) or are below the specified threshold (site is safe) then a decision can be made with confidence and the analysis is complete (Figure 2a). If the simulation results exceed the threshold with a slightly higher probability than is acceptable, then the process continues (Figure 2b).

Sensitivity Analysis

Within the framework described above, sensitivity analysis is identified as the next step. We define sensitivity analysis as a comparison of variations in input parameters with variations in the resulting output values over the previously defined distributions for each input. Techniques for performing this step include rank correlation or regression analysis on normalized input distributions. The purpose of this process is to identify those parameters which cause the greatest variance in estimates of the output based on current estimates of the input parameter distributions. The results of this analysis may help identify parameters for which collecting new data should be evaluated in the data worth step. It may be possible to by-pass this step and consider all combinations of changes to input data distributions, changes in engineering design, etc through the Data Worth step.

Determining the Value of New Data

Data worth involves specifying the options one might take relative to the original question (e.g., safe or not safe, selection of remedial options) and what data one might collect to further refine the confidence in a decision. Quantitative approaches to data worth primarily involve establishing a decision tree and assigning to the component branches of the tree, probabilities of that set of conditions occuring (either from the consequence analysis or a similar computation) and the cost that would accrue if that happens. In addition, if data collection or experimental work is part of the option, the likelihood that the field or laboratory work will yield useful information is a factor in the probability of conditions occuring. By compiling this information, one can determine the least cost, the highest probability of success, the least time consuming, or some combination of the above.

Cost Decision Point

The results of the data worth step (step 7) will show which of the various options, including whether to collect more data or to discontinue the analysis and accept the most conservative answer resulting from the uncertainty decision point, is most cost effective. Then a decision must be made as to which option to pursue.

Data Collection

If the process proceeds to step 9, data is collected or additional information is gathered from other sources depending on the value of that information as specified in the Data Worth step. This information is then added to the existing data compilation, initiating a new iteration of the steps of the framework.

Finally, this new data will be used to re-evaluate the conceptual model, numerical analysis techniques or input parameters. This results in either adjustments to the conceptual model or parameters or potentially eliminates individual conceptual models if several are being evaluated. The new conceptual model is then used in the consequence analysis and so forth until a decision is made due to acceptable uncertainty or it is not cost effective to proceed with the data collection activities.

Applications

Sandia Environmental Decision Support System (SEDSS)

This project is devoted to developing a specific set of tools to perform each step of the decision framework for a set of similar problems. Specifically, the methodology applies to the site safety, remedy selection, and closure steps of the U.S. EPA Superfund program (Webb et al. 1994), new waste management sites selection and licensing process for Low Level Nuclear Waste facilities regulated by the Nuclear Regulatory Commission (NRC) (Kozak et al., 1990) and clean-up of sites for the Department of Energy (DOE) Uranium Mill Tailings Remedial Action (UMTRA) program. Funding from these three sources has helped refine the generalized methodology with a focus on groundwater contamination.

Additionally, the tools defined in the methodology development are being integrated and made available on a computer in the form of a software system known as the SEDSS (Figure 3). Both methodology and software development, to date, have focused on the first five steps of the framework with particular emphasis on developing a generalized query structure for conceptual model development and mechanisms for linking the conceptual model to numerical models selected for the consequence analysis (e.g., flow and transport models). Also, development has focused on representing a single pathway connecting a contaminant source through groundwater to exposure through drinking water and finally human health risk. However, the computer architecture has been developed to provide a robust foundation for future development for a broad range of groundwater problems, other pathways, other exposure and risk calculations, and potentially other problems outside the environmental arena. The computer system is currently developed for a UNIX™ (SOLARIS 2.4™) operating system on a SUN™ workstation and requires MOTIF™ and a commercial object oriented data base called OBJECTSTORE™.

The system is designed for use by all participants in the regulatory process. Thus the SEDSS can be used by *regulators* for either application to specific sites or policy development, *site owners/operators* responsible for the analysis and implementation of remedies, *advocacy groups* interested in verifying the results of existing analyses or in developing other safety and remedy scenarios, along with *technical analysts* supporting each of the groups listed above.

Current work on the SEDSS project involves definition of the methodology for performing the sensitivity, data worth, and cost decision steps of the process. These component steps, which will complete the decision loop, are scheduled for completion by the end of September, 1996. In addition, transfer of the system to a personal computer based UNIX™ operating system will be completed soon. A transfer to a WINDOWS™ operating system is currently scheduled for fall of 1996. The SEDSS methodology and computer tool have been applied to hypothetical problems. However, in conjunction with beta testing of the first operational release of SEDSS (scheduled for early summer 1996), we will initiate field applications of the system.

