NUREG/CR-6948, Vol. 1

Integrated Ground-Water Monitoring Strategy for NRC-Licensed Facilities and Sites: Logic, Strategic Approach and Discussion

Advanced Environmental
Solutions, LLC

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555-0001

AVAILABILITY OF REFERENCE MATERIALS IN NRC PUBLICATIONS

NRC Reference Material

As of November 1999, you may electronically access NUREG-series publications and other NRC records at NRC's Public Electronic Reading Room at http://www.nrc.gov/reading-rm.html. Publicly released records include, to name a few, NUREG-series publications; *Federal Register* notices; applicant, licensee, and vendor documents and correspondence; NRC correspondence and internal memoranda; bulletins and information notices; inspection and investigative reports; licensee event reports; and Commission papers and their attachments.

NRC publications in the NUREG series, NRC regulations, and *Title 10, Energy*, in the Code of *Federal Regulations* may also be purchased from one of these two sources.

1. The Superintendent of Documents
   U.S. Government Printing Office
   Mail Stop SSOP
   Washington, DC 20402–0001
   Internet: bookstore.gpo.gov
   Telephone: 202-512-1800
   Fax: 202-512-2250
2. The National Technical Information Service
   Springfield, VA 22161–0002
   www.ntis.gov
   1–800–553–6847 or, locally, 703–605–6000

A single copy of each NRC draft report for comment is available free, to the extent of supply, upon written request as follows:

Address: U.S. Nuclear Regulatory Commission
Office of Administration
Mail, Distribution and Messenger Team
Washington, DC 20555-0001
E-mail: DISTRIBUTION@nrc.gov
Facsimile: 301–415–2289

Some publications in the NUREG series that are posted at NRC's Web site address http://www.nrc.gov/reading-rm/doc-collections/nuregs are updated periodically and may differ from the last printed version. Although references to material found on a Web site bear the date the material was accessed, the material available on the date cited may subsequently be removed from the site.

Non-NRC Reference Material

Documents available from public and special technical libraries include all open literature items, such as books, journal articles, and transactions, *Federal Register* notices, Federal and State legislation, and congressional reports. Such documents as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings may be purchased from their sponsoring organization.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at—

The NRC Technical Library
Two White Flint North
11545 Rockville Pike
Rockville, MD 20852–2738

These standards are available in the library for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from—

American National Standards Institute
11 West 42nd Street
New York, NY 10036–8002
www.ansi.org
212–642–4900

Legally binding regulatory requirements are stated only in laws; NRC regulations; licenses, including technical specifications; or orders, not in NUREG-series publications. The views expressed in contractor-prepared publications in this series are not necessarily those of the NRC.

The NUREG series comprises (1) technical and administrative reports and books prepared by the staff (NUREG–XXXX) or agency contractors (NUREG/CR–XXXX), (2) proceedings of conferences (NUREG/CP–XXXX), (3) reports resulting from international agreements (NUREG/IA–XXXX), (4) brochures (NUREG/BR–XXXX), and (5) compilations of legal decisions and orders of the Commission and Atomic and Safety Licensing Boards and of Directors' decisions under Section 2.206 of NRC's regulations (NUREG–0750).

NUREG/CR-6948, Vol. 1

Integrated Ground-Water Monitoring Strategy for NRC-Licensed Facilities and Sites: Logic, Strategic Approach and Discussion

Manuscript Completed: August 2007
Date Published: November 2007

Prepared by
V. Price, T. Temples, J. Tauxe, R. Hodges, R. Falta

Advanced Environmental Solutions, LLC
407 West Main Street
Lexington, SC 29072

T.J. Nicholson, NRC Project Manager

Prepared for
Division of Fuel, Engineering and Radiological Research
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
NRC Job Code Y6020

ABSTRACT

This document presents a logical framework for assessing what, how, where and when to monitor underground water in order to ensure that a licensed nuclear site or facility is behaving within the expected limits as described by the performance assessment. The Strategy is implemented as an iterative process beginning with analysis of any existing site and facility characterization and monitoring data, any existing conceptual site model (CSM), in this case generally a hydrogeologic model, and any existing risk assessment or PA model. The iterative nature of the Strategy results in a graded approach to development or evaluation of a monitoring program. Through analysis, an initial assessment of what, how, when, and where to monitor to evaluate system performance is made. Performance Indicators include chemicals, hydrogeologic attributes, and other features, events, or processes (FEPs) that may significantly influence contaminant flow and transport. These PIs may be directly measurable in a monitoring program or may be derived from compilations and interpretations of data. The integrated strategy benefits are:

- Characterization allows development of CSM;
- CSM allows modeling / simulation;
- Modeling allows prediction;
- Monitoring allows refinement;
- Refinement allows confidence.

Paperwork Reduction Act Statement

Public Protection Notification

FOREWORD

This research report was prepared by Advanced Environmental Solutions, LLC (AES), under a commercial research contract (NRC-04-03-061) with the U.S. Nuclear Regulatory Commission (NRC). As such, this two-volume report presents a logical framework for assessing what, when, where, and how to monitor with regard to subsurface ground-water flow and transport, in order to ensure that the environs of a licensed nuclear site or facility behave within the expected limits, as prescribed by the performance assessment (PA).

Volume 1 provides the logic, strategic approach, and examples of how to integrate ground-water monitoring with modeling. Specifically, the integrated ground-water monitoring strategy is implemented in an iterative manner, beginning with analysis of any existing site and facility characterization and monitoring data and the relevant conceptual site model (CSM), hydrogeologic model, and/or risk assessment or PA model. The iterative nature of this strategy provides a graded approach for use in developing or evaluating a ground-water monitoring program. In so doing, the analyst derives an initial assessment of what, when, where, and how to monitor to evaluate system performance. The monitoring is then integrated with modeling through the identification, measurement, and analysis of performance indicators (PIs). These PIs include hydrogeologic conditions and process attributes; chemical conditions and constituents; and other features, events, or processes (FEPs) that may significantly influence contaminant flow and transport. As such, PIs may be directly measurable using a monitoring program, or may be derived from compilations and interpretations of geophysical or other indirect data. This integrated ground-water monitoring and modeling strategy offers the following benefits:

- Characterization allows the development of a CSM.
- The CSM allows modeling and/or numerical simulation.
- Modeling allows prediction of system behavior, while monitoring allows refinement of models.
- Refinement supports confidence in the performance assessment, as well as the need for (and selection of) remediation approaches in the event of a contaminant release.

Volume 2 presents practical examples of the applications of this strategy, which provide practical means of testing, evaluating, and improving both the ground-water monitoring program and its related model. Although the strategy and its applications were originally planned for decommissioning sites, they are also very useful for assessing ground-water monitoring programs, remediating ground water, and identifying and selecting approaches to preclude offsite migration of abnormal radionuclide releases at nuclear facilities.

This approach is consistent with the NRC's strategic performance goal of making the agency's activities and decisions more effective, efficient, realistic, and timely by characterizing and monitoring radionuclide transport in ground water. Toward that end, this report demonstrates, using examples relevant to nuclear facility performance, that ground-water monitoring and modeling can be integrated within a systems approach. This information will assist NRC licensing staff and regional inspectors, Agreement State regulators, and licensees in their decision-making by promoting a greater understanding of ground-water monitoring concepts that relate to PA models. Nonetheless, this report is not a substitute for NRC regulations, and compliance is not required. Consequently, the approaches and methods described in this report are provided for information only, and publication of this report does not necessarily constitute NRC approval or agreement with the information contained herein. Similarly, use of product or trade names in this report is intended for identification purposes only, and does not constitute endorsement by either the NRC or AES.

Christiana Lui, Director
Division of Risk Analysis
Office of Nuclear Regulatory Research

EXECUTIVE SUMMARY

U.S. Nuclear Regulatory Commission regulations are designed so that licensees minimize risks associated with nuclear waste and facility decommissioning sites. The subject of this report is a strategy for understanding an important component of that overall risk -- the component associated with exposure to contamination through ground water. Application of the strategy will confirm site performance, reduce uncertainty in long-term predictions about site behavior or risk, and will permit communication of these predictions to all stakeholders. Fundamentally, the strategy is to use a CSM as the focus for evaluating and interpreting ground-water monitoring data and processing those data to infer ground-water conditions. In essence, all information concerning (or affecting) ground-water flow and contaminant transport is contained (institutionalized) in the CSM. Thus, future predictions made using the CSM always are based on the entirety of the available information and its best interpretation into the CSM.

More specifically, this document recommends an integrated and systematic approach for monitoring subsurface water flow and contaminant transport to test and confirm Performance Assessments, or their functional equivalents. We call this approach “Performance Confirmation Monitoring”. Traditional monitoring to determine compliance with ground-water protection regulations is a mature field rich in technology, data interpretation methods, design optimization studies, and case histories. Much of the technology can be applied to performance confirmation monitoring, but the basic philosophy behind the design of monitoring networks and of data interpretation for performance confirmation is different from compliance monitoring.

Interpretation of ground water data relies fundamentally on the development and testing of a Conceptual Site Model (CSM). However complex the site geology may be, rocks and their structural, stratigraphic, sedimentologic, weathering features and hydrologic and chemical properties can be understood in the context of well known geological processes. Use of geologic understanding and models to illuminate site characterization and monitoring is critical to develop conceptual site models. The CSM is developed initially from site characterization data, and then refined through an iterative process of modeling and monitoring.

Reduction of model uncertainty may require additional site characterization, or it might simply mean a different approach to data analysis is required. Features could include, but are not limited to intrinsic site characteristics, flux of water, concentrations of contaminants or indicator parameters.

Monitoring might include traditional monitoring or geophysical methods, measurement of moisture distributions, and collection and analysis of environmental samples. The point is that compliance with ground water protection standards is not the goal of performance confirmation monitoring, but rather refinement of the concepts and data used to understand site performance and to develop and support a performance assessment in which the aggregate effects of many factors are evaluated.

Evaluating performance indicators and establishing their data quality objectives are important parts of this strategy. Decisions are made on what, how, where, and when data should be collected through the evaluation of the performance assessment and the development of data quality objectives as well as conceptual and computer modeling. This can allow informed decisions to be made before wells are drilled or monitoring devices installed, leading to a reliable, efficient, and cost effective monitoring network design. The integrated monitoring approach can increase the efficiency of the monitoring system, both in terms of data quality and savings realized by selecting the critical monitoring points, adequate frequency, and time period.

CONTENTS

FIGURES

TABLES

ACRONYMS

ACAP	EPA’s Alternative Cover Assessment Program
AES	Advanced Environmental Solutions, LLC
ALARA	As Low As Reasonable Achievable
ASTM	American Society of for Testing and Materials
BMA	Bayesian model averaging
CFM	conceptual facility model
CFR	Code of Federal Regulations
CMP	critical monitoring point
COC	constituent/chemical/contaminant of concern
CSM	conceptual site model
DMS	data management system
DOE	United States Department of Energy
DQO	data quality objective
DSI	Derived System Indicators
EIS	Environmental Impact Statement
EM	expectation-maximization
EPA	United States Environmental Protection Agency
ET	evapotranspiration
FEPs	features, events, and processes
GIS	geographic information system
GMS	Groundwater Modeling System
IAEA	International Atomic Energy Agency
INEEL	Idaho National Environmental Engineering Laboratory
INL	Idaho National Laboratory – formerly known as INEEL and INEL.
KIC	Kashyap Information Criterion
LLW	low level radioactive waste
LTP	License Termination Plan
MBO	Management by Objectives
MCL	maximum concentration limit
MLBMA	maximum likelihood Bayesian model averaging
MLE	maximum likelihood estimation
MP	monitoring point
NEA	Nuclear Energy Agency
NORM	naturally-occurring radioactive material
NPL	National Priority List
NRC	Nuclear Regulatory Commission
NVLAP	National Voluntary Laboratory Accreditation Program
OECD	Organization for Economic Co-operation and Development
PA	performance assessment
PCE	percholorethylene (or tetrachloroethylene)
PI	performance indicator
PNNL	Pacific Northwest National Laboratory
PRA	probabilistic risk assessment
PUREX	plutonium uranium extraction
QC	quality control
RCRA	Resource Conservation and Recovery Act

RIPB	risk-informed, performance-based
SA	sensitivity analysis
SAGEEP	Symposium on the Application of Geophysics to Engineering and Environmental Problems
SDMP	Site Decommissioning Management Plan
SZ	saturated zone
SRS	Savannah River Site
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TCE	Trichloroethylene
TEDE	total effective dose equivalent
UCL	upper control limit
USACE	U.S. Army Corps of Engineers
USGS	United States Geological Survey
UZ	unsaturated zone (vadose zone)
WSRC	Westinghouse Savannah River Company

1 Introduction

The Integrated Ground Water Monitoring Strategy has been developed to guide the monitoring of a nuclear waste or decommissioning site to improve assessment of its performance. To achieve this goal, we present an integrated and systematic approach to monitoring water flow and contaminant transport from the land surface through the unsaturated (vadose) zone into underlying saturated zones. The Strategy can apply to new sites, and provides guidance for assessment of sites with existing monitoring systems. It should be generally applicable to any NRC-licensed site where public or environmental risk through ground-water pathways are to be assessed.

Performance assessment modeling of a site may have a time scale of thousands of years into the future. Yet, the lifetime of a monitoring program may be measured in decades at most. It is for this reason that a strategic approach to identifying the most important indicators of site performance and where and how to measure them in a short period of time so that the long-term predictions can be most useful.

1.1 Scope and Objectives

Nuclear Regulatory Commission (NRC) regulations are designed to ensure that licensees minimize potential risk to the public associated with nuclear waste and facility decommissioning sites. NRC has identified a need for long-term monitoring guidelines for detection of current conditions and changes in system behaviors and guidance pertaining to detection, evaluation, and monitoring of releases from operating facilities via unmonitored pathways (Statement of Work for RES-02-051). In part, the articulation of this need is based on National Academy of Sciences reports (NAS, 2000a and NAS, 2000b). More recently, the NRC Liquid Radioactive Release Lessons Learned Task Force has issued a report emphasizing monitoring needs at licensed facilities with a focus on power plant sites (NRC, 2006a).

The principal objective of this project is to respond to this need. Specifically, the Strategy developed in this document provides a logical framework for assessing what, how, where and when to monitor in order to:

- ensure that a licensed nuclear site or facility is behaving within the expected limits as described by the performance assessment,
- develop and refine conceptual flow and transport models by graded approaches,
- help identify and quantify uncertainties in conceptualization and performance assessment (PA) process and risk,
- aid in evaluation of whether engineered waste isolation systems are operating within their design performance envelope,
- evaluate whether natural attenuation is occurring according to expectations,

- communicate the monitored Performance Indicators (PIs) through effective data management, analysis, and visualization techniques to decision makers and stakeholders,
- improve understanding of site-specific features, events, and processes controlling ground water and contaminant movement,
- assess effectiveness of contaminant isolation systems and remediation activities,
- identify the presence of contaminant plumes and preferential ground-water pathways,
- test alternative conceptual flow and transport models, and
- aid in the confirmation of the assumptions of the PA model, and hence increase confidence in the PA.

This Strategy can be applied to a broad range of sites of varying complexity including any range of geologic and climatic settings, waste compositions, and site design. Figure 1-1 outlines the Strategy logic at a very high level.

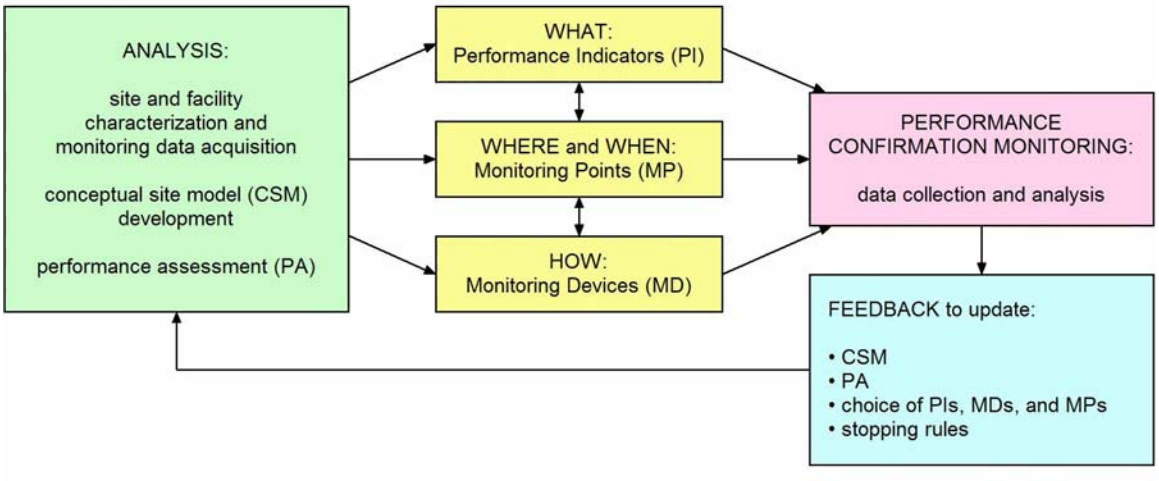


Figure 1-1 Integrated Ground Water Monitoring Strategy logic diagram

The Strategy is implemented as an iterative process beginning with analysis of any existing site and facility characterization and monitoring data, any existing conceptual site model (CSM), in this case generally a hydrogeologic model, and any existing risk assessment or PA model. The iterative nature of the Strategy results in a graded approach to development or evaluation of a monitoring program.

