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A FRAMEWORK FOR EVALUATING INNOVATIVE STATISTICAL AND RISK ASSESSMENT TOOLS TO SOLVE ENVIRONMENTAL RESTORATION PROBLEMS

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1.0 INTRODUCTION

Environmental restoration activities at the U.S. Department of Energy (DOE) Hanford site face complex issues due to history of varied past contaminant disposal practices. Data collection and analysis required for site characterization, pathway modeling, and remediation selection decisions must deal with inherent uncertainties and unique problems associated with the restoration.

In the past, the data collection and risk analysis methods followed the path dictated by regulatory requirements, starting from the position of "prove that all imaginable contaminants aren't there," and "eliminate all risks to the population." Reality, limited budgets, and 10 years experience with the Environmental Protection Agency's (EPA) clean-up actions under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) are leading remediation specialists to reconsider the old approach. Among the lessons learned are that the clean-up process must be streamlined, the characterization effort and remediation needs must be integrated, and some level of residual risk will be present even at the conclusion of a successful clean-up. New approaches such as the observational approach (Myers and Gianti 1989) and data quality objectives (DQO) (Neptune 1990) are useful tools for bringing reality and efficiency into the clean-up process.

The observational approach suggests focusing only on probable conditions of contamination and treating uncertainties as reasonable deviations to be handled by contingency plans. Data are gathered only to the point sufficient to make a remediation decision. The DQO answer such questions as: What type and quality of data are needed to answer key questions and make key decisions? How much data is enough? DQO allow decisions to be based on data with a predetermined and acceptable level of confidence. Both approaches rely heavily on statistical concepts very familiar to risk assessors: expected conditions, quantifying uncertainties, accuracy and precision requirements, setting the level of Type I and Type II errors (false positive and false negative decision errors), explicitly identified probabilities, etc. Other aspects of the environmental restoration problem also draw heavily on statistical tools: sampling strategies, analysis variability analysis, experimental design, data interpretation, etc. A framework for working through the statistical aspects of the site characterization and remediation selection problems is needed. This framework would facilitate the selection of appropriate statistical tools for solving unique aspects of the environmental restoration problem.

This paper presents a framework for selecting appropriate statistical and risk assessment methods. The following points will be made: 1) pathway modelers and risk assessors often recognize that "some type" of statistical methods are required but don't work with statisticians on tools development in the early planning phases of the project; 2) statistical tools selection and development are problem-specific and often site-specific, further indicating a need for up-front involvement of statisticians; and 3) the right tool, applied in the right way can minimize sampling costs, get as much information as possible out of the data that does exist, provide consistency and defensibility for the results, and give structure and quantitative measures to decision risks and uncertainties.

2.0 THE FRAMEWORK

The framework described below has five steps. Step 1: designing and evaluating a remediation options matrix. Step 2: setting DQOs using the results of the options matrix evaluation. Step 3: designing and evaluating a statistical tools matrix. Step 4: using the results of the tools evaluation to collect data and conduct analyses. Step 5: incorporating the data and analyses from Step 4 back into the options matrix, and reiterating through the steps until a remediation decision can be made. Figure 1 is a flowchart of the activities in the step. Since this paper deals with statistical tools, Step 3 is the focus of our discussion.

Step 1: The Options Matrix

The selection of a remedial action under both CERCLA and Resource Conservation And Recovery Act (RCRA) Corrective Action follows a structured approach, starting with a conceptual model, then investigation and feasibility studies, leading to a preferred option for the remediation. Working through the options matrix helps identify this preferred remediation option.

Figure 2 shows an example of an options matrix where alternative remedial actions are evaluated against a list of criteria. A very short criteria list is shown here: health risk, ecological risk, schedule, and cost. An expanded list could include cultural impact, public acceptance, and land use impact. It is assumed that all options meet regulatory compliance. Other aspects such as economic impact and technical feasibility are included in cost and schedule. The example shown is for a simplified problem of buried waste. Options are to leave the waste where it is or retrieve it. A third option of deferring the decision is handled by the iterative approach in the framework. Variations on the two main remedial options are: 1) leave -- stabilize/contain the waste, treat it in situ; and 2) retrieve -- separate the waste and use less expensive treatment and disposal for cleaner wastes, treat it ex situ, and combinations thereof.