Delineating Dense Non-Aqueous Phase Liquid (DNAPL) Contaminant Sources in the Subsurface

We are also currently engaged in applying our framework to the problem of locating DNAPLs in the subsurface. DNAPLs include such commonly used substances as chlorinated solvents, coal tars, etc. Release of these types of solvents and their migration through the subsurface have created pervasive groundwater contamination problems because of their ubiquitous use, their toxicity and persistence in the environment, combined with the difficulty of recovering them from the subsurface. Approximately 50% of the nation's Superfund sites are plagued by contamination by organic solvents.

Because DNAPLs (e.g., organic solvents) are more dense than water and immiscible with water, they migrate downward and laterally under the influence of gravity and capillary forces. Variations in soil texture that the solvents may encounter as they migrate can have a profound influence on the migration path. This interplay between gravity, capillarity and textural heterogeneities complicates the migration of the solvents and, therefore, it is not straightforward to predict the locations at which spilled solvents may ultimately reside in the aquifer. Uncertainties in the region of solvent contamination translate to higher remediation costs as the remedial system must be designed in light of these uncertainties. Additional site characterization can reduce these uncertainties, but additional characterization carries costs as well. The trick is to characterize only to the degree that it reduces overall cleanup costs (where overall cleanup costs include the cost of characterization and remediation).

We have developed an approach which follows the framework described above and which utilizes Monte Carlo simulation of subsurface material properties and solvent migration to suggest the best sampling locations for delineating where DNAPL may reside in the subsurface. In this approach, the goal is to identify the area, delineated by a certain degree of probability, that must be remediated and optimize the balance of characterization and remediation costs. The performance measure is the probability of detecting a residual DNAPL. To date we have applied the analysis process to hypothetical problems with simple site conceptual models. For, a single hypothetical case, multiple modeling realizations of possible solvent migration are generated and combined to form a probability map of location of DNAPL (consequence analysis). These realizations capture the physics of solvent movement through the geologic features controlling migration. In this way, our uncertainty about the distribution of geologic features and the disposal history at the site can be propagated through the modeling to reflect the degree of uncertainty in the extent of solvent contamination. No uncertainty based decision is made nor sensitivity analysis performed. It is assumed that the only parameter for which additional data can be obtained is the detection of DNAPL, and optimization of site characterization is driven by cost. Thus, a data worth analysis is the next step. The probability map, produced by the consequence analysis, is used as a basis for designing an optimized sampling scheme. The objective of the optimization is to reduce the uncertainty in estimates of the extent of contamination with the addition of as few sampling points as possible. Collection of that data, completes the steps of the framework and initiates a new iteration. Within each iteration, as additional data are collected, the probability map is updated to be consistent with the new data until a balance of cost for sampling verses reduction in cost for remediation is reached.

While much of this work has involved simulating the geologic media and modeling the physics of solvent migration through that media, a significant component of the work has involved applying decision tree techniques for evaluating data worth. This work builds on decision analysis in groundwater remediation first introduced in a collection of papers by Freeze and colleagues (Freeze et al., 1990). James and Gorelick (1994) employed a decision tree approach similar to ours in considering the worth of monitoring data in designing a pump-and-treat remediation system. As discussed earlier, our intent is to minimize the total cost of remediation and data collection. This is achieved by only collecting data which reduces uncertainty in the location of DNAPL sufficient to reduce cleanup costs by an amount that is equal to or greater than the sampling cost. We stop once uncertainty has been reduced sufficiently, or once the cost of data collection exceeds the reduced cost of remediation.

Within our overall framework of decision making, we have dealt here with a fairly narrowly defined problem. Our presumption is that decisions about site safety and remedial options have already been answered. Given these decisions, we consider the cost of implementing the selected remediation system given the uncertainty associated with the location of the solvent contamination in the subsurface. We have further simplified the analysis by assuming that the only useful sampling information is information on "hits" and "misses". (Any borehole drilled through the aquifer that encounters solvent is considered a hit.) A more sophisticated analysis would also consider the geologic information obtained from the borehole, but this was not possible for us given that the particular geologic simulator we used was not amenable to conditioning on available geologic information. Additionally, the data worth analysis might consider various remediation schemes, collection of data related to transport properties, and so forth.

A decision tree was used to calculate the utility of each possible sampling location in defining the extent of solvent contamination. Iteratively, we pick the location yielding the greatest overall benefit and update the probability map based on the result of the sampling (hit or miss). Figure 4a, shows the original probability map for a hypothetical problem before collection of additional data. Figure 4b, illustrates the reduction in areal extent of the possible solvent contaminated area after three sampling iterations. This process continues until the combined cost of characterization and remediation can no longer be reduced through additional sampling (i.e., the cost of an additional sample is expected to be more than expected reduction in cost of the remediation design resulting from a more highly defined area of contamination due to this additional data). The benefits of this approach are twofold: it improves sampling efficiency; and, it provides a well-defined endpoint to the characterization activities.