Through analysis, an initial assessment of what, how, when, and where to monitor to evaluate system performance is made. Performance Indicators include chemicals, hydrogeologic attributes, and other features, events, or processes (FEPs) that may significantly influence contaminant flow and transport. These PIs may be directly measurable in a monitoring program or may be derived from compilations and interpretations of data (as discussed in Section 1.2.2).

1.2 Introducing the Concepts

This Section will briefly define some of the terms and concepts used in this document. Further development of the concepts will be covered in succeeding sections.

1.2.1 Performance Confirmation Monitoring

Performance Confirmation Monitoring (PCM) is intended to verify that the data going into and the predictions coming out of the PA are sufficiently accurate and that a facility is behaving within expected limits. The objective of monitoring in the context of this Strategy is to understand the functioning of a hydrogeologic system.

A conceptual model of a hydrogeologic system (including engineered components such as waste sites, and natural components such as geology) is developed from site characterization and monitoring data. This conceptual model serves as the basis for computer simulations of ground water flow and contaminant transport, and ultimately of risk via the ground water pathway. This risk prediction ultimately derived from a conceptual model and appropriate input parameters is called a Performance Assessment. Performance Confirmation Monitoring of ground water within the area of the model can test whether the computer simulations represent the actual subsurface system.

Performance Confirmation Monitoring as discussed here differs fundamentally from other forms of monitoring in its objectives. For example, Detection Monitoring required for Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act, is intended to detect if a release has occurred. Compliance Monitoring serves to determine if a particular standard (i.e., ground water protection standard, MCL etc.) has been exceeded once a release occurs. (CFR 40, Part 264/265, Subpart F et sequel) In addition, Appendix B contains descriptions of types of monitoring.

While the fundamental objectives of these forms of monitoring differ, the information acquired through these monitoring programs may be quite useful to a Performance Confirmation Monitoring program as these data often can be used to refine and validate the Conceptual Site Model. As such, these sorts of monitoring activities are a subset of Performance Confirmation Monitoring as depicted in Figure 1-2. It is important to note, however, that the driver for selecting what, when, where, and how to monitor is different because the goal is to understand system performance rather than system compliance.

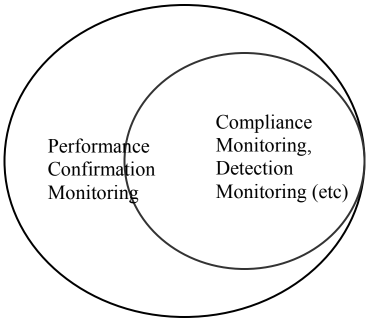


Figure 1-2. Relationship between Performance Confirmation Monitoring and other ground-water monitoring requirements.

A useful discussion of existing NRC regulatory monitoring requirements is contained within The Liquid Radioactive Release Lessons Learned Task Force Final Report, published in 2006 (NRC, 2006a). In addition, Appendix A includes some existing regulations and guidance pertaining to monitoring at NRC-regulated facilities and other hazardous waste sites and disposal facilities (e.g., CFR Title 10 for NRC; CFR Title 40 for EPA).

1.2.2 Performance Indicators

Site and system Performance Indicators (PIs) are measurable or observable features that provide insight into reliability of the CSM, and hence simulations and assessments based on the CSM.

Performance Indicators can be grouped into three classes. The first two classes include chemicals that are the primary risk drivers and their surrogates, as well as chemical and physical controls on flow and transport (e.g., pH, rock permeability). All of these are measurable through sampling and analysis. The third class of PIs results from interpretation of results of measuring the first two classes; these PIs are referred to in this document as Derived System Indicators (DSI). Included in this third class would be statistical and spatial outliers, and risk-significant phenomena identified through PA modeling. Examples are given in Tables 3-1 through 3-3.

1.2.3 Logical Approaches to Problem Solving

Management by Objectives, Systems Engineering, and the Data Quality Objectives (DQO) process are examples of approaches to logical problem solving. Application of the Strategy outlined in Figure 1-1 will be aided by understanding these approaches to problem solving. Details of these approaches are beyond the scope of this document. Each of these is discussed briefly in Appendices D, F, and G to this document.

1.2.4 Data Quality Objectives

The DQO process outlined by the U.S. Environmental Protection Agency (EPA 2000) is an aid to environmental decision making, guiding practitioners through identifying the decision and developing support to make that decision defensible. The seven sequential steps of DQO are adapted for application in this document in Appendix D. The process is iterative with certain outputs requiring input back into a previous step. A component of the proposed Strategy is to use the DQO process to aid in the selection of PIs and monitoring points thereby reducing uncertainty.

This process provides guidance useful for determining the type, quality, and quantity of data necessary for the design of an adequate monitoring system. Through the development of DQOs, decisions can be made on what (the PI), how (type of monitoring device), where and when (monitoring points) data should be collected relative to the monitoring objectives established. The process also establishes practical constraints on the monitoring program and aids in the establishment of an acceptable level of uncertainty.

The product of the DQO process should be a series of statements, or in the case of this Strategy, a series of questions that are asked to define the objectives and specifications of the proposed or existing monitoring plan. The answers to these questions should determine the degree of acceptability or the amount of uncertainty that can be tolerated in the program and still meet the objectives. For example, the DQO should establish measurement needs in terms of sensitivity, accuracy, and precision so that the selection of monitoring devices—and the selection of spatial and temporal locations for monitoring—can be determined.

Decision Rules can be developed by following the DQO process. These rules should be formulated into a series of “if…. then” statements that require a decision to be made. Rules can be expressed as stated questions, a series of flow charts, or as a decision tree. There are four parts of each decision rule:

1. identification of the PI (e.g., arsenic concentration),
2. identifiable requirement (What does the PI tell me about site performance?),
3. an action level (What PI values are within a range consistent with the site PA?),
4. determination if the requirement has been met so that further action – or no action – should be taken. (Do observed data match modeled predictions of the PA? If not, then the CSM and modeling/simulations should be revisited or refined to improve the PA.)

The number of required decision rules is based on the nature and complexity of the site as well as the amount of risk associated with it. The established rules should be clear and concise so that they can be used as a basis for decisions.

1.2.5 Graded Approach

In applying this Strategy to various facilities, it becomes necessary to make some informed decisions concerning the level of effort necessary to ensure the site is performing to design standards, utilizing a graded approach. The graded approach can be defined as a process of determining the level of investigation, characterization, or monitoring of a site necessary to ensure a degree of confidence needed to minimize risk and verify the performance of the system.

The graded approach ensures that the level of analysis, documentation, and actions used to comply with requirements are commensurate with:

(1) The relative importance to safety, safeguards, and security (level of risk);

(2) The magnitude of any hazard involved;

(3) The lifecycle stage of a facility (age, status, and condition of facility or process);

(4) The programmatic mission of a facility (complexity of products or service involved);

(5) The particular characteristics of a facility;

(6) The relative importance of radiological and non-radiological hazards; and

(7) Any other relevant factors. (Ponke, 2002)

Use of the graded approach in the application of the Strategy to a given facility is an intrinsic part of the process, resulting in a constant re-evaluation of the level of effort required to characterize the site and ensure Performance Assessments are complete and accurate. Factors that will influence the level of investigation of a site will include:

- waste inventory
- distance to receptors
- complexity of geology, and
- intended use of the data.

Additional discussion of this topic is included in Chapter 4, in the context of selection of an appropriate flow and transport model for a site.

2 The Conceptual Site Model

Identifying the most appropriate CSM is the heart of the monitoring strategy application. The key word is “appropriate”. “Far better an approximate answer to the *right* question, which is often vague, than an *exact* answer to the wrong question, which can always be made precise.” (Tukey, 1962)

A CSM is a hypothetical picture of the site used to organize and communicate information about site characteristics. Consistent with the methods of scientific inquiry, this conceptualization is subject to testing with new data. If new data are inconsistent, either the data need evaluation, or the model needs to be revised. Successful resolution normally requires an iterative process of data collection and analysis (Shaw, 2006; EPA, 1999).

The CSM forms the basis for all geologic ground water flow and contaminant transport modeling for the site. In the Strategy we are largely concerned with constructing and confirming the CSM and computer simulations through monitoring. Our CSM and its simulation predictions are limited to where and when contaminants are distributed through a ground water pathway. It does not include some components important to risk estimates such as population distribution or behavior. The first step in the monitoring Strategy is to analyze the problem – that is, establish DQOs, and develop useful CSMs. Conceptual Site Models form the basis for performance modeling, including flow and transport modeling; estimated exposure routes, pathways, travel times, and contaminant concentrations in space and time. The CSM includes these components:

1. a geologic model (framework for hydrogeologic model),
2. a hydrogeologic model (hydraulics for flow and geochemistry for transport), and
3. chemical release scenarios.

Development of a CSM requires that, in addition to the facility-related waste inventory and release scenarios, the natural system in which the facility is located be evaluated. In this context, the CSM becomes the connection between performance confirmation monitoring, site characterization, and the PA.

Table 2-1 below, from Pope et al. (2004), lists the information included in a general CSM. Its most critical elements are those that have the greatest influence on estimated risk. This table is a useful guide to the collection and analysis of site data.

Table 2-1 Summary of information in a conceptual site model for contaminant fate and transport in ground water

Contaminant Inventory	• contaminant inventory and uncertainty in the amount, location, and concentration, nature and history of contaminant releases • source release information, such as container type and expected degradation rates, source control and other proposed remedial actions
Demographic*	• location and information on human (and perhaps ecological) receptors under current and anticipated future conditions
Geological	• regional and site geologic settings, structures, faults, and fractures • depositional environments and paleogeology • lithologic facies, distribution, thickness, and transmissive features • borehole core descriptions, geologic units and boundaries • geophysical data such as log and seismic data interpretations • anthropogenic features including buried corridors and heterogeneous fill materials that control ground water flow and contaminant migration
Hydrologic & Meteorological	• characteristics of surface water bodies, locations, depths, flow rates and recharge and discharge analysis • seasonal or temporal variation of surface water bodies • precipitation distributions in time and space • meteorological and climatic records, evapotranspiration potential
Hydrogeologic	• characteristics of vadose zone and aquifer structures or heterogeneity, identification of preferential flow or barriers • water content variation in vadose zone • hydraulic gradients and the variation in temporal and spatial domain • hydraulic properties, including the conductivity, storage, porosity, transmissivity, homogeneity, and anisotropy of these parameters • aquifer boundary conditions • ground-water recharge and discharge • ground-water interaction with surface water • quantitative description of ground-water flow field • ground-water level trend analysis. • aquifer usage information, location and production data for water-supply wells, and estimates of future uses
Geochemical	• general geochemical conditions at the site • chemical characterization of sources for ground water contamination • geochemical processes that affect or are indicative of contaminant transport and fate, and mineralogy • temporal trends and variations of contaminant sources and concentrations, mobility of contaminants in each phase • sorption information, distribution coefficients, and sorption mechanisms • potential for mobilization of secondary contaminants • contaminant attenuation processes
Biological*	• identification of plants and animals that could facilitate contaminant transport in the near surface • plants and animal communities that could occupy the site in the future

modified from Pope et al. (2004)

**Demography and biology are not integral parts of the CSM for the Integrated Ground Water Monitoring Strategy*

2.1 Development or Review of a Conceptual Site Model

Figure 2-1 below, is a high level flow chart of the logic path to evaluate (or construct) a CSM using a graded and iterative approach. It includes (Step C) interfacing with geologic and flow modeling software, which in turn provide computer renderings for visualization. Features of the model thought to be critical to monitoring should be identified and their basis in field data clarified. Some of these may be location of flow paths, ground water velocity, preferential pathways, etc. These, in turn, become the FEPs that influence results of the PA. Therefore evaluation of the CSM is basically an evaluation of the uncertainties in the model relative to how well the model is able to constrain the outcomes of the PA.

Normally, a CSM will be available as a starting point, but if this is not the case, then step C of Figure 2-1 will result in developing such a model by entering and interpreting data using geologic modeling and visualization software. Further discussion and illustration of this software is included below and in the case studies of Volume II.

The three major steps are directly related to the components of the CSM:

1. Development or evaluation of the geologic model,
2. Development or evaluation of the flow and transport model, and
3. Evaluation of risk sources and pathways.

As part of the evaluation process, the logic path contains a provision to take steps to reduce uncertainties if uncertainties in the model elements critical to performance assessment are found to exist in the evaluation. Development or evaluation of flow and transport should begin with simple exercises like plotting piezometric data and water chemistry data. This is illustrated in several chapters of Volume II.

Note that the subsurface information classed as geology also includes anthropogenic features (Table 2-1). Such features have proven to be pathways for contaminant migration at power plants (NRC, 2006a). Pipe or cable trenches, backfilled with gravel, can provide high-permeability pathways for rapid spread of leaking contaminants. Pathways provided by such features may lead contaminants in directions not predicted by contouring a few points on a water-table map. Roof drains and water supply leaks can inject large amounts of water into the vadose zone in such a way as to drive ground water and contaminants in directions that would not be predicted based on water levels from scattered monitoring wells.

Because data acquisition and characterization for geologic and flow and transport modeling can rapidly become resource intensive, the Strategy supports and encourages a graded approach to these activities. Therefore part of the evaluation process is to determine the appropriate level of effort and sophistication for the CSM.

Model and monitoring requirements are a function of site complexity. The appropriate level of complexity for flow and transport models is discussed in Chapter 4.

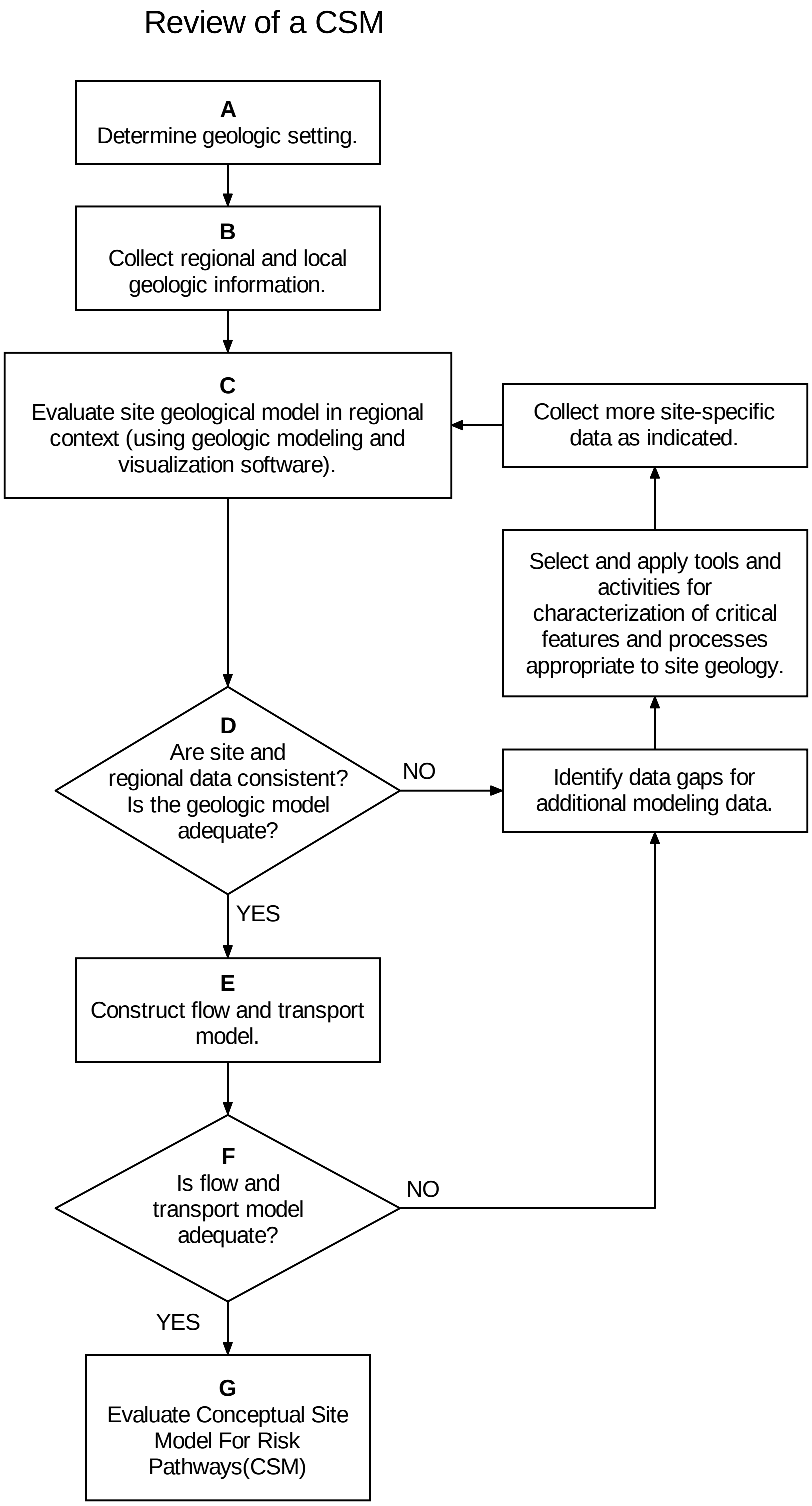


Figure 2-1 Evaluation of a conceptual site model. This process starts with evaluation of data to develop an initial simple model, and gradually moves to more complex interpretation if needed.