With the axes of the options matrix defined, the next task is evaluating the options relative to the criteria. This process can take years, often taking as long as there is money to fund the clean-up. The evaluation process is patterned after pathway modeling, starting with characterizing the contaminants on-site. The contaminant mix and concentration levels determine what options are viable, the health and ecological risks of each option, and the cost and schedule for each option. If the contaminants, their concentrations and locations are known, there are probably uncertainties as to how the various clean-up options will perform. Even if all of the above are known, there are undoubtedly disagreements over the criteria and the relative weights to be applied to them. Some options may perform well when evaluated against one set of criteria but poorly against another set. If one clean-up option is clearly dominated by another, it can be eliminated from further consideration.

In theory, output from Step 1 is a completed options matrix. The entries in the matrix can be binary (zeros and ones), ordinal (rankings), or cardinal (numerical scores). A more likely scenario is that the matrix cannot be completely filled out with the information that is available, and Step 1 results in a list of questions to be answered and a need for additional data. Before data is collected, objectives must be set for collecting and analyzing the data.

Step 2: Setting Data Quality Objectives (DQOs)

In setting Data Quality Objectives, the following questions are asked: What decisions need to be made? What data are required to make the decisions? What is a sufficient quantity and quality of data to meet pre-set levels for Type I and Type II decision errors? In addition to setting DQOs for data collection, this is the time to begin using the observational approach (Smyth and Quinn 1991) to identify probable conditions and reasonable deviations for the clean-up. The observational approach relies on current information and most likely assessments to narrow the range of options to evaluate. The DQOs can direct the observational approach by focusing on those options that meet the objectives of the clean-up.

Continuing with the buried waste example, suppose health risk data is missing for each of the options. The type of data required to complete the options matrix is the following:

1. **Option:** Do nothing
   Question: Will contaminant get into the drinking water?
   Data Required: Groundwater model predictions; sample well monitoring data.
   DQO Issue: Contaminate data accuracy required only to point of determining if drinking water standard has been exceeded.

2. **Option:** Transport off-site
   Question: What is maximum exposure to transportation worker?
   Data Required: Maximum hypothetical exposure time, probability of hot spots within truckload.
   DQO Issue: Only investigate 95th percentile (and beyond) of accident scenarios.

Step 3: Statistical Tools Matrix

The data and analysis needs from Step 1, directed by the objectives from Step 2, are used to define the type of statistical tools that are needed to make the site characterization determinations and remediation decisions. Figure 3 shows on the horizontal axis some of the data collection and analysis problems associated with environmental restoration. On the same axis are shown some of the innovative tools that can be used when these problems are present. A general laundrylist of issues and tools is presented here to give a flavor of the complexity of environmental restoration problems.

Issue 1: Boundary Conditions: Concern is often focused on the boundary of a land-fill area where contaminants can be released to the environment. Unique conditions associated with the boundary can override average conditions within the land-fill as it relates to remedial action. Special statistical tools applicable in determining boundary conditions deal with sensitivity in detecting differences, ability to override central tendencies and focus on exceptions, and quickly sensing that a shift in conditions has occurred. Some of the statistical tools applicable to boundary problems are: 1) experimental design, systematic sampling, sequential sampling for setting up experiments and sampling designs that can quickly detect changing conditions; 2) simulation to assess the ability of engineered barriers to inhibit releases to the environment over a range of hypothetical conditions; and 3) sensitivity analysis used with pathway analysis models to investigate the range of outcomes, finding under what conditions algorithms used in the models break down or lose accuracy (IAEA 1989).

Issue 2: Spatial Variability: Heterogeneity in general, whether it is over time, over space, or between units of buried waste such as debris in drums or boxes, causes a special set of problems. A small number of samples may be unrepresentative of the total population of contaminants. Costs may be prohibitive for collection of large numbers of samples. The two key parameters used to describe wastes, central tendency (mean) and dispersion (standard deviation), may not be sufficient to describe the wastes under conditions of variability. The full distribution probability density function (pdf) is often required. If insufficient historical or sampling data is available to generate an empirical pdf, it may be possible to use process information to infer a pdf. Some geostatistical techniques have been developed to address spatial variability. Also, visually displaying data using a geographical information system (GIS) can facilitate analysis of spatial data sets for communication, planning and analysis purposes. In some situations, analysis of variance (ANOVA), can be used to assess between- and within-variability of data sets and establish the degree of interaction among variables.

Issue 3: Less-Than Values: With increased sensitivity of measuring equipment, limits of detection for contaminants are being lowered. Determining if a contaminant is detectable above background is a key concern. Substituting a less-than value for an actual measurement, or eliminating extreme values (censored data sets) can lead to erroneous results for many statistical methods. Many times, categorical rather than quantitative analyses are required when the variables being considered are binary (contamination vs. no contamination) or ordinal (rankings). Special statistical methods must be used with censored data sets (Helsel 1990).