Greater Confinement Disposal (GCD) Project

The decision based approach is used in the GCD performance assessment to generate defensible and definitive results, to efficiently identify and prioritize site characterization data needs, and to incorporate new data in the analyses. To date, the process of evaluating multiple conceptual disposal designs and the minimization of characterization cost (data worth) components of the decision framework have not been utilized.

The Department of Energy contracted Sandia National laboratories in 1989 to assess the likelihood that the GCD facility would meet the containment and protection requirements in 40 CFR 191 (EPA, 1985). The GCD facility consists of thirteen, 36.6 meter deep, boreholes located at the Area 5 Radioactive Waste Management Site (RWMS), Nevada (Figure 5). Four of these boreholes contain transuranic wastes that are regulated under 40 CFR 191. The disposal system is configured with the bottom 15.2 meters filled with waste and the remainder of the borehole backfilled with native sediments. This configuration provides more than 21 meters of cover and places the waste approximately 198 meters above the water table.

The focus of the performance assessment analyses is estimating the probability and magnitude of the integrated release to the accessible environment over the next 10,000 years. The performance assessment analyses are conducted in an iterative fashion, following the decision framework described above, to efficiently identify significant uncertainties, prioritize data collection activities and incorporate new data in the analyses. The defensibility of the performance assessment is enhanced by evaluating all uncertainties. Incorporation of all the uncertainties provides a definitive result. The uncertainties fall into two categories: conceptual model uncertainty (including numerical model) and parameter uncertainty.

Conceptual model uncertainty is incorporated in the analysis using either multiple models of the system, or the most conservative model. Conservatism is invoked in order to simplify the analyses and maintain the defensibility of the results. The effect of parameter uncertainty on the results is analyzed using Monte Carlo simulations as part of the consequence analysis. Uncertainty in the future conditions is incorporated in the analyses using probability weighted scenarios. Processes and events with no consequence or insignificant probability of occurrence, as defined by the containment and protection requirements in 40 CFR 191, are eliminated from the analyses.

The first iteration of the performance assessment, completed in 1991, was a preliminary evaluation of the performance of the site given existing information about site condition (Price, et al., 1993). The first iteration was conducted to identify site characterization data needs and evaluate the uncertainty in the conceptual model to see if there was any possibility that the site would be in compliance with applicable regulations. It was concluded that the site was likely to meet the performance objectives under the existing conditions, but changes in the system, particularly increased recharge as a result of climate change, could impact the site's performance. The evaluation of the uncertainty in the conceptual model indicated that if the transport system is dominated by the diffusive transport of contaminants to the ground surface, it could result in significant releases of radionuclides to the accessible environment. Sensitivity analyses of the results of the preliminary assessment indicated that the recharge rate, plutonium solubility and plutonium sorption were the most important parameter uncertainties. As a result of the preliminary analyses site characterization data collection was initiated to determine the current recharge rate, site specific K_d and solubility estimate for the plutonium isotopes, and the response of the system to climate change. In this case, no specific data worth evaluation was performed.

The recharge studies were completed in 1994 (Tyler, et al., in press). Based on the results of natural tracer profiles in the unsaturated zone, it was concluded that there is no recharge under the existing climatic conditions. The distribution of chloride in the subsurface was used to infer recharge rates under past climatic conditions. As a result of the recharge studies, the conceptual model of the system changed and the system was represented using a diffusion dominated transport model. The second iteration of the performance assessment incorporated a more complex adsorption-diffusion model that includes the ability to simulate plant uptake of contaminants. Additionally, the model parameter values for the solubility and sorption of plutonium were revised based on site characterization data from the geochemical studies. The results of the second performance assessment iteration, after refinement of the transport models and parameter distributions, indicate that tortuosity is now the most important parameter. However, as the plant rooting depths increase, the model becomes less sensitive to tortuosity (Baer, et al., 1994). This is an important consideration in the third iteration of the performance assessment, because one of the consequences of returning to a cooler, wetter climate would be the growth of deep rooting plant species at the site (e.g., migration of pinion-juniper woodlands to the site).

The third iteration of the performance assessment is designed to evaluate the likelihood that the site will meet the performance objectives, given the uncertainty in future conditions at the site. Current activities include developing and implementing the consequence models of climate change, subsidence, drilling intrusion and irrigated agriculture. Other activities include revising the transport model to incorporate upward advection, refining the plant uptake model and updating the parameter uncertainties based on the results of site characterization activities.

Conclusions

The framework is versatile and the generalized approach has worked well for a suite of evaluations or as a foundation for evaluation tools including developing the SEDSS computer software system for evaluating site safety for EPA Superfund problems, NRC Low-Level Nuclear Waste facility siting, and UMTRA site remediation decisions; iteration through the performance assessment of the Greater Confinement Disposal Facility; and optimizing data collection for DNAPL problems. In particular, the SEDSS computer system makes a portion of these tools accessible for broad scale application. Development of both details of the process and computer tools to support individual steps continues.