2.1.1 Evaluation of Geologic Models

The site geologic model contains the critical hydrogeologic elements that form the underpinnings and control the behavior of the flow and transport models associated with the PA. For this reason, a thorough evaluation of the geologic facet of the CSM (particularly the hydrogeologic and geochemical elements) is a fundamental element of the strategy. The complexity of the geologic portion of the CSM should be adequate to characterize these elements and to reduce the uncertainties associated with them to an acceptable level.

Computer simulation of flow and transport will require simplification and estimation of hydrogeologic features. The process of developing a computer model from a geologic model is called abstraction. "Model abstraction is defined as the methodology for reducing the complexity of a simulation model while maintaining the validity of the simulation results with respect to the question that the simulation is being used to address."(NRC, 2006b) A computer simulation for a regional water resource issue might be quite simple, whereas a model to address a contamination problem on the scale of a nuclear facility may include very small features. With improvements in computing power, almost any needed level of detail can be realized.

2.1.1.1 Congruity with Regional Setting

Any decision loop based on geologic investigation begins with the regional picture. Has the geologic model fully integrated the local model into the regional framework? Once the regional framework is determined, all site data should be compared to the regional framework for congruity, and incongruous data accounted for. For example, if joints and fractures are present and intersect regional geology at 45 degrees, the local site geologic model must reflect this joint pattern or explain either why it deviates from the trend or is not important to the PA. This test of congruity may lead to a selection between competing geologic models.

2.1.1.2 Review of Existing Site Characterization and Monitoring Data

Site specific and other local characterization and monitoring information contained in reports by the site operator or subcontractor should be reviewed for internal consistency with the CSM.

Some brief case studies are included in Chapter 4. Additionally, more extensive case studies are the focus of Volume II. No one site allowed thorough testing of the Strategy. Each site presented some limited data pieced together from available sources. Still, each site teaches something that can be applied generically to all sites. In all of these case studies, examination of site data revealed Derived System Indicators appropriate for the sites under study. Once revealed, these DSIs can be applied to evaluate the validity of data used in models and interpretations.

Any consideration of the adequacy of a monitoring system at a site level must fit into the context of the regional geologic and hydrogeologic framework, including FEPs such as faults, fractures, channels, bars and other geologic features that have an impact on the distribution of significant parameters affecting the flow of ground water within the local system. The monitoring data must be examined to determine if regional system parameters contain a representative range of values that effectively capture conditions at the site. Characterization and monitoring data should be evaluated for outliers and trends that might suggest alternative conceptual models. Examples might include water levels that deviate from smoothed contour potentiometric maps or trend surfaces. In the Savannah River Site case described in Chapter 4, the anomalous data were first discarded and only later identified as clues that indicated a need to revise the CSM.

2.2 Evaluate Model Uncertainty

Uncertainty analysis is the assessment of the effects of uncertainty in various forms on the modeling results. In the context of the Strategy, these results are estimated ground water concentrations or risk to some member of the public. Parameter uncertainty, be it from natural variability or from imperfect knowledge, is propagated through the model, causing uncertainty in the results. Conceptual model uncertainty is manifested in different computer models, also producing uncertainty in results. Through sensitivity analysis (described in the following section), opportunities can be identified to cost-effectively reduce these uncertainties either through data analysis or additional data acquisition.

The natural variability of many hydrogeologic properties contributes greatly to uncertainties in the CSM. Because this variability is spatial, and in some cases temporal in nature, its distribution and properties can be estimated as spatiotemporal averages and used to update the geologic model. Every effort should be made to characterize this variability through data analysis in its geologic context. The use of a mean permeability, for example, may obscure preferential flow pathways that become evident only when displayed in the context of the site geology.

Characterization data are often subject to non-unique interpretation. Thus a family of conceptual models is possible, all honoring the available data (Neuman and Wierenga, 2003). It should be possible to conduct field tests to determine which of the possible models is most likely to represent reality, though it must be recognized that we cannot know if we have a "correct" model. Multi-well pumping tests, tracer tests, and cross-well geophysics can fill in data gaps that might help discriminate between models.

An example is a long-term pumping test that suggests a permeable zone at some distance from the pumping well (Figure 2-2). The pump test, combined with knowledge of the geologic depositional setting (Walker, 1984) from regional data, might direct additional site characterization toward looking for buried stream channels, oyster beds, pumice beds, or other high permeability lithofacies.

In Figure 2-2, drawdown reaches a maximum of about 0.4m in about 2 months, but then partially recovers and levels out after 3 months at about 0.25m. In this case, interconnected fractures begin to supply water after pressures at the pumping location are reduced. Examples can also be found in the literature or on the internet of somewhat similar response from wells near streams where the stream begins to supply water once the cone of depression from pumping reaches it. (Discussion of dual-porosity, dual permeability, and recharge boundary interpretation of pumping tests in fractured rocks is given in Craig and Reed, 1989)

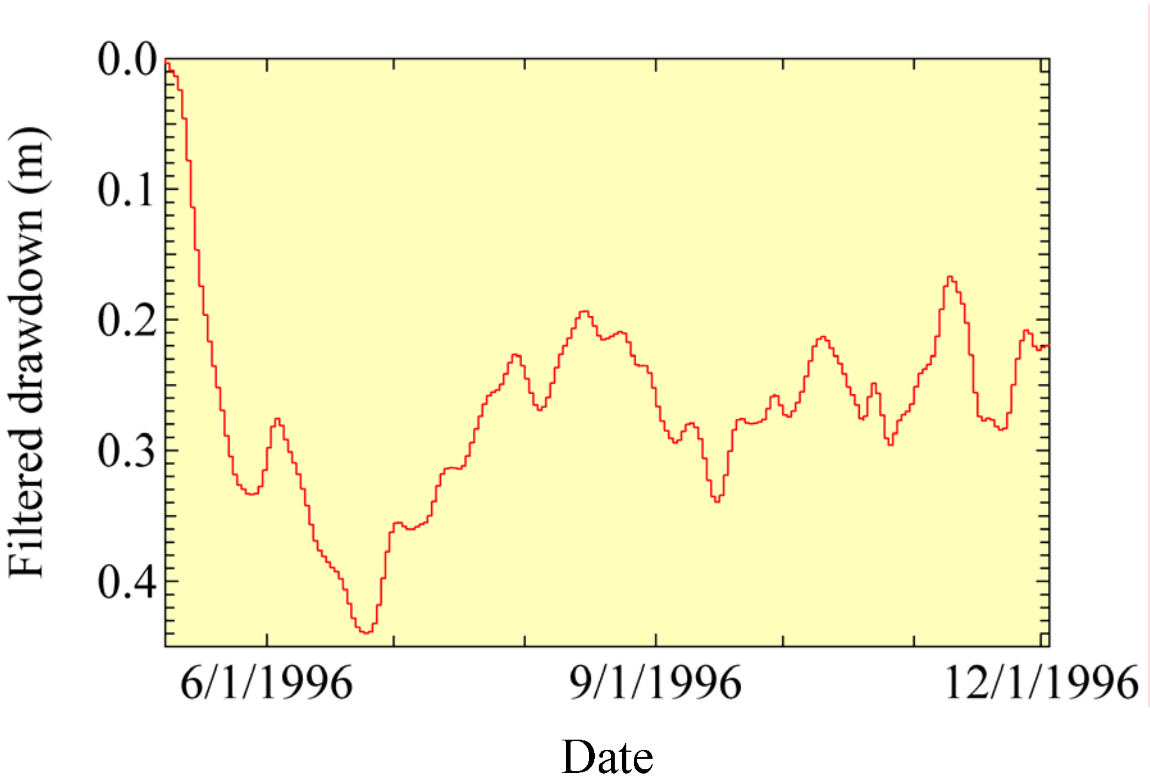


Figure 2-2 Drawdown Curve. (Scott C. James, DOE / SNL, personal communication, 2007)

2.2.1 Risk-Informed Sensitivity Analysis

A sensitivity analysis focuses on the question of which uncertainties (parameter or modeling uncertainties) are the most significant in contributing uncertainty to a selected result, such as an estimate of a ground water concentration of some contaminant, or future potential risk to a member of the public. A global sensitivity analysis systematically evaluates the correlation between each source of uncertainty in the model to the uncertainty in the result. Even in complex models, results are typically influenced significantly by only a handful of parameters or modeling constructs (or, more generally, FEPs).

If a parameter is identified as having a strong influence on determining a risk endpoint, for example, that parameter is said to have risk-informed sensitivity. In other words, the value of that parameter is important in determining the estimated risk. In the context of the Strategy, such a parameter would be a candidate for a PI, or might suggest a PI that is influential in determining the value of that parameter.

As discussed in the following section, the identification of sensitive parameters assists the iterative process of updating the model by improving (i.e. reducing the uncertainty of) parameter distributions. The cycle of identification of sensitive parameters, improvement in characterizing the uncertainty of those parameters, rerunning the probabilistic model, and performing another sensitivity analysis continues until some stopping rule is met. Typically, this stopping rule is the outcome of some cost/benefit analysis applied to the updating of the parameters. It may be found that the uncertainty cannot be practically reduced, or that doing so would incur excessive cost. If the point is reached where the uncertainty of the most sensitive parameters is irreducible, then the iterative process is terminated and the model uncertainty is considered minimized.

A global sensitivity analysis should be performed to identify the critical FEPs characterized by the model to which the PA is the most sensitive and could potentially impact the outcome of a release to the environment or risk to members of the public. It should be noted that those parameters to which one result is sensitive will generally be different from those for another result. For example, the parameters that are most influential in determining the peak concentration of tritium in the ground water will have little to do with long term potential doses, which would be caused by some other contaminant, given tritium's relatively short half-life. This illustrates the importance of thoughtful selection of modeling endpoints for sensitivity analysis.

2.3 Model Parameter Development

The sensitivity analysis described above requires a probabilistic model, with stochastic definitions of input parameters. Any parameters that are defined deterministically (i.e. as a single value, implying no uncertainty) cannot be evaluated for sensitivity. This does not mean that the result may not depend heavily on the value of the parameter; rather, it means only that the degree of dependence remains unknown. It is important to appreciate this fact, recognizing that although the model may in fact be sensitive to a deterministic parameter, a sensitivity analysis can reveal only sensitivities produced by stochastic parameters, conditional on their distribution. In general, modifying the statistical distribution used to define a parameter value will change its role in result uncertainty. In some cases, a reduction in the uncertainty of a parameter (by including new information, for example) may remove the parameter from the list of sensitive parameters altogether.

A model will typically go through several iterations of uncertainty reduction by improving the definition of sensitive stochastic parameters. There is generally nothing to be gained from improving distribution definitions for those parameters that have little influence on the result of interest.

In Figure 2-3 an example is given of a modeling parameter (porosity) for which there is initially no data so that a uniform distribution between 0 to 100% porosity is chosen for the model. The first step of improvement is the choice of a more likely distribution (triangular) based on expert opinion. Additional data from field measurements can improve the quality of the probability density function (PDF) until a representative set of values is available for model input.

An optimization example after Deschaine (personal communication, 2003) uses geostatistics to reduce the uncertainty in plume location. In this case, the initial estimate of the plume location identified as baseline in Figure 2-4 was inadequate. The existing monitoring network defined the plume with 93% confidence. Adding one well in an area of uncertainty increased the confidence to 98%. Further wells do not increase confidence significantly enough to warrant installation. This technique can be used to derive stopping rules for additional characterization and monitoring.

Both of these examples illustrate, on different scales, the Bayesian concept of iteratively updating the knowledge base of the PA and associated analyses, gradually improving the model and reducing overall uncertainty by obtaining more field or laboratory data. This knowledge base includes not only parameters, but sub-models (e.g., the model for unsaturated hydraulic conductivity discussed earlier) and conceptual models as well. As better knowledge is gained, through fieldwork, interpretation, or even improved insight into the workings of the PA model itself, the project team will be faced with revising the project at many levels. In simple cases, a new distribution for a parameter may be devised and modified in the PA model. If more global information is gained, then major revisions in the conceptual model may be in order.

Techniques used to monitor for spatially distributed parameters have the usual concerns associated with accuracy and precision. However, in realistic settings many of these parameters show short-range spatial correlation characteristics so that the cost effectiveness of the technique becomes even more of an issue. Also, the temporal nature of these parameters must be accounted for. Some are relatively constant such as transmissivity and can be calculated in a one time sampling event. However, others, such as moisture content, may need to be monitored at specific intervals or due to some triggering event.

Parametric updating example

In this example of the iterative development of a distribution for a stochastic parameter, porosity of a porous medium is used. Based on its geometrical definition as the ratio of the volume of voids to the entire volume, the physical limits for porosity are 0 to 1, 0 meaning no porosity (a solid with no void space in it) and 1 meaning an empty volume with no solid material in it. A prior distribution based on that information alone would be uniform(0, 1).

A hydrogeologist's first guess at porosity may be 0.3, based only on the knowledge that the material is a sandstone, for example. This single value is represented here as a discrete distribution. Combining the knowledge of the physical limits with this point estimate leads to the triangular distribution tri(0, 0.3, 1). We know that a porous medium cannot actually have a porosity of exactly 0 or 1, and that 0.3 is expected, and the triangular distribution reflects that elementary state of knowledge. This might be a reasonable starting point for a distribution for a probabilistic model, such as a PA.

As site-specific data are obtained for field investigations, these data can be represented by some parametric distribution (a normal distribution is used in this example), which can be refined as more data are acquired.

In this example, a beta distribution may in fact be more appropriate, since truncating the normal at 0 and 1 will slightly alter the mean value.

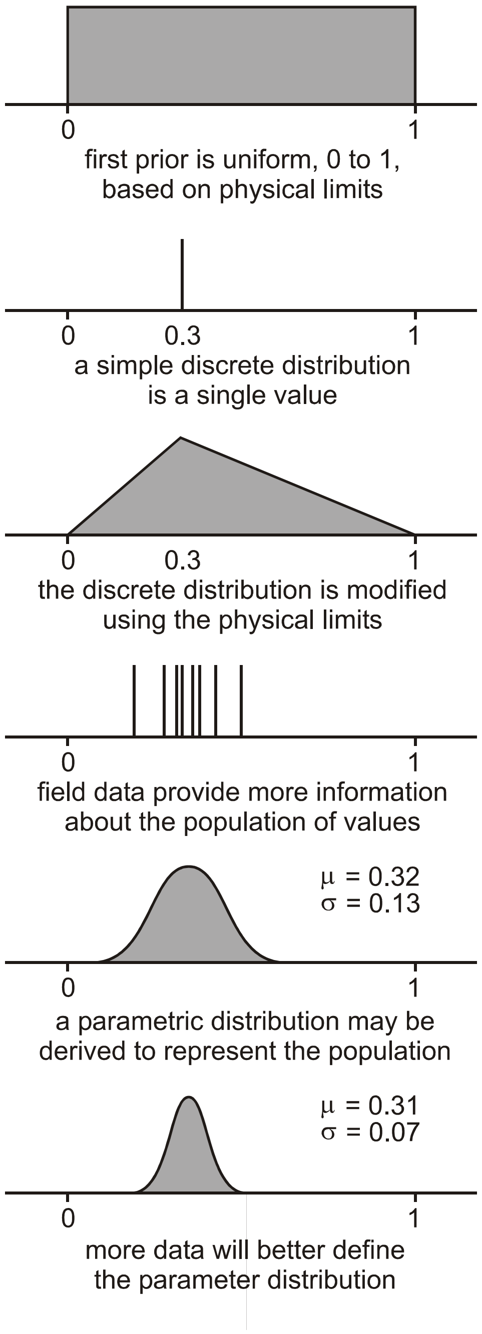


Figure 2-3 Parametric updating example

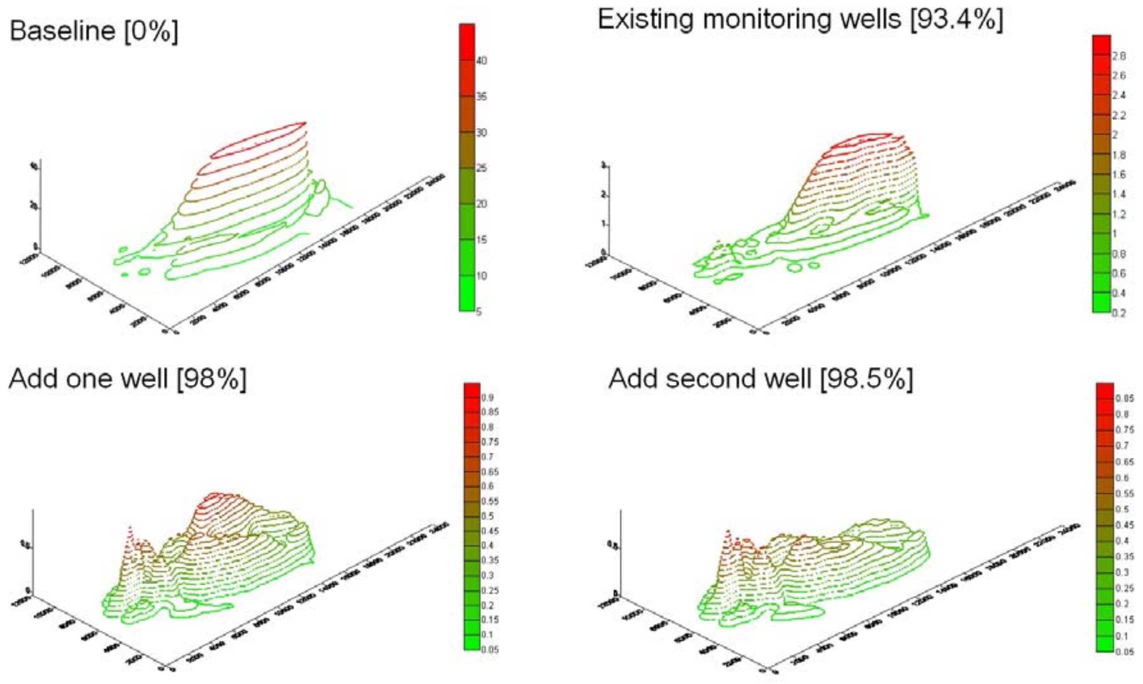


Figure 2-4 Plume refinement with addition of monitoring wells (after L. Deschaine, personal communication 2003).