Issue 4: Non-normality: The distribution of natural phenomena data is rarely normal (Gaussian). The assumption of the familiar bell-shaped distribution required by many statistical tools (e.g., the familiar Student test for testing whether sample results indicate contamination above some limit) cannot be justified. Outliers, measurement insensitivity, measurement errors, can all contribute to violating the normality assumption. In such cases, non-parametric tests and methods can frequently be used (Gilbert, 1987), although these methods are not as familiar to regulators or practitioners.

Issue 5: Uncertainty: Decisions must be made taking into account the magnitude of the uncertainty in the data, the uncertainty in parameters used in pathway models, and the uncertainty in the formulations used to model natural processes. If the data and model predictions are highly uncertain, the probability of making the wrong decision can be large. Hence, there is a need to access uncertainties and to use that information in the decision-making process. The concepts "most likely, expected conditions, reasonable deviations, worst case, and interaction of errors" require some knowledge of the distribution associated with one or more variables. Empirical probability distributions must be estimated; confidence or tolerance intervals must be reported along with the point estimate of a variable. Statistical tools can be used to make such assessments if the assumptions upon which the tools are based are not violated by existing environmental conditions.

Issue 6: Hot Spots. Hot spots are a special case of spatial variability. Most buried wastes exhibit the potential for areas of very concentrated contamination or rare events, such as ordinance buried along with chemically hazardous wastes. Some sampling designs (e.g., triangular grids) have a greater probability of detecting the hot spots, but usually come with associated higher costs. DQOs are required to specify the confidence the decision makers requires, i.e., how willing he/she is to miss one of the hot spots. The statistician can assist with matching objectives to sampling designs and determining the type of test to use to detect hot spots. Gilbert (1987) gives nomographs for selecting the distance between samples located on a grid for the purpose of detecting hot spots.

Issue 7: Multiple Sources of Conflicting Data: Opposite of the "too little data" syndrome, the decision maker often is confronted by the problem of conflicting results. For example, historical records may show one type of contaminant buried at a location, sampling results may be inconclusive, remote sensing devices may indicate a second contaminant but have a very high and questionable detection limit, and prior modeling results may point to a third contaminant. Resolving discrepancies, establishing "best estimators," identifying relationships among variables, and finding correlations among the data values must be done within the context of the decision that must be made and how much confidence is required in the result. Bayesian analysis can be used with data that is obtained in stages, using the additional information gained in later stages to test prior assumptions (prior probabilities) in a backward logic approach (Mood, et. al. 1974). Discriminant analysis can be used with observational data to make assignments and discriminate among elements of a population (e.g., discriminate among waste types). Principal components and factor analysis can reduce the dimensionality of a problem (e.g., rather than deal with every chemical species and nuclide, reduce the problem to a few key ones) (Berenson, et. al. 1983). Many of these techniques have not been used in environmental restoration problems but with modification could be applied.

Issue 8: Trade-offs: How do you trade tax dollars today for health benefits for future generations? How do you trade increased risk for remediation workers against saving a habitat of some rare species? Utility functions can be used to reveal preferences, interpersonal utility comparisons can be made, and multiple attribute utility functions can be generated. However, these tools must be stylized to the environmental restoration problem before they can be applied directly.

The tools of decision analysis--decision trees, influence diagrams, trade-off matrices, utility functions, and multi-attribute utility functions -- require input. The input -- probabilities on the states of nature, possible outcomes, decision alternatives, and lottery results--require a familiarity with rules of probability. The statistician can assist in developing the consistent and defensible probability distributions assigned to outcomes that are the key to the successful application of these decision tools (Chamberlain 1991).

Site characterizations and pathway models may not have all of the issues presented above associated with them. Further, many statistical tools are not applicable to a situation given the nature of the data and the hesitancy of the restoration manager to make assumptions and/or accept stated decision risks. The discussion demonstrates there is a need to identify the issues that may be encountered and the statistical tools to address them early in the planning process in order to have the tools available and validated at the time data collection is planned.

Once the horizontal axis of the tools matrix is established, the vertical axis that lists the criteria for evaluating the tools needs to be identified. Five criteria are shown in Figure 2: robustness, amount of data required to implement the tool, sensitivity of the tool to outlying data points, whether the tool has been demonstrated/validated/benchmarked, and whether the tool is fully developed and functional. Tools are evaluated against a set of criteria to select the right tool for the right job. Not every statistical tool can or should be used for a particular environmental problem.