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Decision Framework

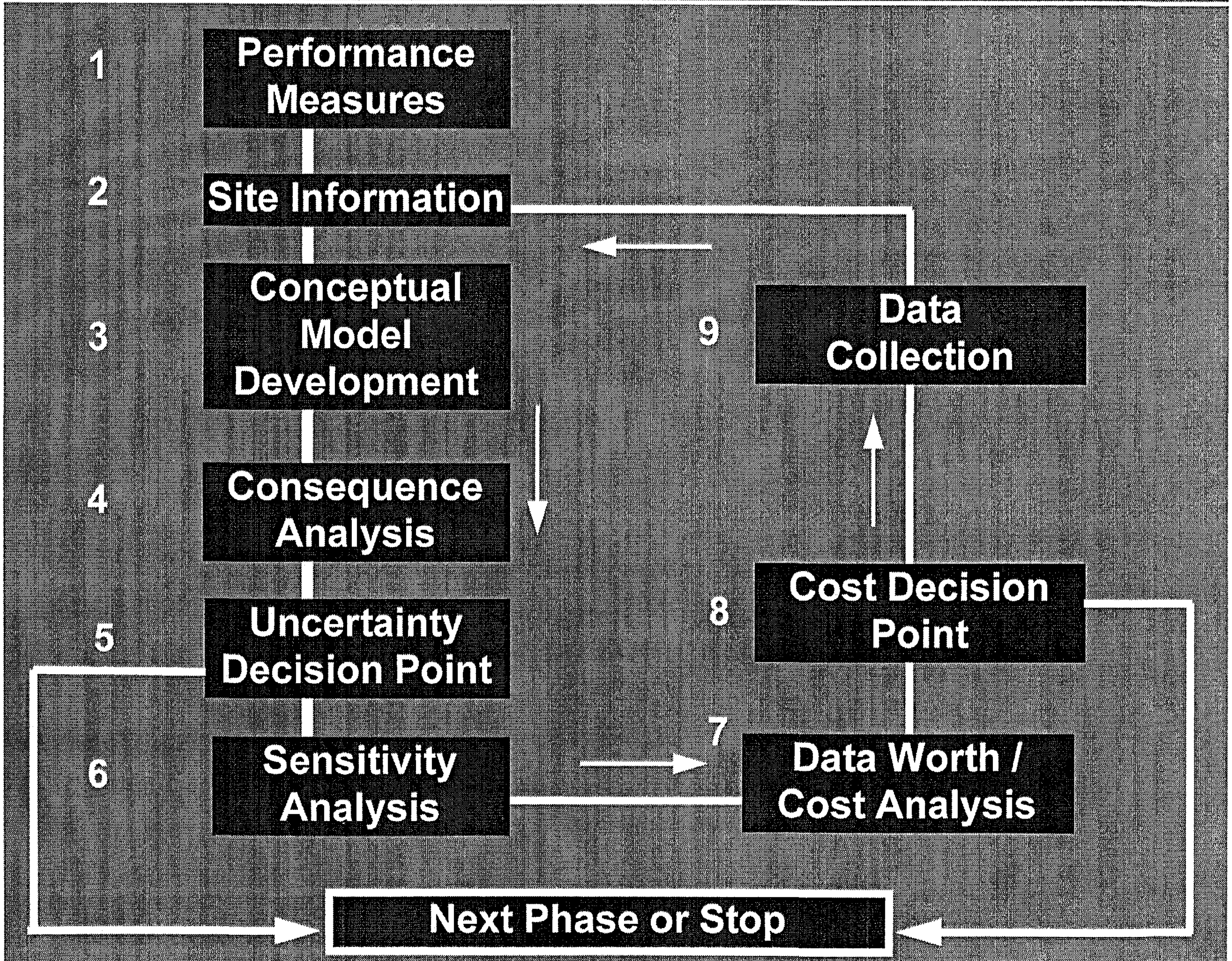