3 Performance Indicators

As noted above, site and system Performance Indicators are measurable or observable features that provide insight into reliability of the Conceptual Site Model (CSM), and hence simulations and assessments based on the CSM.

This chapter outlines some considerations in developing indicators of site performance. These include developing PIs (including Derived System Indicators [DSIs]) from analysis of site characteristics, modeling, analysis of the PA, statistical analysis of the monitoring data, and from the CSM.

Effort should be focused on identification and application of selected site-specific PIs that are critical to the review and or development of a monitoring plan. Through implementation of the Strategy, appropriate PIs, monitoring devices, and decision criteria can be identified. PIs should also identify the relevant information needed to assist the decision maker in the determination of the adequacy of the existing or proposed system for reduction of risk and uncertainty.

While it is possible to construct general lists of possible PIs, actual PIs are always site specific. While some may be obvious, others must be developed through expert analysis of site features and available data. Chapter 8 of Volume II discusses some data analysis methods that may lead to selection and evaluation of site PIs.

3.1 Develop Preliminary List of Performance Indicators

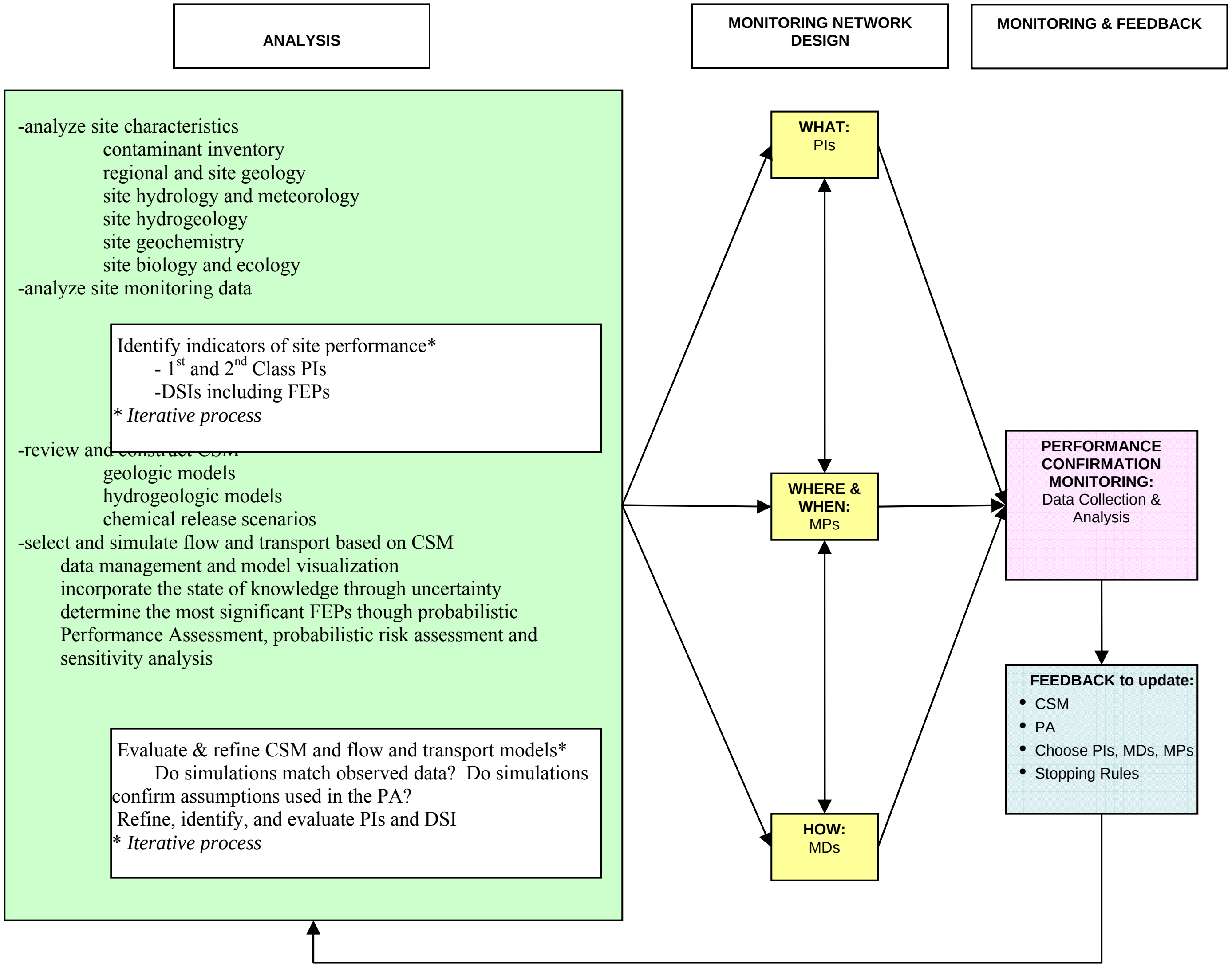
The purpose of this exercise is to develop a preliminary list of site and system PIs through analysis of the site characterization, the facility design, and the PA. Site-specific data on inventory, potential leak points, known surface and subsurface contamination, analysis of characterization and monitoring data, and modeling for risk-significant contaminants and FEPs will suggest a number of site-specific PIs.

We find it useful to think of Performance Indicators in three classes. The first two classes include chemicals that are the primary risk drivers and their surrogates as well as chemical and physical controls on flow and transport (i.e., pH, rock permeability). All of these are measurable through sampling and analysis. The third class results from interpretation of results of measuring the first two classes of PIs. Included in this third class would be statistical and spatial outliers.

Confirming site performance includes evaluation of risk-sensitive PA modeling assumptions related to FEPs. These FEPs, such as hydrologic system geometry and behavior and associated uncertainties, are evaluated through analysis of site characterization and monitoring data, including analysis of the distribution of primary PIs. This analysis can also yield a set of indicators that show whether the actual system is behaving as predicted by the models. We refer to these derived indicators as DSIs, because they function at the system level rather than at the component level. An analogy to a car's indicators would be to use the oil temperature gauge as a primary indicator, and the *check engine soon* light as a Derived System Indicator.

Primary PIs are the direct risk drivers if present in sufficient concentration at points of exposure. All the others may be just as critical to estimating risk as the primary list because they are either phenomenon in need of quantification in order to estimate transport or they are indicators of model validity. Because risk ultimately exists only given certain behaviors at the point of exposure, these others that may control flow and transport are no less important than concentration measurements of a regulated substance.

In Figure 1-1 the step called *Analysis* reviews the PA, the Site, and the Facility for potential PIs. The process is iterative - reviewing data gathered for the PA, risk related contaminants and FEPs from the PA, as well as characteristics of the facility under study to produce an exhaustive list of PIs and DSIs. In Figure 3-1 below, we have expanded the *Analysis* step to show, with more detail, what is involved in the selection of PIs.



-analyze site characteristics
  contaminant inventory
  regional and site geology
  site hydrology and meteorology
  site hydrogeology
  site geochemistry
  site biology and ecology
-analyze site monitoring data

Identify indicators of site performance*
  - 1st and 2nd Class PIs
  -DSIs including FEPs
* *Iterative process*

-review and construct CSM
  geologic models
  hydrogeologic models
  chemical release scenarios
-select and simulate flow and transport based on CSM
  data management and model visualization
  incorporate the state of knowledge through uncertainty
  determine the most significant FEPs though probabilistic Performance Assessment, probabilistic risk assessment and sensitivity analysis

Evaluate & refine CSM and flow and transport models*
  Do simulations match observed data? Do simulations confirm assumptions used in the PA?
Refine, identify, and evaluate PIs and DSI
* *Iterative process*

Figure 3-1. Monitoring Strategy Logic Flow with expanded *Analysis* step.

3.2 Classification of Performance Indicators

Listed in this section are the items to be considered in the development of a preliminary PI list. This section is structured around the class types in Table 3-1.

Table 3-2, below gives examples of PIs that might be chosen based on a Performance assessment. Table 3.3 in section 3.4, below, is adapted from a recent paper by Long and Yabasuki discussing PIs that are specific for a bioremediation project The PIs they use are cross-referenced to provide site and project-specific examples of the generic PIs in Table 3-1.

Table 3-1 Classification of Performance Indicators

Class 1: Chemical

A. regulated and direct drivers of risk – i.e., U, Cs-137, Pu, Sr-90, tritium, Rn
  - these are Primary PIs

B. surrogates and indicators that a process is occurring -
  - gross alpha for uranium
  - chloride or nitrate from same source as risk drivers
  - degradation products – i.e. Am-241 for Pu-241, organic breakdown products for MNA

C. process control chemical indicators needed to model transport
  - pH, alkalinity, conductivity, major cations, major anions, redox indicators...

Class 2: Physical
  - examples include water content, pressure distributions
  - physical properties of rocks (porous/fractured media)
  - physical properties of subsurface fluids

Class 3: DSIs modeled or derived from data analysis

A. distribution of uncertainty
  - this would be determined by examining the distribution of characterization data available to develop a CSM and flow model. (areas of sparse or questionable data would have high uncertainty.)

B. lack of congruity
  - tests of flow and transport models
    - Do actual plume maps match predicted plumes?
    - Does site geology match regional geology?
    - Does site geology match geology reported from adjacent areas?

C. outliers
- spatial - for example:
    - “bulls eyes” around data points on contoured maps
    - areas of high characterization uncertainty
- statistical (with no spatial component)
    - univariate, including control chart anomaly,
    - multivariate, including single-sample cluster

D. risk-informed sensitive parameters (defined in text)
    - can identify which probabilistic parameters are the most significant in estimating risk. (some may be suitable as PIs or DSIs).

3.2.1 Class 1: Concentrations in Natural Media

PIs that could indicate leaking waste or undesired/unexpected water flux through radioactive materials in the ground will be manifested as contaminant concentrations in: ground water, surface water, the vadose zone, (bulk soil or as soil gas), and in local flora and fauna.

3.2.1.1 Contaminants in Ground Water

The most important PI is the concentration of contaminants found in ground water, including the vadose zone. Once waste has reached the water table, transport of waste constituents in solution or suspension may be monitored through direct sampling of ground water. This is normally done through permanent wells, but can also be done with direct-push technologies.

Typically, samples are analyzed in the field for highly unstable parameters (in terms of transporting samples), such as pH, alkalinity, redox potential, *etc.*, which may be early indicators of system failure. After stabilization, samples can be transported to a laboratory for analysis for other constituents.

Daughter products from decay of uranium, thorium, plutonium, tritium or other parent radionuclides may be more mobile, or may produce radiation that is more readily detected than the primary waste constituents. For example, ^{208}Tl, ^{214}Bi, and ^{241}Am are gamma emitters that may provide evidence for the presence of U, Th, or Pu. ^{3}He can be used to detect tritium at depth. These can be measured and used as early warnings of a potential system release. In Table 3-1 these are classed as surrogates for primary contaminants.

Even though ^{90}Sr is not a gamma emitter, low energy gamma rays are emitted from some materials when irradiated by ^{90}Sr's beta radiation through a process called *bremsstrahlung*. This radiation has been detected and used in monitoring programs at Hanford's high-level waste tank farm. (Hartman et al., 2003)

3.2.1.2 Contaminants or Indicator Parameters in Soil Gas

Some radioactive and organic liquids waste constituents may move without the assistance of water, including mercury, iodine, tritium, radon, argon, krypton.

While most radionuclides do not exist in the gaseous phase, several do partition between water and gas phases, including tritium (as tritiated water), ^{14}C (as $^{14}CO_2$ and other volatile carbon compounds), and the noble gases Ar, Kr, and Rn. Many RCRA constituents are volatile or semi-volatile, and are detectable in soil gas.

^{3}He is produced by decay of ^{3}H, and as a noble gas, is mobile in soil. Helium and radon in soil gas and ground water have been used to prospect for uranium deposits. ^{3}He/^{4}He ratios in soil gas have recently been used by Pacific Northwest National Laboratory (PNNL) to trace a tritium plume at the water table (Gee et al., 2001).

Gases such as helium or sulfur hexafluoride can be used as tracers to detect leak locations in underground tanks, lines, or other structures.

3.2.1.3 Contaminants in Other Fluids

Kerosene containing traces of t-butyl phosphate and uranium or plutonium (from the PUREX process) has been disposed of at some sites. Biodegradation of kerosene will produce methane and halogenated solvents (as well as their degradation products) which are readily detectable in soil gas. Carbon tetrachloride and other halogenated organic solvents may represent issues at some waste or decommissioned nuclear sites. Dense non-aqueous phase liquids such as trichloroethylene (TCE) are also a special problem at many sites. Since they exist in a separate phase from water, they sink through ground water due to their high density, and present a long-term source for slow dissolution into natural waters. They are notoriously difficult to clean up.

3.2.1.4 Surface Water

Surface water sampling may provide a method of locating preferred pathways of ground water. For example, sampling along a seep line, or of shallow subsurface water along a creek edge (where upwelling is expected) may provide more relevant information than sampling the flowing stream.

3.2.1.5 Plants and Animals

Vascular plants can transport waste constituents, and may extend roots significant depths to obtain water. Insects, especially ants and termites, and burrowing vertebrates can invade buried waste and may redistribute hazardous or radioactive constituents (Hooten and Myles, 2006).

Plants have been used in geochemical exploration for many years (Brooks, 1968). Phytoaccumulation of Cr, U, and Pu was the topic of a literature review by DOE’s Amarillo National Resource Center for Plutonium (Hossner *et al.* 1998). The focus of this work was soil remediation, but plants that accumulate metals are also useful integrating samplers for detection of metals. Sagebrush (Erdman and Harrach, 1981) and fir (Dunn, 1980) are known to be useful for uranium exploration, and should also serve as indicators of actinides in ground water near waste sites. Andraski *et al.* (2002) used tritium concentrations in creosote (*Larrea tridentata*) as a system indicator to map tritium plumes in the unsaturated zone in the Amargosa desert (See Chapter 4 of Volume II).

3.2.2 Class 2: Physical

3.2.2.1 Water Content

Waste disposal sites are generally designed to keep water from making contact with or flowing through the waste. Water is reactive with some waste components, promotes biological activity, and can transport waste components in solution or suspension. These aqueous reactions vary greatly depending on the waste form, the method of disposal, and the packaging materials used.

Water can react directly with waste metals such as sodium, aluminum, lithium, uranium, or plutonium, releasing potentially explosive hydrogen gas and producing transportable ions. Water can promote corrosion or degradation of containment devices or structures. For example, at WIPP, halite may react with steel containers, releasing hydrogen gas. MgO added to fill is expected to ameliorate the situation (NAS/NRC, 2001). Water can promote biodegradation of organic packaging materials and produce organic or inorganic corrosive, complexing, and solubilizing agents.

The ground-water flow and transport model will be based on a water budget. This budget will include some fraction of precipitation flowing through a cap or cover – thus the PIs include water flux at selected points.