- Robustness - Does the tool perform well under the conditions present at the restoration site? Do the algorithms break down under special conditions such as values close to zero, large variability, correlated variables, non-linearity, disjoint data sets? Do the tools provide the same answer using similar data? Does a transformation of the data cause problems? Many of the environmental problems have unique aspects (interacting effects, measurement errors, compounding errors), and the tools to be applied must be able to handle the full range of contingencies.

- <u>Data Requirements</u> - Some tools require significant amounts of data before they can be applied. Other tools can become reasonably accurate with minimal data sets, or can be designed to quickly converge to an answer. For example, exponential smoothing for forecasting heavily weights more recent observations thus minimizing the effect of historically unreliable data. Sequential sampling can minimize sampling costs since it ends sample collection as soon as a decision can be reached.

- <u>Sensitive to Outliers</u> - Extreme values can cause problems for some statistical tools. Other tools can quickly recognize the difference between major shifts and the influence of only one or two extreme observations. For example, the mean can be affected by one or two extreme values, whereas the median is not. Tools that use ranks rather than quantitative values are usually better in situations when outliers are prevalent.

- <u>Demonstrated</u> - Many statistical tools look good on paper but have not been validated or benchmarked against field data. Complicated process models that predict concentrations of a contaminant at points in time and place may be quickly invalidated once sampling begins.

- <u>Developed</u> - Many tools have not beend modified or adopted to handle the unique conditions of environmental restoration. Tool development should be included in the planning phases of an environmental restoration.

Evaluating tools relative to a set of criteria, i.e., filling in the tools matrix can be done on an absolute level (each tool given a numerical evaluation) or a relative basis (each tools receives a "good" or "bad" evaluation). Applying some of the criteria requires some knowledge of expected site conditions (e.g., data availability, outliers). The primary benefit of filling out the tools matrix is to quickly eliminate some tools from consideration, and arrive upon a short list of tools that can be given further consideration. The effort of evaluating the tools relative to the criteria can benefit the analyst in fully understanding the capability of possible tools and understanding site conditions.

The output of Step 3 is a set of tools to be applied, considering the DQO objectives and from Step 2.

<u>Step 4: Application of Tools</u>

In Step 4, the selected tools are applied and the results are analyzed following the tenets of DQOs and the observational approach. Many times, this step involves sample collection for characterizing a site -- determining the contaminants that are present, their concentrations and locations. Other times, if data are already available, this step may consist of a test of a hypothesis that contamination is present at some level. The data and analyses from Step 4 are used to answer the questions posed from trying to fill in the options matrix: the cost for cleaning up a site depends on what contaminants are there; the health risks for an option depend on the probability the contaminant will reach a populated area before remediation can begin. The application of the statistical tools provides the expected values, range of outcomes, and probability estimates to evaluate the options relative to criteria (cost, schedule, health and ecological risk) from the options matrix.

Step 5: Iteration of Steps 1 Through 4

Tools are not applied in isolation but rather in an integrated fashion. Sometimes they are used in parallel, other times sequentially, but always they are applied with the DQOs in mind. The application of one set of tools may provide some of the answers required to make a selection among remediation alternatives. These answers often lead to more questions as to how an option will fare under a refined set of criteria. Thus, there is an iteration through steps 1 through 4. Each time the analyst works through the options matrix, more options are eliminated, and more options are clearly dominated by other. Each time a candidate set of options is identified, the DQO questions must be asked: What data are required to select among the options? What quality of data is required to gain the confidence in the decision? Each time the DQOs are established, the tools necessary to obtain the data, analyze the data, and put it in a decision framework must be selected and applied again and again. The iteration stops when a decision can be made and its level of confidence quantified and accepted.

3.0 CONCLUSIONS

This paper has made the following points. Pathway modelers and risk assessors often refer to statistical methods but don't include tools selection in the early planning phases of the project. Statistical tools selection and development are problem-specific and often site-specific. The right tool, applied in the right way can minimize sampling costs, get as much information as possible out of the data that does exist, provide consistency and defensibility for the results, and give structure and quantitative measures to decision risks and uncertainties.

A framework for selecting and applying the right tools consists of developing an options matrix for evaluating a set of potential remediation options. Knowing these options and setting objectives for the quality of the data to be collected, a statistical tools matrix for tools selection can be developed. Applying the tools and iterating through the steps in the framework allows the remediation project manager to make a decision, at a quantifiable risk level, and be able to statistically defend the decision.