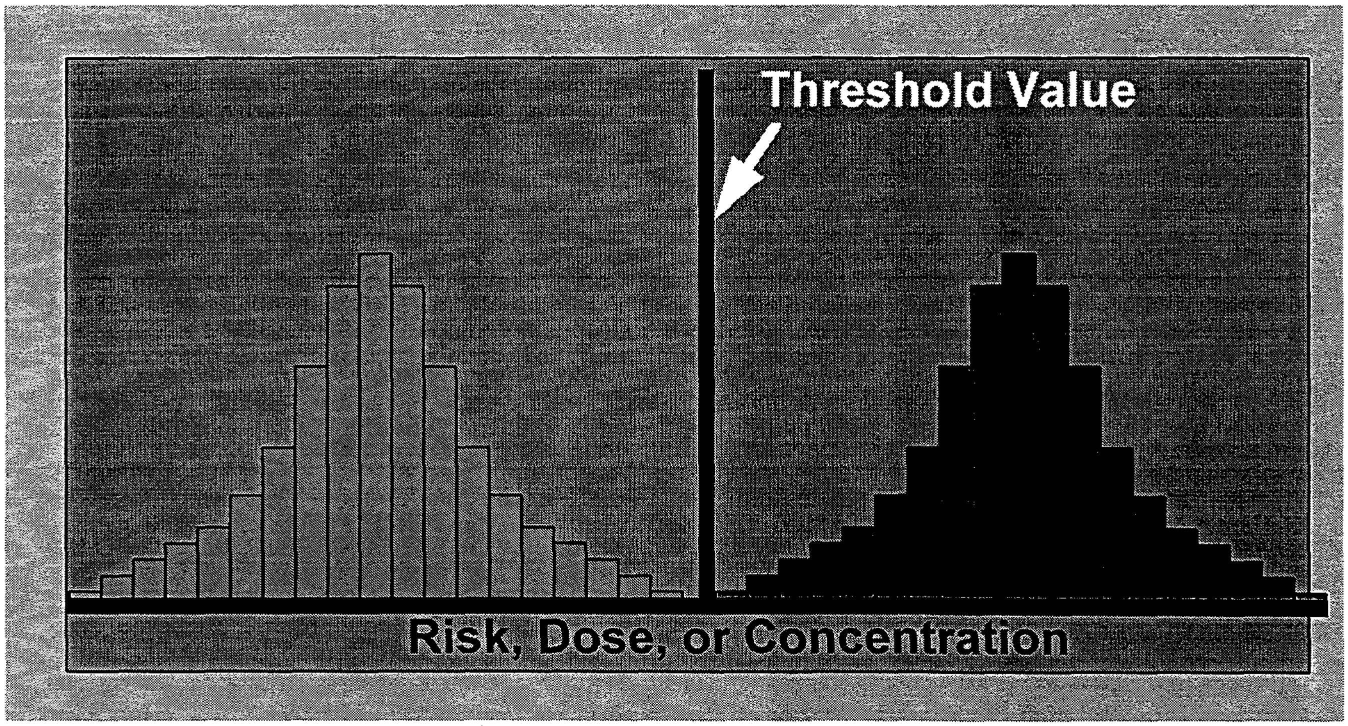
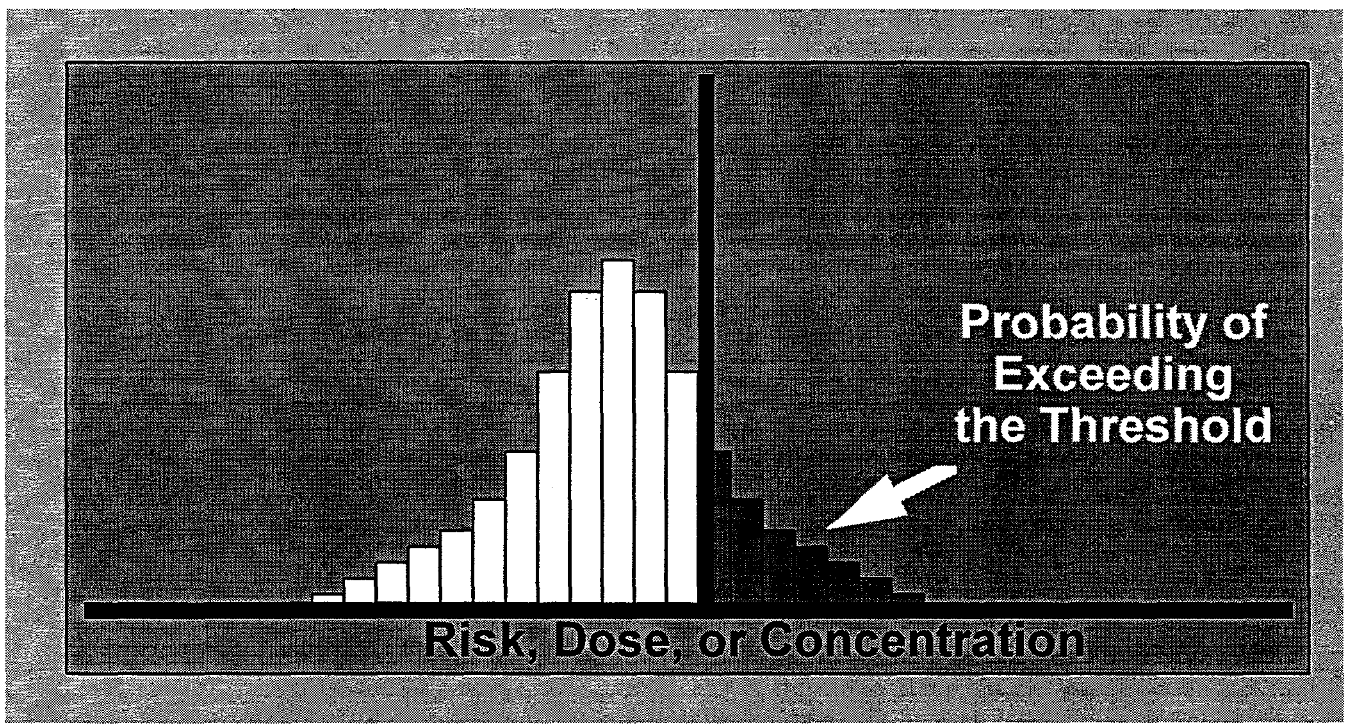