The amount of water found in the unsaturated zone or in engineered components of a disposal system can also be an indicator of the performance of a disposal system or the potential for transport in the unsaturated zone. Water can transport waste constituents *both* downward and upward through infiltration, capillary action in the unsaturated zone, or fluctuations in water table elevation. In addition to these purely advective processes, water presents an opportunity for contaminant migration through diffusion.

For these reasons much of the published work and research on waste site monitoring, especially in the western U.S., has focused on detection of water and assessment of water flux. (e.g., NRC sponsored research at the University of Arizona and PNNL, Young et al., 1999a.)

Pressure head distribution must also be understood in order to model flow and transport. An example is shown in Section 4.4.2 below where an anomalous water level led ultimately to major revision of the CSM.

3.2.2.2 Physical Properties of Rock or Sediment

These include transport-controlling features such as, porosity, permeability, stratification, fractures, etc. Heterogeneity is a function of the interrelationship of these controlling features.

Radar data (Wyatt and Temples, 1996) typically collected as part of the geotechnical phase 1 of characterization can be used to map fractures and other small scale features present at a site. Data can be collected and reviewed to determine if the condition is present in the data set, but missed during the initial interpretation. Existing monitoring points can be used to collect new information that will be used to update the CSM. Chapter 4 of Volume II includes a discussion of the application of three-dimensional computer modeling techniques to previously published geophysical data for the Amargosa Desert Research Site. Re-evaluation of the data resulted in the identification of a previously unidentified structure that could act as a vertical pathway for the migration of contaminants and was subsequently used to update the CSM.

When the CSM fails to produce satisfactory results, existing data can be reviewed to assess the possibility of a FEP that was missed in the original interpretation or new data can be obtained to update the CSM.

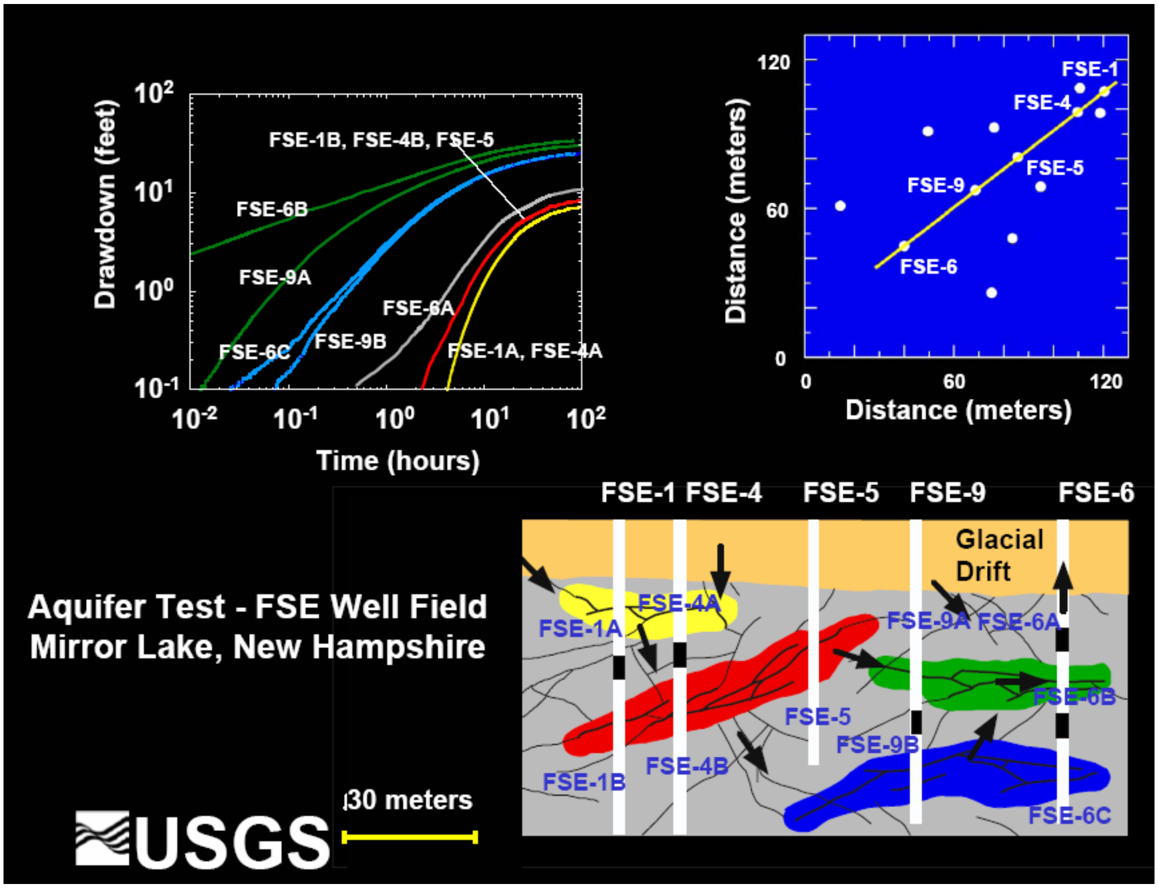


Figure 3-2. Aquifer heterogeneity in fractured rocks (Hsieh and Shapiro, 1996).

Figure 3-2 provides an example of heterogeneity in fractured rocks and the potential for high permeability pathways based on pump tests from the Mirror Lake FSE Well Field in New Hampshire. Fractures with a high degree of interaction create highly transmissive zones within less permeable fractured rock. The highly transmissive fracture clusters in the FSE well field exert a strong influence on multiple-borehole hydraulic tests. In the Figure 3-2 the top left panel shows drawdown in other wells when FSE-6B is pumped. Multiple plumes may be present in an aquifer and isolated from each other due to these heterogeneities. At the Mirror Lake FSE Well Field, there are at least four distinct transmissive fracture clusters present (Hsieh and Shapiro, 1996). Dershowitz et al., 1998, is an excellent reference on the issues related to modeling flow in fractured rocks.

Because geology controls certain distributions of properties such as porosity and permeability rather than these being associated with random events, we can analyze existing data to determine if there is a spatial component to the data. If trends are present, data can be evaluated and reinterpreted to improve confidence in its distribution. Most of this type of analysis has been pioneered by the petroleum industry (Yarus and Chambers, 1994).

3.2.2.3 Physical Properties of Subsurface Fluids

Fluid properties such as density and viscosity are important inputs to the modeling process. These, as well as temperature and salinity, are generally assumed to be constant throughout the modeling domain, but in some cases these parameters must be allowed to vary in time and/or space in order to sufficiently mimic natural conditions.

3.2.2.4 Features, Events, and Processes as Performance Indicators

Performance Assessment of long-term monitoring systems requires the identification and evaluation of all the FEPs that could potentially affect the risk to potential receptors over very long timescales (e.g., millennia). To assess the potential impact of these FEPs, it is possible to conceive different scenarios in which combinations occur, and to develop conceptual models to represent the behavior of the system in those scenarios.

The FEPs are classified according to their probability of occurrence in the timescale of interest. FEPs that are quite likely to occur are used to define the natural, or expected, evolution of the site and its environment, in the absence of any major disturbances. This is known as the “base scenario”. The less likely FEPs are used to define a number of alternative scenarios.

In 10 CFR 61, Section 50 (disposal site suitability requirements for land disposal), NRC has identified characteristics of sites that might be conducive to facility siting. These include a geologic and hydrologic setting that presents no undue hazards, and is simple enough to be characterized, modeled, analyzed, and monitored. Our concern in this section is with hydrogeologic FEPs that control or influence water-borne radionuclide transport, and which are or can be identified as part of site characterization.

The International Atomic Energy Act (IAEA) has also published guidance on the same topic (IAEA, 1999). IAEA/NEA has published a database of FEPs that have been considered at nuclear sites in many countries (OECD/NEA, 2000). FEPs to be included in the PA must be evaluated on a site-specific basis, and confirmed in the PA examination process. A number of groups have compiled lists of site FEPs and scenarios under which these may be important (Guzowski, 1990, and Guzowski and Newman, 1993).

Idaho National Laboratory (INL) has published an exhaustive summary of unsaturated zone FEPs for which there is considerable uncertainty (Wood *et al.,* 2000). The document reviews unsaturated zone investigations conducted at INL between 1960 and 1999. It makes recommendations for programs to address issues with spatial variability, data, numerical models, conceptual models, source terms, geochemistry and microbiology, as well as organization and communication.

Some of the FEP uncertainties that can be reduced through monitoring are:

- changes in redox conditions along flow path,
- uncertainties in K_d, and the conditions under which it is valid,
- uncertainty in fluid-matrix interactions,
- possible chemical alteration of sediments from reaction with leaked fluids (Pruess et al., 2002), and
- uncertainty in assumptions about dispersion, both horizontal, and vertical (dispersion is often used as a proxy to account for flow controls).

Each hydrogeologic FEP represents a factor to be considered in a PA, and may be critical to site-specific monitoring plans. Such FEP lists should be reviewed, and appropriate PIs and DSIs selected for the preliminary PI list.

DSIs derived from analysis of site characteristics or data analysis are discussed in Chapter 8 of Volume II, including examples of the identification of outliers through multivariate data analysis.

3.2.2.5 Elicitation of PIs from Analysis of a Facility

A systems analysis of the facility should be performed to determine normal operating ranges and possible failure modes, and what could be measured to indicate a failure. For reactor or processing facilities, at least part of this analysis should be available from the Safety Analysis Report.

Floor joints, floor-to-wall seals, drains, wall or floor piping openings, and other potential points of release to the environment should be considered as potential monitoring points.

PI definition is a function of technical requirements for the facility design envelope. The facility design envelope technical requirements are quantitative values identifying optimal performance. The facility design envelope defines the technical requirements that outline the expected performance ranges and identifies those parameters that are critical to overall system performance; e.g., hydraulic performance, structural stability, projected system durability, etc. To illustrate this overall process, a hypothetical Low Level Radiological Waste Disposal Facility will be examined in the following paragraph.

The facility footprint is static but the overall system is dynamic. An example to illustrate these concepts for selecting appropriate performance parameters is a near surface radiological waste disposal facility. The facility is a complex system incorporating various components and materials; the design of which is driven by its primary intended functions. The covered trench is an old and simple disposal concept consisting of waste in trenches covered with soil. Disposal sites using this concept frequently have retrofitted engineered barriers. A generic cross-section is shown in Figure 3-3.

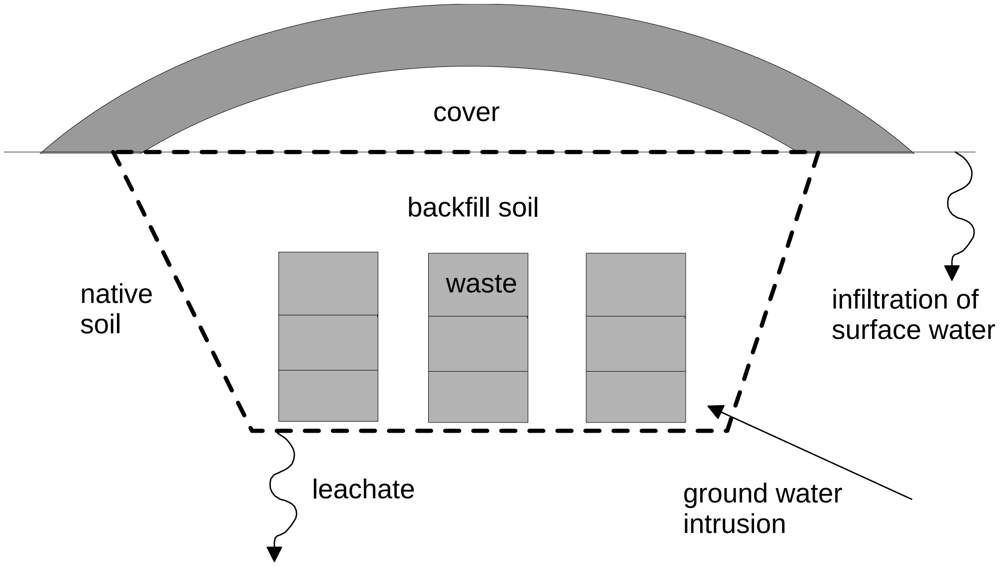


Figure 3-3 Cross-section through a generic disposal trench

There are a number of pathways by which radionuclides and hazardous waste constituents may migrate from the waste to ground water, including:

- infiltration of surface water,
- ground water intrusion,
- migration of contaminated water (leachate), and
- movement of gases in vadose zone (An example is discussed in Volume II, Chapter 4 for the USGS ADRS).

Each of these pathways provides opportunities for monitoring. Moisture distribution in a cap or cover, changes in water table elevation, and contaminants or indicator parameters detected in lysimeters or wells are all potential system PIs.

For an engineered system, a PI could be any characteristic or consequence that would indicate degraded performance. These should be derived from a careful review of the facility design and performance requirements of the engineered system. The PI provides a measurable quantity related to performance to support an overall system understanding and to assess the quality, reliability or effectiveness of an engineered system, as a whole or of particular aspects or components (IAEA, 2003).

An example of a measurable quantity for an engineered system component is the hydraulic performance of an engineered barrier. Degradation of barrier component hydraulic performance is a predominant effect and may be a Derived System Indicator in shallow waste disposal facilities. EPA, 2006, reports on final results of the evaluation of a compacted clay barrier near Albany, N.Y. as part of the Alternative Covers Assessment Program (ACAP), and suggests that the site's wet/dry cycles and root penetration caused the clay barrier to begin failing within the first eight months of service. These findings are similar to those of other ACAP laboratory and field studies showing that conventional clay barriers also degrade quickly in cool/humid or warm/dry environments and only minimally reduce percolation. An evapotranspiration cover seemed to perform better than compacted clay alone at the Albany site. (EPA, 2006). This effect portrays the degraded effectiveness of the engineered system as a whole and the necessity to adapt a monitoring strategy that can indicate degrading performance conditions. A direct impact of this effect is an unexpected accelerated release of short lived radionuclide contaminants into the biosphere. Engineered system designs should incorporate a multiple barrier configuration to compensate for component degradation.

From the standpoint of monitoring system design, it should be assumed that landfill covers will fail far short of any 30-year design lifetime. Monitoring should be planned at the time of landfill design and, if possible, integrated into the engineered facility.

3.2.3 Class 3: Indicators Derived from Data Analysis or Modeling

Derived System Indicators (Class 3 PIs) are derived from data analysis or are components of ground water or geologic modeling to which PA results are sensitive. Data analysis may be as simple as producing a contoured map; may involve computer methods such as cluster or factor analysis; or may include evaluation of computer model predictions.

Some examples are presented as part of the discussion, and others are described in detail in Chapter 8 of Volume II. Additional discussion illustrating derivation of performance indicators is in Section 4.3.2, below.

The discussion in this section illustrates the process of deriving indicators through data analysis and modeling. Many of the PIs actually called out in this section are Class 1 (Chemical) or Class 2 (Physical PIs), but in document construction, it seemed more logical to keep the PA and facility discussion (above – including Class 2 and 3 indicators) intact. This document is a review draft, it follows that we invite clarifying reviewer comments.

3.2.3.1 Indicators from Performance Assessment

This section discusses the PA process in a context of PI development. A more generalized discussion is in Chapter 4.

A site-specific PA can be used to identify PIs which may be used to test the assumptions and results of the PA. In order for this to work, the PA must be subjected to a sensitivity analysis.