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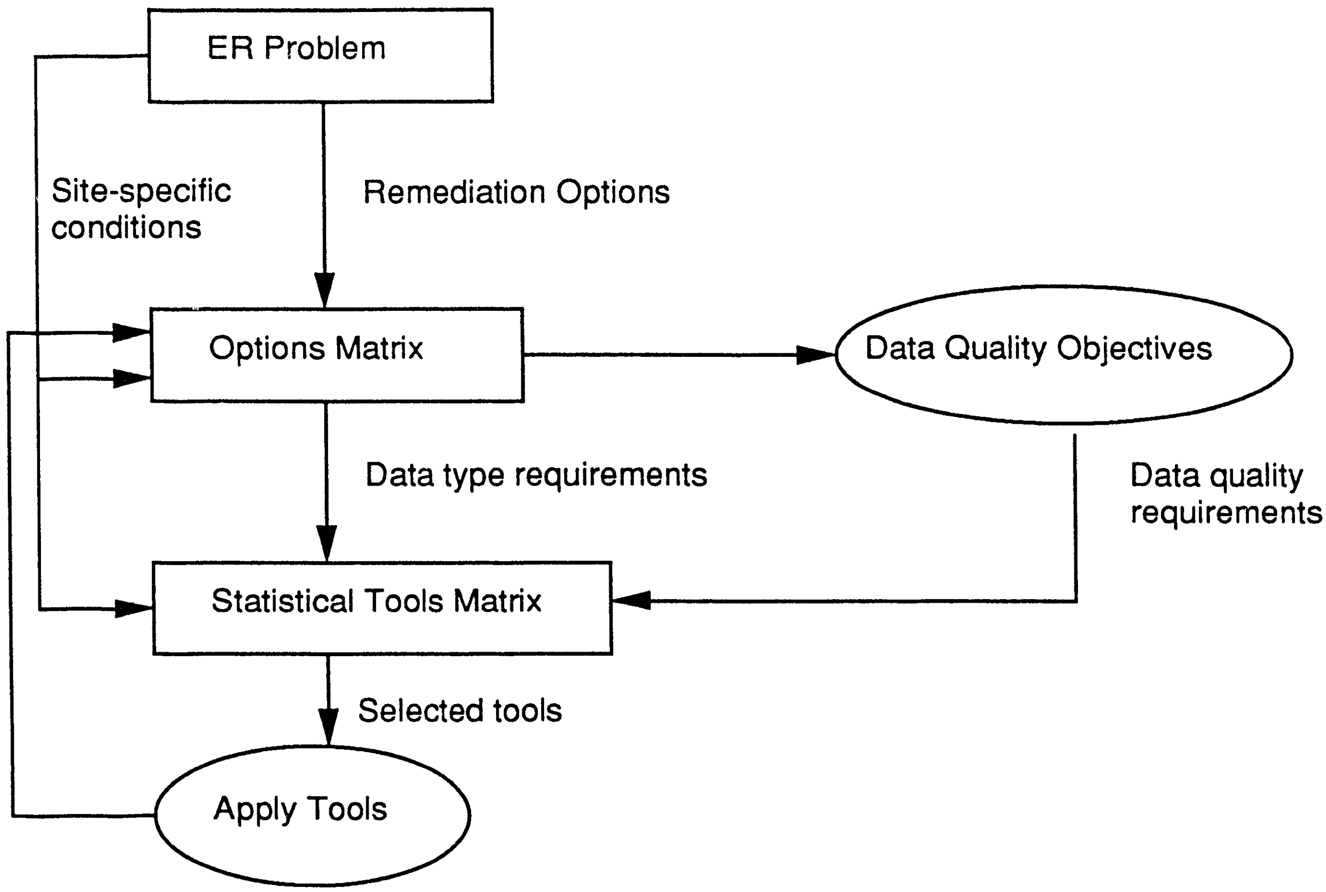

Figure 1. Framework for Environmental Restoration Tools Selection

Options / Criteria	Leave			Retrieve		
	Do Nothing	Stabilize/ Contain	Treat In Situ	Transport off-site	Separate	Remove/ treat on-site
Cost						
Schedule						
Health Risk						
Ecological Risk						

Figure 2. Remediation Options Matrix

Aspects of Problem/	Boundary Cond	Spatial Var.	Less-than-Values	Non-normal	Un-certainty	Hot Spots	Multiple Sources of Conflicting Data	Trade-offs
Tools / **Criteria**	Syst. Design Expr.Design Seq. Sampling	ANOVA Geo Stat GIS	Methods for Censored data Categ. Analysis	Non-Param. Stat	Empirical Prob. Dist Confidence Int.	Sampling Tech., H_0 Testing	Bayesian Analysis Modelling	MUA Decision Analysis
Robust								
Data Reqt								
Sensitive to Outliers								
Demonstrated								
Developed								

Figure 3. Statistical Tools Matrix

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