Fig 2



A. Unambiguous Results



B. Ambiguous Result

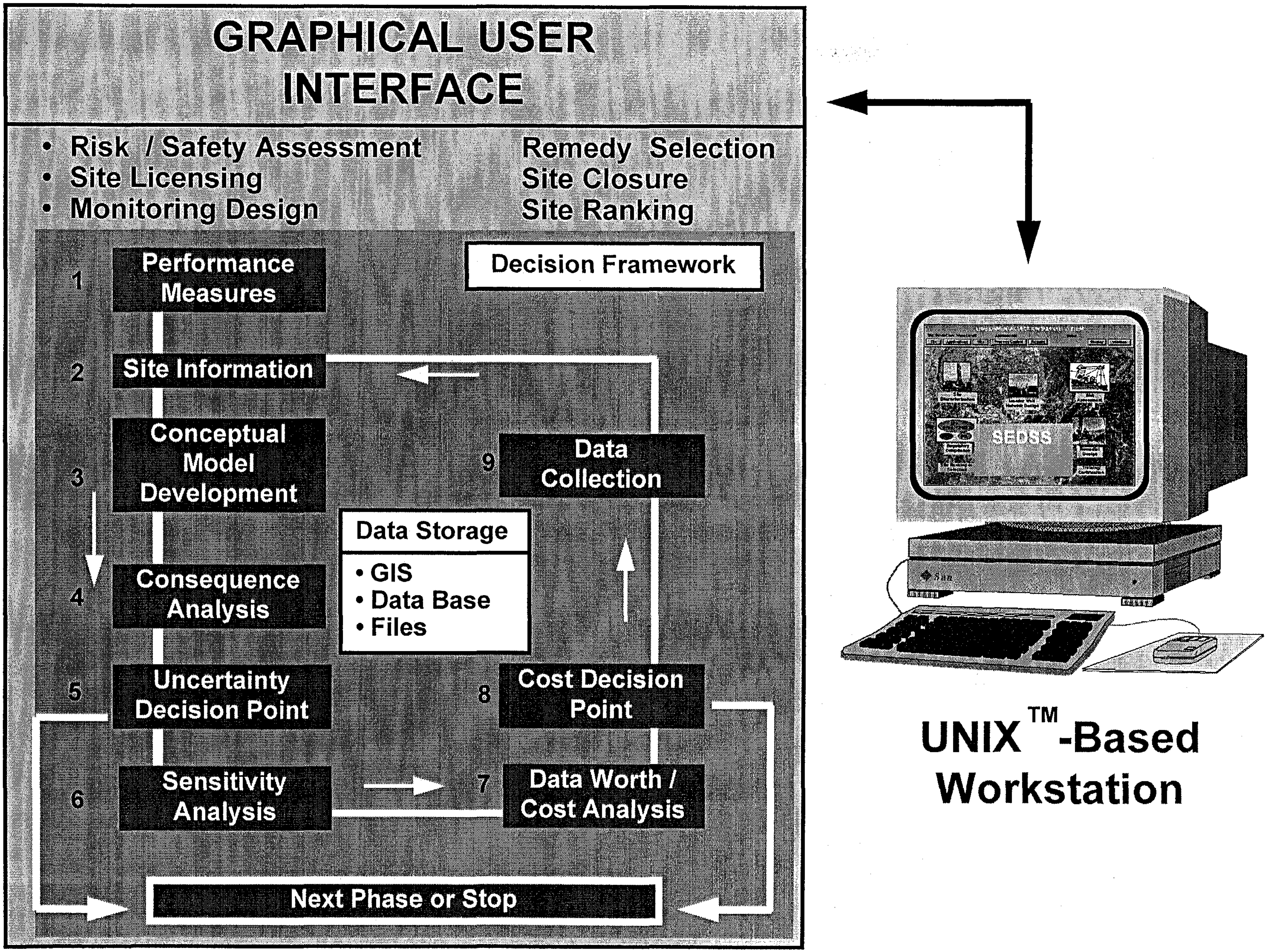