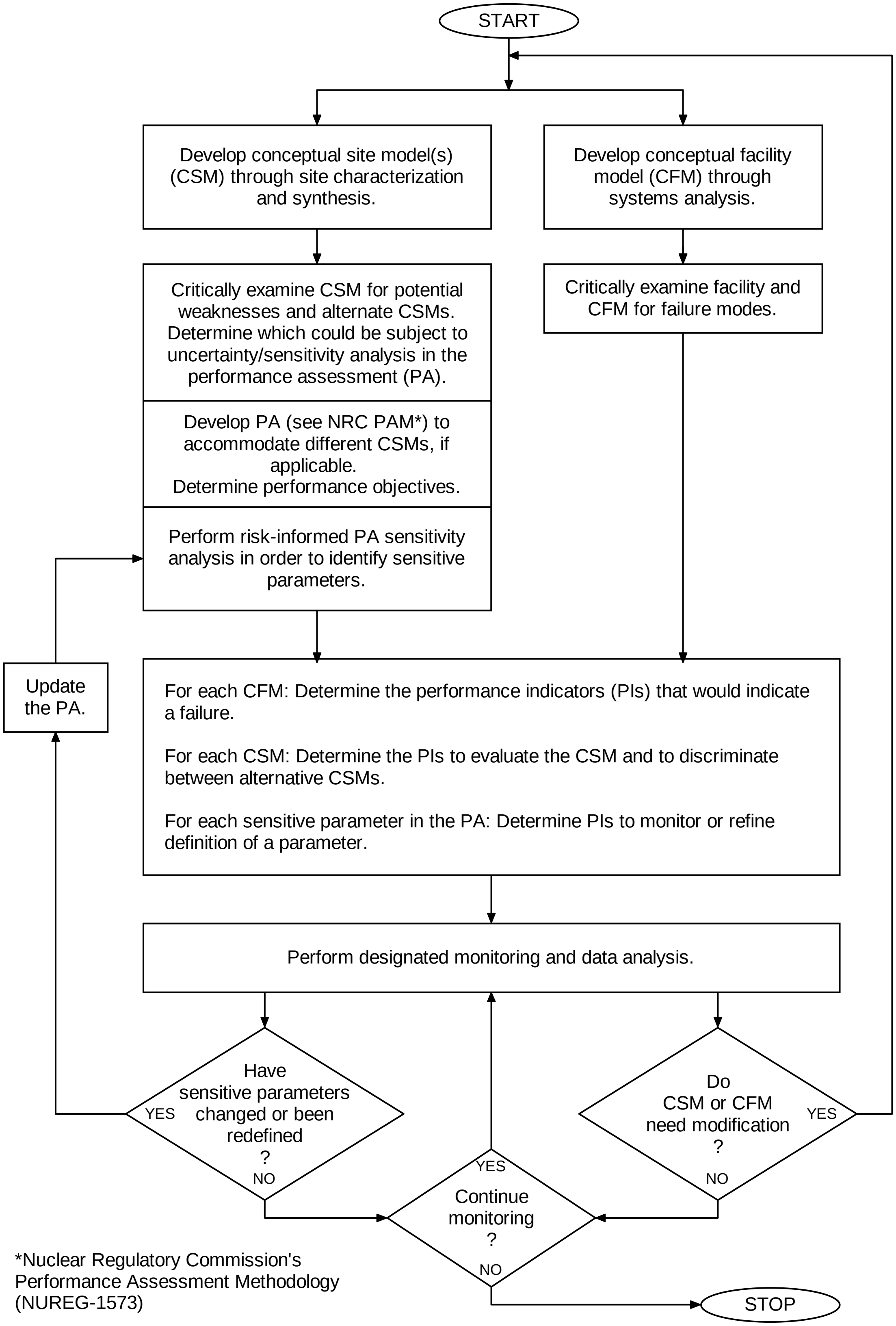
The process of iterative PA development, as outlined in Figure 3-4, assumes a probabilistic approach. NRC has developed a methodology for development of PAs of LLW disposal facilities (NRC 2000).

PA development begins with some conceptual understanding of the facility and the site, based on what data are initially available from site characterization (see Figure 3-4). For an operating facility, some information should be available, but for legacy sites (or for proposed sites), a site characterization may have to be performed as a starting point. Given one or more CSMs and (if a facility exists) a conceptual facility model (CFM), one may embark on a preliminary version of the PA. As the PA is developed, the analyst should consider its weaknesses and data gaps as potential PIs.

As emphasized in Neuman and Wierenga (2003) and their discussion of Bevin's work (Bevin 1993, Bevin 2000, Bevin and Freer 2001), the analyst must be aware that many CSMs may fulfill the requirement of agreement with available data. The analyst must pick a starting point and proceed, without the misconception that the selected model is correct *a priori*, but with the intention of testing the CSM through monitoring (and the PA, which is the modeled implementation of the CSM) as a working hypothesis.

Those input parameters or PA models that are highly uncertain will be subjects for an uncertainty analysis, which identifies how the parameter uncertainty affects the uncertainty of the PA results (being ground water concentrations, dose, or risk). A sensitivity analysis identifies which of these parameters are the most significant to some endpoint in the model (e.g. dose to a hypothetical future human receptor) and appropriate indicators (i.e. a measurable component) should be developed. A flexible PA is desirable—one that will accommodate the most probable conceptual models, perhaps even simultaneously.

The PA must also be constructed to produce specific results. Most importantly, it must evaluate the site's compliance with performance objectives, which are defined by the regulations driving the PA. For NRC's work, these regulations are derived from 10 CFR 61, but associated regulations for disposal of radioactive wastes (which could be construed to include the residuals of a decommissioned facility) include 40 CFR 191, 40 CFR 194, and DOE Order 435.1. The performance objectives are all rooted in risk and can be used to derive system PIs.



*Nuclear Regulatory Commission's
Performance Assessment Methodology
(NUREG-1573)

Figure 3-4 The relationship between performance assessment and monitoring

Through sensitivity analysis, the PA relates the CSM to the performance objectives, and provides information on what is most important to the process. Those parameters and processes that are most significant are the ones to examine as possible PIs. In some cases, the PA monitoring plan depends entirely on the existing regional monitoring network at a site, thereby saving substantial costs in developing new monitoring wells (INEEL 2002, WSRC 2000).

At this point, different kinds of uncertainty will be identified. Each of the contributors to uncertainty in the PA can be used as an indicator of performance. Some examples are given below and in Table 3-2.

- <u>Precipitation: an example of aleatory uncertainty (natural variability)</u>. In some cases the nature of the distribution is not shaped by ignorance, but rather by the variability in space and/or time. An example of this is precipitation. Even though recording of precipitation will not reduce its variability, if it is a sensitive parameter in the model, it could be selected as an appropriate PI. Such monitoring will help to identify when some precipitation event lies outside the assumed PA distribution, or it may suggest that a PA model that assumes some spatiotemporal average precipitation be modified to account for transient effects in infiltration.

- <u>Disposed inventory: an example of epistemic uncertainty (incomplete knowledge)</u>. There are many examples in the radioactive waste management world where our knowledge of the makeup of a legacy disposed inventory is very poor. Short of a thorough excavation and physical analysis of the disposed materials, a process which most site managers are loathe to undertake, the analysis may have to rely on poor records and aging memories of site workers. In this case gross alpha, non-volatile beta, or gamma ray detection could be used a PI.

While the PA may have to accept these uncertainties, the sensitivity analysis will always identify other parameters whose distributions can be refined (narrowed), resulting in a reduction of overall uncertainty in performance objective results. Some examples follow:

- Soil/water partition coefficients (K_ds, or distribution coefficients) are generally not known for a specific site. Preliminary values are often taken from the literature, and have wide (generally lognormal) distributions. Because contaminant transport is heavily dependent on site-specific K_ds, these are likely to show up as sensitive parameters, and are good candidates for uncertainty reduction through site-specific *in situ* or laboratory analyses. Such analyses have been performed in support of LLW disposal at Los Alamos National Laboratory, the Savannah River Site, and the Nevada Test Site.

- An example of a sub-model that may be a sensitive component in the overall model is the unsaturated zone hydraulic conductivity modeled as a function of water saturation. The unsaturated flow component model of a given PA may implement one of several mathematical models, including van Genuchten (1980), Brooks and Corey (1964), or the Rossi and Nimmo (1994) modification to Brooks and Corey. In essence, this represents conceptual model uncertainty

> manifested in mathematical form. If there is any question about which of these models is most appropriate for a given site, the PA may incorporate all three, selecting different models for different realizations in the stochastic Monte-Carlo runs. One of these models may be found to produce more reasonable results, depending on site conditions, and the material properties associated with that model may be subject to additional investigation, further refining the performance objective estimates.

Once a sensitivity analysis has identified those parameters or processes to which the model's outcome is sensitive, the analyst must identify which of those might be suitable for further investigation as PIs (Figure 3-5). The resulting list of potential PIs needs to be discussed with the rest of the project team (geologists, hydrologists, hydrogeologists, ecologists, and environmental engineers) to determine which are feasible for implementation as monitoring subjects.

Other PI candidates are intermediate results in the PA, such as aqueous concentrations in ground water, surface soil concentrations of constituents of concern (COCs), or other media concentrations. These DSIs are useful intermediate results that provide indicators of system performance.

If a nuclear facility is not expected to release radionuclides to the environment for some centuries, and if the site behaves as expected, monitoring will provide only a partial confirmation of the PA, if nothing is ever detected. The monitoring should still be done, however, since detection in such a circumstance would prompt a revision of the PA. In the spirit of Karl Popper's philosophy of science, the PA can never be proven, but it can be invalidated (Popper, 1963). PIs should be chosen with the highest likelihood of disproving the PA hypothesis.

Table 3-2 is a list of PIs that could be derived from a PA. These could be monitored if they are determined to be risk-significant (by the sensitivity analysis following a probabilistic PA that includes risk assessment) or if they fill potentially significant data gaps. Most of these are dynamic, meaning that they have a temporal component. The changes through time will have to be evaluated in order to determine whether the variation needs to be modeled, or if perhaps some sort of temporal average will suffice. Many are spatially variable as well, and a similar determination will have to be made. Note that a preliminary list of PIs developed from a PA may well have some of the same entries as a list developed from site or facility analysis. This redundancy in the list development process helps assure that important PIs are not missed.

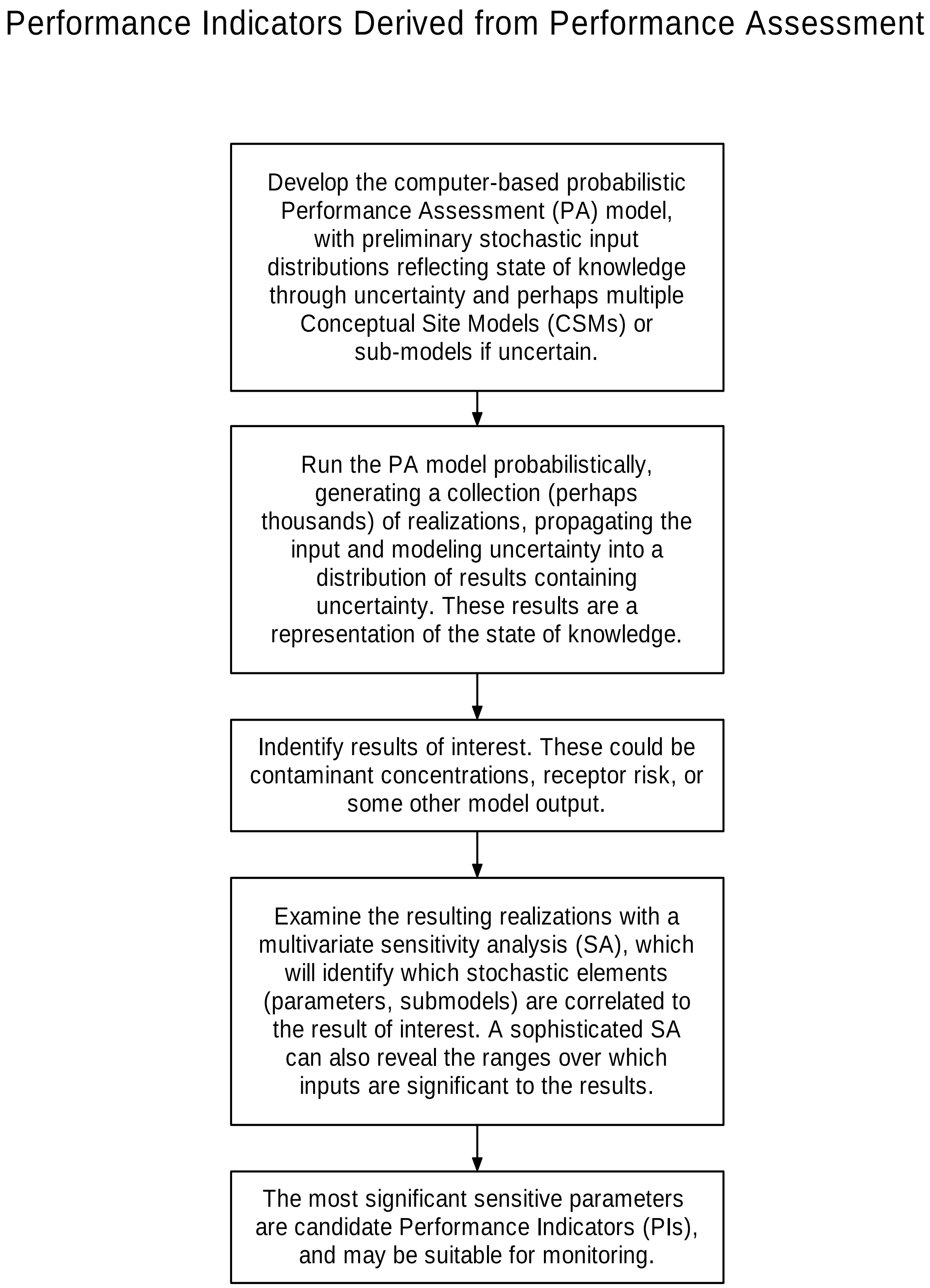


Figure 3-5 Performance Indicators derived from Performance Assessment

Table 3-2 PIs for ground water that can be derived from the PA

Performance Indicator	Significance
water chemistry (*e.g.* pH, alkalinity, major cations and anions)	affects contaminant transport through speciation, solubility, partitioning, etc.
unsaturated zone (UZ) moisture content profile	affects UZ hydraulics and water flow
water table elevation	affects UZ travel times and "smearing" of contamination at the water table
aquifer (saturated zone, SZ) properties, such as hydraulics, flow rates, dispersivities	affects SZ transport: dispersion and travel times
contaminant aqueous concentration in leachate	output of waste sub-model; input to UZ model
contaminant aqueous concentration in recharge water	output of UZ sub-model; input to SZ model
contaminant aqueous concentration in SZ, perhaps in various places	output of SZ sub-model; summary output to the whole transport model; input to the dose model (ground water ingestion and irrigation pathways)
contaminant gas phase concentration in the UZ	immediate data for volatiles (e.g. ^{3}H, TCE); may be useful in tracer work or at sites where RCRA volatiles are involved
contaminant concentrations in surface water, if ground water discharges are modeled	provides data for comparison to ground water discharges
ecological assemblages, concentrations in ecological media (plant and animal tissues)	aids in evaluation of biotically-induced transport (disruption and translocation of contaminants) and in ecological exposure (risk assessment)
human health risk assessment exposure parameters, such as demographics, land use, individual behaviors, dose conversion factors, dose pathways, etc.	these are critical inputs to the dose assessment model
Atmospheric dispersion parameters (meteorological data, such as stability arrays)	critical input to atmospheric dispersion models

3.2.3.2 Derived Indicators from Flow Models

The flow and transport models will estimate water heads and concentrations of chemical components at points within the modeled area. Thus the comparison of the parameters predicted from the model to measurements at monitoring points is indicative of model validity. Variation between predicted and measured heads or predicted and measured concentrations indicates that the system is not performing as modeled.

While the reliability and accuracy of even a calibrated model is inherently unknown (Neuman and Wierenga, 2003), it can be tested against PIs. A performance indicator in this case would be a measured field quantity such as hydraulic head or spring discharge rate that has not been used in the calibration process. Typically, historical data are used in the calibration process, while new data (in space, time, or space and time) are used as PIs. The key distinction between calibration targets and PIs is that the model must be able to predict the value of the PI without any adjustment. Successful prediction of PIs is known as model validation. Unfortunately, this validation step is often omitted in studies.

If only hydraulic data are used as PIs to validate the flow model, then the model is only valid for prediction of these types of hydraulic variables. Since the main goal of the flow model is usually to provide an accurate distribution of flow velocities to the transport model, additional flow model validation using the coupled flow and chemical transport model is required. Some basic challenges to the flow model validation using hydraulic PIs are:

> *Was the model adjusted to match the PI?* If so, this is not validation but just further calibration.
>
> *Is the PI sensitive to site conditions and behavior?* If the PI does not change much with changing conditions, then matching it is not very demanding.
>
> *Is the PI relevant to important site behavior?* If the PI is largely irrelevant, then so is the validation performed using it. Unfortunately, common hydraulic measurements, such as hydraulic head, may not be of primary importance in the successful prediction of chemical transport. While it is still necessary to correctly predict the heads, this does not guarantee that the flow model is predicting the correct velocity distribution. On the other hand if the rate of water discharge to a sensitive wetland is important, then this discharge makes an excellent PI.

3.2.3.3 Performance Indicators from the Coupled Flow and Chemical Transport Model

It is best to validate the flow and transport models simultaneously using all available hydraulic and chemical data. Chemical data used as PIs consists mainly of chemical concentrations measured in observation wells (that have not been used in the calibration process). Natural or forced gradient tracer tests can be performed at uncontaminated sites to provide these data. If chemical concentration data of some type are not available, the coupled model cannot be validated. The same basic questions apply to the validation of the coupled model as to the flow model:

> *Was the model adjusted to match the PI?* Not allowed for validation.

Is the PI sensitive to site conditions and behavior? This is less likely in the case of chemical concentration data PIs.

Is the PI relevant to important site behavior? The most relevant data are contaminant concentrations, but reactive or non reactive tracer concentrations are also useful. Again, the model is only validated for the processes that it actually predicts.

3.2.4 Performance Indicators from a Bioremediation Project

Long and Yabusaki (2007) discuss evaluation of a uranium bioremediation project at the DOE Hanford Site. They focus on some monitoring needs and present a table of indicators of performance for the project. This table is adapted below to provide an illustration of site- and project-specific PIs.

The first column in Table 3-3 lists the PI type from Table 3-1 which best matches the PI described by Long and Yabusaki (op. cit., Table 5.1). Note that their Table 5.1 includes not only performance indicators, but CSM features and recommended information for project planning.