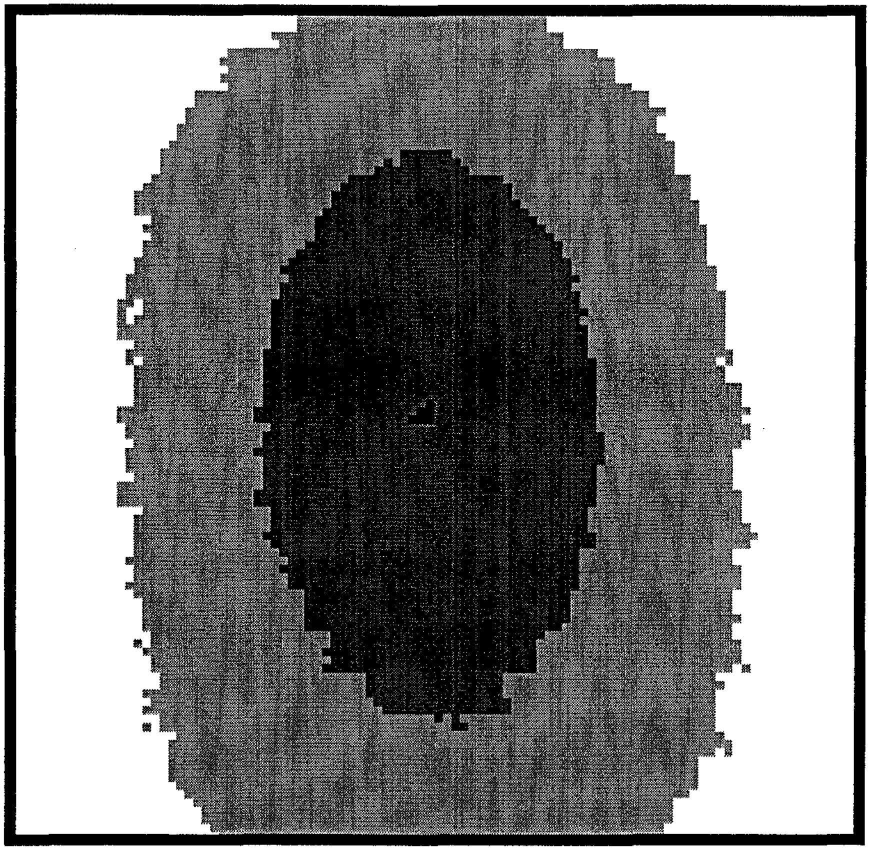
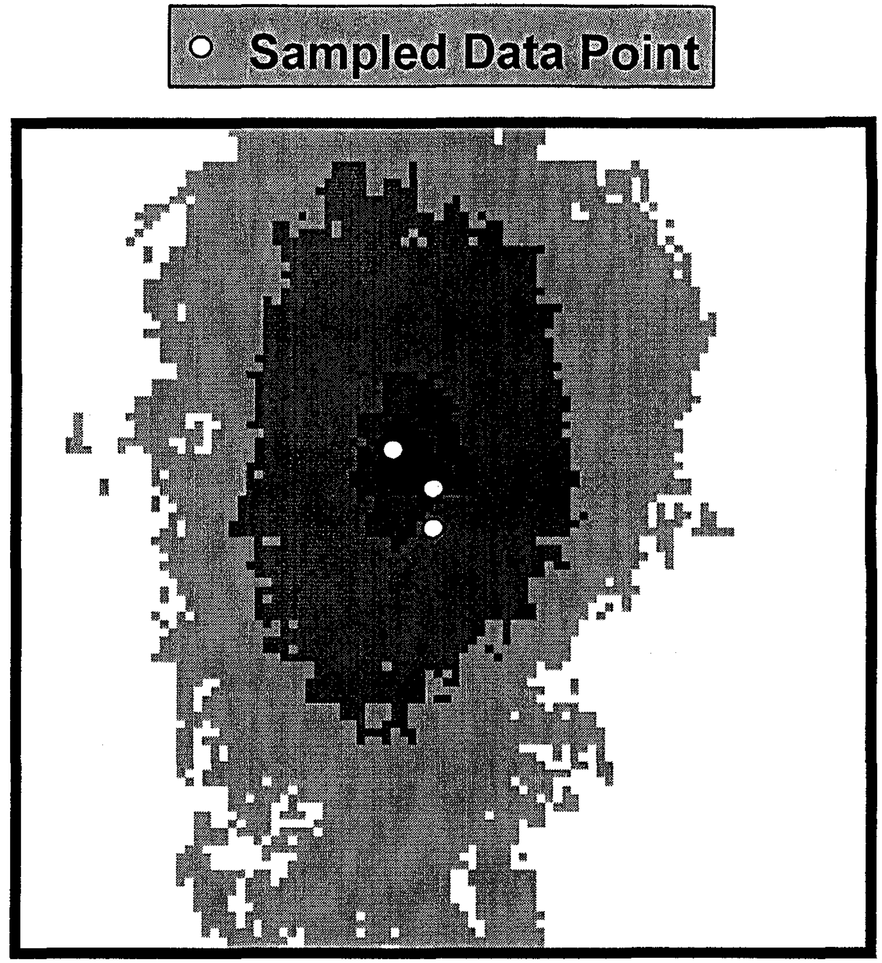