Table 3-3 Examples of Recommended Information and Performance Indicators for Bioremediation Project (after Long and Yabusaki, 2007)

AES PI Class	***Information area/Parameter/Method***	***Desired Range***	***Comments***
	Remediation process conceptual model	NA	Fundamental to prioritization of monitoring parameters
1 / CSM	Depth-discrete data for mandatory geochemical parameters	NA	Characterizes spatial distribution of fundamental biogeochemistry in aquifer
1 / CSM	Depth-discrete data for desirable monitoring parameters	NA	Characterizes spatial distribution of desired biogeochemical reactions in aquifer
1 A/C	*In situ* redox status of U using *in situ* sediment incubators (ISIs)	Significant U(IV) present	Evidence that precipitation of U(IV) is occurring *in situ* obtained via differential U extraction.
1 B/C	Organic and inorganic carbon analyses	NA	More accurate documentation of carbonate geochemistry
1A / CSM	Background U(VI) concentration, monthly or bi-monthly and event-base (e.g., high water table)	NA	Number of sampling points based on plume and treatment zone complexity and size (including depth)
1A / CSM	Treatment zone and down-gradient U(VI) concentration	Below MCL	Number of sampling points based on plume and treatment zone complexity and size

1A / CSM / 3B	Depth discrete U(VI) data (upper/mid/lower part of contaminated zone)	Regulatory Compliance Criteria	Decreased effectiveness of treatment in the uppermost part of the saturated zone may be problematic
1B	Major dissolved gas components in ground water	NA	Evidence for key TEAPs and microbial metabolism
1B – ratio is indicator of process	*In situ* redox status of U by direct sampling of *in situ* materials		U(IV)/U(VI) measurements on *in situ* sediments provide "ground truth" for U bioreduction
1B / 1C	Tracer for electron donor	>0 in treatment zone	Typically Br is used for conservative tracer, accurate indication of donor distribution
1C	DO, ORP, specific conductivity, and pH measured hourly to 4 times daily in background and treatment zone (autonomous multiparameter probes)	DO<0.5, ORP<0, conductivity initial increase, pH ~ steady	Values used as overall dynamic indicator of impact of bioremediation on subsurface geochemistry
1C	DO, ORP, specific conductivity, and pH measured at time of ground-water sampling in background and treatment zone using flow-cell with multiparameter probe	See above	Linkage of U(VI) concentrations with parameter change evidence for bioremediation process conceptual model
1C	Aqueous electron acceptors and reduction byproducts in background and treatment zone: nitrate, nitrite, ammonium, Mn(IV/II), sulfate, sulfide	NA	Significant concentrations of oxygen and/or other electron acceptors above the U TEAP on the redox ladder must be addressed by the bioremediation strategy and their reduction products monitored. Sulfur isotopic analyses may provide supplemental information.
1C	Fe(III) mineral abundance	NA	Fe(III) minerals provide sorption sites for Fe(II) & U(VI), terminal electron acceptor for Fe-reducing bacteria, dissolved Fe(II) source
1C	Fe(II), sulfide measured in field at time of sampling for U(VI) (up gradient, treatment zone, and down gradient)	Increasing Fe(II); sulfide indicator of sulfate reduction	Maintaining metal reduction may optimize U(VI) removal from ground water; sulfate reduction may enhance long-term immobilization in sulfate-rich systems

1C	Electron donor concentration in treatment zone	>0	Evidence of delivery and treatment zone distribution; consumption calculation based on tracer data
1C	Alkalinity (measured in the field)	NA	Indicator of carbonate geochemistry, dissolved carbonate/bicarbonate forms strong anionic complexes with U(VI) to decrease its adsorption and increase its solubility and mobility
1C	Major cations and anions	NA	Provides additional evidence for dominant geochemical aqueous complexation and mineral solubility reactions
1C	Microbiological assessment using coupons or *in situ* incubators	Shift to metal and/or sulfate reduction	Evidence for desired *in situ* microbial respiration obtained from deploying coupons or *in situ* incubators in well bores and periodically measuring microbial parameters (see text for additional discussion)
1C	Microbiological assessment performed directly on sampling of treatment zone materials	Shift to metal and/or sulfate reduction	Measurements directly on ground-water filtrates or sediment cores provide "gold standard" assessment of microbial community structure (e.g., PLFA, 16S, DNA / RNA chip arrays, or functional chip arrays)
1C	Form and mobility/lability	± 30% of estimate	Experiments and sediment extractions to identify uranium form and potential for future mobility based on labile fraction
1C / CSM	Depth-discrete sediment sampling/extraction for U, Fe, AVS	NA	Evidence for conversion of terminal electron acceptors
2	Temporal recharge	±20%	Seasonal and episodic impact to unsaturated flow, extreme recharge event and impact must be considered if flooding probable at the site
2	Ground-water flow velocity (Darcy flux) and direction	±30% of estimate	Seasonal and episodic impact critical

2	Water table dynamics (use hourly data as event-based geochemical sampling driver)	NA	Relationship between water table and U concentration critical
2	Site hydrogeology: hydraulic conductivity, porosity, dispersivity, hydrofacies	NA	Fundamental to both site and process conceptual model
2	Particle size characteristics	NA	Reactive surface area, clays, upscaling lab to field
2	Impact of treatment process on ground-water flow directions (hourly water level at minimum 4 points)	Dependent on background flow	Helps to provide assurance that ground water is not rerouted around treatment zone
2	Time-lapse GPR Cross-well or Electrical Measurements	Shift in geophysical attributes in zone of electron donor	Indicates 2-D distribution of electron donor, although impact of other transformations on geophysical signatures must be assessed and errors associated with tomographic inversion procedures can 'smear' amendment boundary.
2 / CSM / 3?	Impact of treatment process on hydraulic properties	<15% change	Documents possible system clogging of pores
2/ CSM	Vadose zone hydrogeology: porosity, water retention function parameters	±20% of estimate	Seasonal and episodic impact to flow direction critical
3	Time-Lapse Electrical Resistivity and Self Potential Tomography	NA	Can indicate the 3-D distribution of dominant TEAP's
3	Time-Lapse Seismic Tomography	NA	Sensitive to gas evolution and secondary mineral precipitation
3B / Rem Design	Spatial extent of contamination zone (plume geometry)	±20% of estimate	Differentiate between vadose zone and aquifer concentrations; aqueous and sediment associated uranium; geometry drive layout of bioremediation system
NA/CSM	Site conceptual model for uranium source term	NA	Consideration of alternative conceptual models critical
NA/CSM	Site conceptual model for subsurface (vadose zone and ground-water) flow and contaminant transport	NA	Consideration of alternative conceptual models critical

4 Modeling to Support Site Performance Assessment

4.1 Introduction

Performance Assessment for most sites requires a quantitative analysis that uses the CSM in conjunction with flow and transport modeling. For example, the Groundwater Modeling System (GMS), a commercial modeling/visualization software package, can be used for developing water flow and contaminant transport models and presenting the results visually. A very simple site may be assessed qualitatively by reviewing the CSM and quantitatively by using an analytical solution of contaminant transport.

The PA process is conducted iteratively starting with the analysis of generic and limited site-specific information in support of relatively simple conceptual models, and progressing to more realistic, site-specific and detailed analysis, such as a numerical and stochastic modeling, to reduce uncertainty in assessing performance of the site (NRC, 2000). Modeling begins with an assessment of the purpose, goals and objectives of the PA.

Statistical analysis to determine if existing populations of data can be extrapolated using predictive models can be used to fill data gaps based on regional geologic/hydrogeologic concepts. This is illustrated in Section 4.3.1, below. Statistical methods can also be used to evaluate data uncertainty if current values are unacceptable.

After the local model is verified to be in compliance with the regional model, critical flow paths relevant to the PA should be identified. As a further check these local flow paths should be compared to regional flow paths to determine if there is a reasonable fit, and if not an explanation should be developed that can be supported with actual data.

4.1.1 What is the Purpose of the Modeling Effort?

The most important issues to address during the review of any modeling report are 1) What is the purpose of this modeling effort? And 2) Does the model reliably accomplish this purpose?

It is important to determine if the purpose of the modeling effort is reasonable in view of the site history and conditions. The typical reasons for performing a modeling study at a site are:

a) to describe possible contaminant pathways and travel times to human or ecological receptors at a site where contaminant releases have not yet occurred,

b) to predict pathways, travel times, and concentrations at receptor locations for a site where a release has occurred, but where the current extent of contamination is limited,

c) to identify and refine the CSMs and to estimate model parameters,

d) to identify data to which model results are most sensitive, through sensitivity analysis

e) to predict plume behavior, and to help document natural attenuation processes at a site where ground water contamination is extensive,

f) to design and manage remediation systems to control or remove ground water contamination,

g) to evaluate and update the existing monitoring network,

h) to evaluate regulatory compliance,

i) to estimate potential doses to a receptor at some point in the future.

Modeling studies whose purpose is to satisfy goals a), b) or c) usually are smaller and less sophisticated than those whose purpose is to satisfy goals e), f) or g).

4.1.2 What is an Appropriate Level of Effort and Sophistication for the Modeling Study?

An important and obvious metric for choosing the level of effort given to a modeling study is an assessment of the current or potential threat the site poses to human or ecological health. The first question to ask is: *What is the overall mass and toxicity of the chemicals at the site?* If either the chemical mass or the chemical toxicity is very low, then obviously there is little reason for computer simulation of flow and chemical transport. Potential risk may be demonstrated to be low with a simple “back of the envelope” calculation. If the contaminant mass and toxicity are high, then the next task should be to asses the potential risk of chemical transport in the ground water. This potential can be approximately quantified by

> *threat = (likelihood of a release) × (mobility of chemical) × (persistence of chemical) × (ground water velocity) × (inverse of distance to sensitive receptor)*

If each of these five variables is high, then the threat posed by the site is very large. If three or four of the five variables are high, the threat is lower, but still significant, while if only one or two of the variables are high, the threat is smaller. The modeling effort should be consistent with the threat level, and sites where the threat is high deserve a comprehensive flow and chemical transport modeling effort. These cases should use flow models such as class F4c or higher (as identified in Table 4-1), coupled with chemical transport models C3 or higher, depending on site conditions. If a site has a low threat level, then a comprehensive modeling effort is likely not justified, and simpler models such as F0 through F3a and C0 through C3 may be appropriate.

The amount and quality of site geologic, hydrogeologic, and chemical data should also be consistent with the magnitude of the ground water threat. Thus it should be expected that sites that pose lower risks will have less field data for constraining and calibrating models. This would be an additional justification for use of simpler models that do not have large data needs. Sites that pose higher threats typically (but not always) have more field data for constraining and calibrating more complex models. The sophistication and level of detail in the models must be consistent with the quality and quantity of field data.

4.2 Selection of Appropriate Flow and Transport Models

Site specific ground water models, like the CSM geologic portion, must also be developed in the context of the regional ground water flow and transport paths. All too often the ground water model developed for a site is in total disagreement with the regional data. As the local model is developed it must be compared and adjusted so that it fits into the regional ground water flow regime.

Conceptual hydrogeologic models are developed for a site as abstractions of existing characterization and monitoring data. Each possible interpretation of the data is a working hypothesis, to be confirmed, improved, or rejected as new data are obtained (Chamberlain, 1890).

It is very important to select a model or models that are consistent with the modeling purpose, and with the quantity and quality of the site data. Many modeling efforts give poor or unreliable results because these basic considerations are not observed.

Models are constructed from site characterization data that can include, but are not limited to: local and regional geologic setting, geophysical logs, cone penetrometer (CPT) logs, core descriptions, core property measurements, field mapping, fracture studies, geophysical surveys (e.g. seismic, resistivity, electromagnetic, magnetic, gravity, natural radiation), aquifer test data, piezometer data, and water chemistry. The objective of a hydrogeologic conceptual model is to represent all the physical features of the site that can control subsurface movement of water or contaminants.

Analytical and numerical mathematical models of ground water flow and chemical fate and transport are commonly used at both contaminated and uncontaminated sites. The complexity and capabilities of available models vary tremendously, ranging from simple one-dimensional, steady-state analytical solutions, to comprehensive three-dimensional transient numerical solutions. Analytical solutions are exact algebraic solutions to governing differential equations. Derivation of these solutions always requires making simplifications to the problem geometry, parameter distributions, and time dependency. In many instances, these simplifications or assumptions are reasonable, and in these cases, analytical solutions provide very efficient and easy-to-use tools. Analytical solutions are commonly used in cases where field data are limited, or where rough estimates are sufficient for decision making.

In many instances, the problem geometry, boundary conditions, parameter distributions, or chemistry may be too complicated to be represented by an analytical solution. In these cases, numerical flow and transport models are commonly used. A numerical model recasts the governing differential equations into discrete algebraic equations, and the variables of interest (hydraulic heads, chemical concentrations, etc.) are solved for at discrete points in space and time. Numerical solutions are always approximate solutions to the governing differential equations, but in most cases, they can be mathematically very accurate. Numerical models have the advantage of allowing for flexible three-dimensional geometries, complex parameter distributions, and fully transient behavior. This flexibility and complexity, however, must be balanced with the quality and quantity of site data. In other words, a sophisticated numerical model can only provide results that are as reliable and complete as the data used to help construct the model.

As a general rule, it is advisable to use a graded approach, starting with the simplest possible model for a site and increasing the complexity of the model only as the site data and site needs justify it. At each stage in the process, consistency checks must be made, and the different models should generally support each other.

4.2.1 Types of Flow and Transport Models

The three basic types of models used at field sites are ground water flow models, chemical fate and transport models, and multiphase flow models. These three categories of models are often used independently, but they can be combined in many instances as well. For example, a chemical fate and transport model requires information on the ground water velocity field. One approach is to simply assume a simple one-dimensional uniform ground water flow field, and then solve the chemical fate and transport equations.

A more flexible approach couples a chemical fate and transport model with a ground water or multiphase flow model. With this approach, the flow field is calculated by the appropriate flow model, and the velocity field is passed on to the chemical transport code. Depending on the problem, the chemical transport may affect the flow field (for example if the fluid density changes due to high dissolved solids), and in this case the flow and transport should be fully coupled. One-way coupling, where the flow field is assumed to be independent of the chemical transport is used for most problems involving ground water contamination, while full coupling is commonly used in multiphase flow problems such as high-level waste isolation modeling.

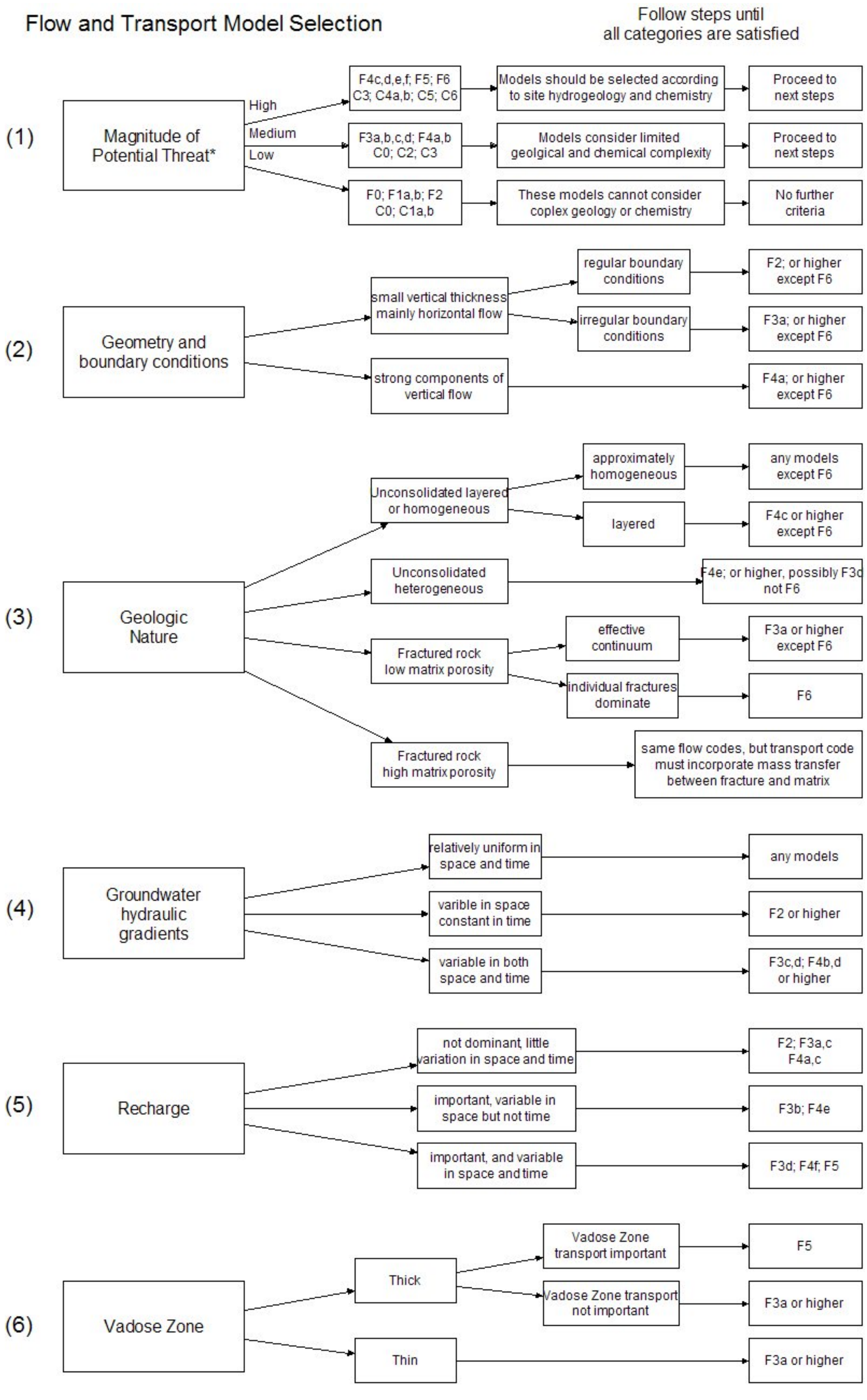
Table 4-1 lists different categories of ground water flow models, and Table 4-2 lists different categories of chemical fate and transport models. The various flow and chemical transport models can be combined in many ways, depending on the site. For example, it may be appropriate to use a very simple flow model with a very complex chemical fate and transport model at a site where the ground water flow is nearly uniform, but where the contaminant fate and transport involves complex reactions of multiple species. Similarly, it may also be appropriate to use a very complicated flow model with a very simple chemical fate and transport model at a site where the geology is complex, but well understood, and contamination is either nonexistent, or characterized by simple advective transport. Figure 4-1 and Figure 4-2 illustrate the model selection tables in decision tree format.