GRAPHICAL USER INTERFACE
• Risk / Safety Assessment
• Site Licensing
• Monitoring Design
Remedy Selection
Site Closure
Site Ranking
Decision Framework
1 Performance Measures
2 Site Information
3 Conceptual Model Development
4 Consequence Analysis
5 Uncertainty Decision Point
6 Sensitivity Analysis
7 Data Worth / Cost Analysis
8 Cost Decision Point
9 Data Collection
Data Storage
• GIS
• Data Base
• Files
Next Phase or Stop
SEDSS
UNIX™-Based Workstation

Fig 4



a.



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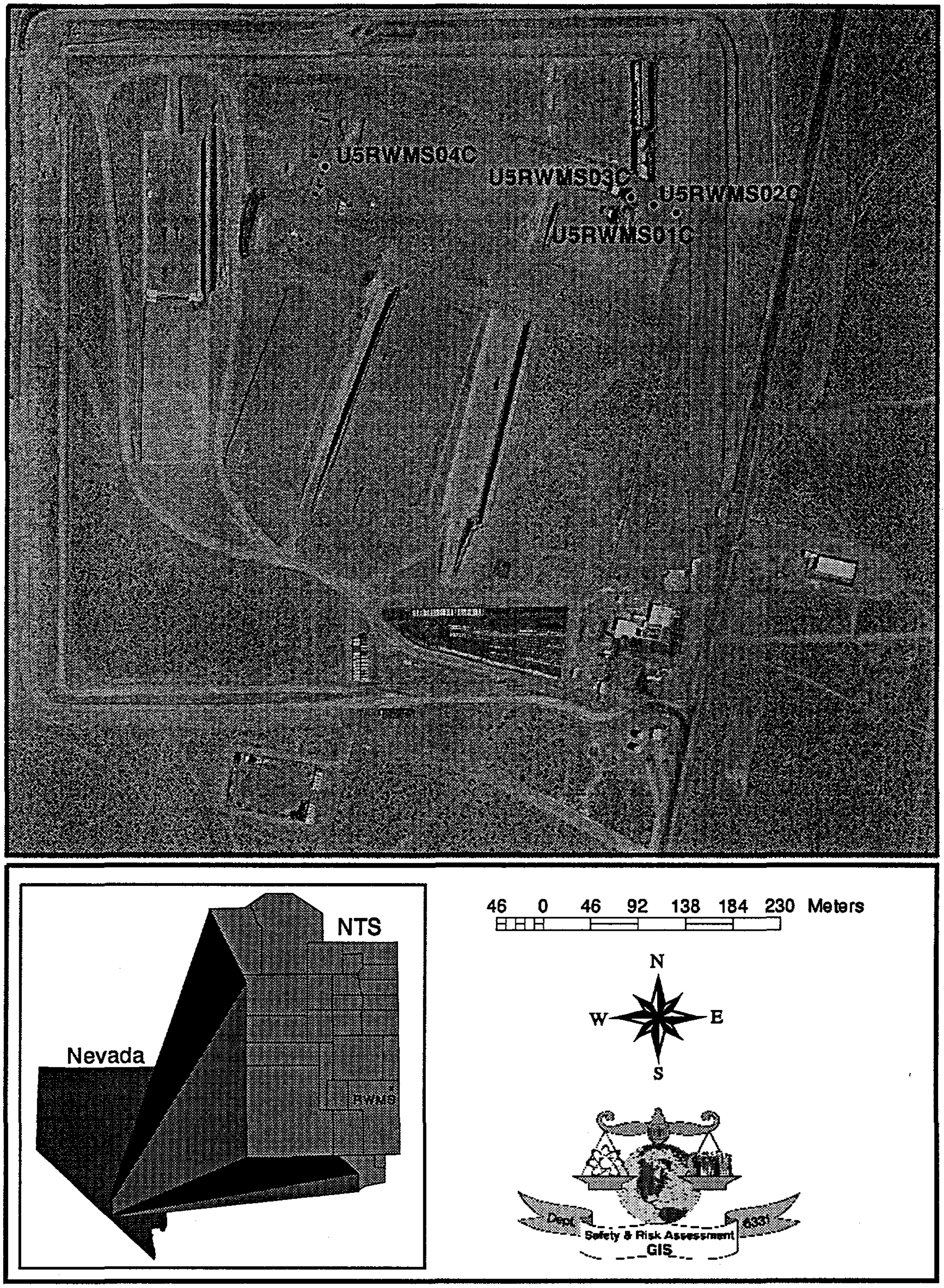
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