Table 4-1 Categories of ground water flow models

Model Category	Solution Method, flow type	Dimensionality	Time Dependency	Permeability Distribution	Infiltration
F0	None; GW flow velocity assumed	One	Steady-state	Homogeneous	Not considered
F1a	Analytical GW	One	Steady-state	Homogeneous	Variable in space
F1b	Analytical GW	One	Transient	Homogeneous	Variable in space, time
F2	Analytical GW	Two (x-y)	Steady-state	Homogeneous	Constant
F3a	Numerical GW	Two (x-y)	Steady-state	Homogeneous	Constant
F3b	Numerical GW	Two (x-y)	Steady-state	Heterogeneous	Variable in space
F3c	Numerical GW	Two (x-y)	Transient	Homogeneous	constant
F3d	Numerical GW	Two (x-y)	Transient	Heterogeneous	Variable in space and time
F4a	Numerical GW	Three	Steady-state	Homogeneous	constant
F4b	Numerical GW	Three	Transient	Homogeneous	Variable in time
F4c	Numerical GW	Three	Steady-state	Layered	constant
F4d	Numerical GW	Three	Transient	layered	Variable in time
F4e	Numerical GW	Three	Steady-state	Fully heterogeneous	Variable in space
F4f	Numerical GW	Three	Transient	Fully heterogeneous	Variable in space and time
F5	Numerical multiphase	Three with dual domain capability	Transient	Fully heterogeneous	Variable in space and time
F6	Numerical fracture flow	Three	Transient	Heterogeneous fracture apertures	Not usually considered

Table 4-2 Categories of chemical fate and transport models. These are used with some type of flow model, and are almost always transient

Model Category	Solution Method	Advection-Dispersion	Adsorption	Reactions	Coupling with flow
C0	Numerical, particle tracking	Only pathlines, two- or three-dimensional	None	None	One-way using GW velocity
C1a	Analytical	One-dimensional for both	Constant K_d	First order parent daughter	One-way, uniform GW velocity
C1b	Analytical	One-dimensional for advection, 3-D for dispersion	Constant K_d	First order parent daughter	One-way, uniform GW velocity
C2	Numerical	2-D for both	Variable K_d	First order parent daughter	One-way with GW
C3	Numerical	3-D for both	Variable K_d	First order parent daughter	One-way with GW
C4a	Numerical	3-D for both	Nonlinear adsorption isotherms, variable in space	Multiple species nonlinear reactions	One-way with GW
C4b	Numerical	3-D for both, dual domain system with mass transfer	Nonlinear adsorption isotherms, variable in space	Multiple species nonlinear reactions	One-way with GW
C5	Numerical	3-D for both	Nonlinear adsorption isotherms, variable in space	Multiple species nonlinear reactions	Fully coupled with GW
C6	Numerical	3-D for both, dual domain system with mass transfer	Nonlinear adsorption isotherms, variable in space	Multiple species nonlinear reactions	Fully coupled with multiphase flow



*Threat ~ (likelihood of release)x(chemical mobility)x(chemical persistence) x(groundwater velocity)x(inverse of distance to sensitive receptors)

Figure 4-1 Flow and Transport Model Selection

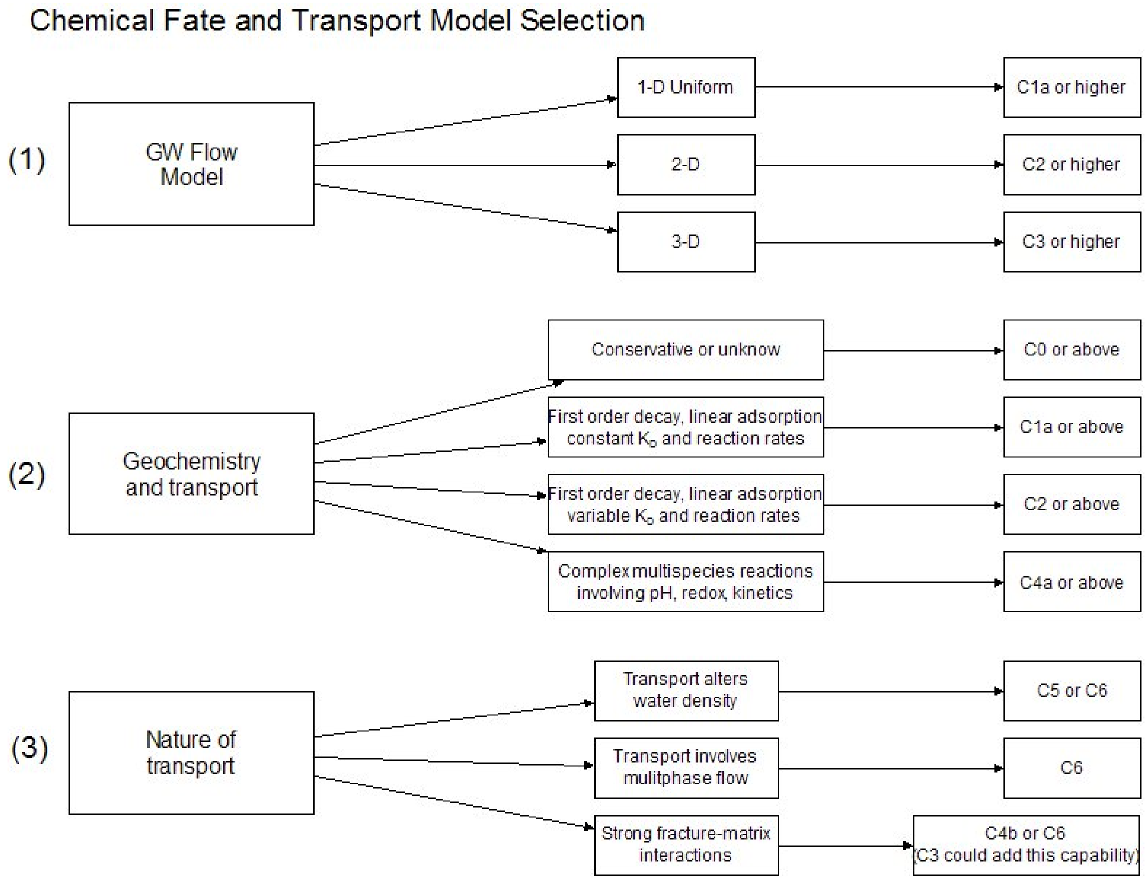


Figure 4-2 Chemical Fate and Transport Model Selection

4.2.1.1 Is the Flow Model Appropriate for the Site?

Assuming that the site poses a moderate to high threat to ground water, the following hydrogeologic considerations should guide the selection of the fluid flow model. Note that the model must be able to simultaneously address all of these considerations, so each consideration acts as a "filter", reducing the number of acceptable models.

Site Geometry and Boundary Conditions

a) Site has a very small vertical thickness compared to area, and flows are believed to be essentially one- or two-dimensional (e.g., wholly vertical or wholly horizontal). One or two-dimensional models may be appropriate (F0 through F3d). If the site has irregular boundary conditions, a numerical model (F3a-F3d) will be needed

b) Site has a large vertical thickness, or significant horizontal and vertical flows. A three-dimensional model is probably needed (F4a through F6)

Geologic Nature

a) Approximately homogeneous, unconsolidated – any of the flow models may be appropriate in this case, but be aware that no sites are truly homogeneous.

b) Unconsolidated, approximately layered. Models F4c or F4d could be appropriate, but more flexible models that consider full heterogeneity could also be used.

c) Unconsolidated, strongly heterogeneous. Models F4e, F4f, or F5 should be used. These types of models will have very large data requirements, however.

d) Fractured rock, low matrix porosity. If the flow can be considered as an effective continuum, then a standard ground water flow code can be used but if the individual fracture flows are important, then a fracture flow code (F6) should be used.

e) Fractured rock, high matrix porosity. The same flow codes usually apply here as in the low matrix porosity case, but the chemical fate and transport code will need to account for fracture-matrix interactions (C4b or C6).

Ground Water Gradients

a) Relatively uniform in space and time. Simple models (F0 through F3b) could be appropriate.

b) Variable in space, but constant in time. Steady-state models (F2, F3a, F3b, F4a, F4c, F4e) could be appropriate.

c) Variable in space and time. Transient models required (F3c, F3d, F4b, F4d).

Recharge

a) Recharge is not dominant, and doesn't vary much in space or time. Models F2, F3a, F3c, F4a, or F4c may be appropriate.

b) Recharge is important, and is highly variable in space but not time. Models F1a, F3b, F4e could be appropriate.

c) Recharge is important, and is highly variable in both space and time. Models F3d, F4f, F5, or F6 would be needed.

Vadose zone

a) Thick – the model may need to simulate flow through the vadose zone. If this effect of the thick vadose zone is expected to be dominant, then a multiphase flow code (F5) is required. Otherwise the vadose zone flow may be estimated.

b) Thin – a standard ground water model should be sufficient.

4.2.1.2 Is the Chemical Fate and Transport Ground Water Model Appropriate for the Site?

Because the chemical transport model is coupled in some way to the flow model, its choice is largely driven by the choice of the flow model. Beyond this, the transport model choice is driven mainly by the nature and complexity of the contaminant reactions.

Contaminant Geochemistry

a) Very simple conservative, or unknown. Particle tracking algorithm (C0) will show the likely path and travel time for a conservative tracer, but it will not predict concentrations.

b) Simple first order decay with linear adsorption, constant K_d and reaction rates. Models C1a through C3 could be appropriate, depending on the flow model.

c) Simple first order decay with linear adsorption, but variable K_d and reaction rates. Models C2 or C3 would be appropriate

d) More complex, involving multiple species, pH, Eh dependencies and kinetic (nonlinear) reactions. Model C4 would apply.

e) Transport of chemicals alters ground water density. Fully coupled models C5 or C6 would be needed. Multiphase flow (vadose zone) is needed. Model C6 is required.

g) There are strong fracture-matrix interactions. A dual domain model (C4b or C6) should be used.

4.2.1.3 How is the Flow Model Constrained?

A mathematical model may allow for a large range of values in its parameters. Numerical models further allow for flexibility in geometry and parameter distributions. In order to be meaningful and mathematically unique, the model must be constrained by hydrogeologic features or measurements. Even under the best of circumstances, there will still be some uncertainty in the values for some parameters, especially distributed parameters such as permeability. These uncertainties can be reduced by model calibration, which is discussed later. Some specific considerations:

Are the dominant geological features incorporated in the model? It is critical that the flow model, to the extent possible, include significant known geologic features that are believed to affect the hydrogeology. This is often an ongoing process where mathematical models are revised as more information becomes available.

Are the model boundary conditions well-defined? The mathematical model boundary conditions can have a tremendous influence on the calculated results, so they must be justified by hydrogeological features at the site such as constant head boundaries (rivers and lakes and swamps), or no-flow boundaries (very low permeability rock boundaries, sealed faults, permanent ground water divides). If the model boundary conditions are not well-defined, then it must be demonstrated that the model is insensitive to the boundary condition.

Are the spatially distributed parameters reasonable? Important parameters such as permeability and recharge can be highly variable in space (and time for recharge), but there are typically few measurements available. Nonetheless, it is important to at least show that these parameters are within expected ranges for the site location. These parameters are typically calibrated to develop the final site flow model.

4.2.1.4 How is the Chemical Fate and Transport Model Constrained?

Given a correct representation of the ground water flow field, the chemical transport model is constrained by measured chemical properties and concentrations from the laboratory, and from the field site. Chemical properties include basic properties such as density, molecular weight, solubility, radioactive (or biochemical) half-life, as well as more complex properties such as speciation, partition coefficients, and multi-species solubility relationships. These properties may be obtained from the literature, or they may be measured in batch experiments, though it has been shown that batch studies are poor estimators of adsorption behavior in the field. Other laboratory experimental data may include soil water distribution coefficients (K_d) and other local scale transport parameters. Field site constraints are often lacking or poorly defined. For example, if a ground water plume does not exist at a site, there will be few or no chemical field data for model constraint. Still, there are "reasonableness" checks that can be made on the model. The most important term in a chemical transport model is usually the chemical source term. This is the contaminant loading to the subsurface as a function of time and space. Unfortunately, this most important parameter is usually poorly constrained, and is often almost completely unknown. The uncertainty in the past and future source strength can lead to large uncertainties in the relevance of the model output. Some specific considerations for constraining a chemical fate and transport model are:

> *Are the dominant chemical reactions and transport phenomena accurately represented in the model?* The model must be able to reproduce laboratory experimental results, and the transport phenomena must be consistent with site conditions. Consideration should also be given to specialized chemical environments, such as conditions within a degrading concrete slab, or those of the surrounding natural environment.
>
> *Is the source term well defined by the field data?* In cases where the source term is known to a reasonable degree of certainty, it should be used as a primary constraint (i.e. boundary condition) on the model. If it is not well known, it may be used to calibrate the model, along with other parameters. For cases without any contamination, the source strength can be varied to show likely effects of various releases.
>
> *Are the boundary conditions realistic?* Chemical transport boundary conditions (other than the source term) usually consist of inflow and outflow conditions. The inflow condition would typically be a fixed background concentration or mass flux. The outflow condition should not artificially influence concentration phenomenology inside the model domain.

4.2.1.5 How is the Flow Model Calibrated?

The spatially distributed parameters (mainly permeability and recharge) are usually calibrated using an automated or manual technique. This process involves selecting measurements in space and time such as hydraulic heads in observation wells, or discharge from springs or creeks. The model parameters are then adjusted to get a best fit of the data. Note, however, that this best fit does not guarantee that the parameter set is unique, or that some other possible model configuration couldn't produce a better fit. Some questions that arise in model calibration are:

How sensitive is the calibration to the parameter? Calibration works best when a model fit of the calibration data is very sensitive to the parameter, but this is often overlooked.

Do the calibration data points give a good representation of the important site behavior? The calibration is meaningful only if it is relevant to the important site processes. Unfortunately, these are often not measured. For example, the ground water velocity distribution is of key interest to most sites, but this is difficult and expensive to measure (using, for example, tracer tests), so hydraulic heads are typically used as calibration targets.

Does the calibrated model fit the calibration data? Sometimes, a model configuration is incapable of fitting the site data well. In this case, the configuration should be discarded, and new conceptual models should be tested until a sufficiently good fit is achieved.

4.2.1.6 How is the Chemical Fate and Transport Ground Water Model Calibrated?

Calibration of the chemical transport model is similar to calibration of the flow model. Because the two models are coupled, calibration of the two is often done together. For example, the ground water flow velocities and directions determine the movement of dissolved chemical plumes. Therefore, the flow model can be calibrated by hydraulic heads, but it must also produce the correct flow field so that the chemical transport model matches the chemical plume. Aside from the flow field, the main chemical transport parameters are reaction rates, adsorption coefficients, dispersion coefficients, diffusion coefficient (for small Péclet numbers,) and in some cases, the source term, salinity, density, and temperature. Consideration should be given to the potential significance of changes in these properties in space and/or time. The primary data for model calibration are measured concentrations of chemicals (or tracers) from observation wells. If the site is not contaminated, and there have been no tracer tests, then there are essentially no data available for calibration, and the reliability of the model will be low. The basic questions to be asked of the calibration process are the same as for flow model calibration:

How sensitive is the calibrated model to the parameters?

Do the calibration points give a good representation of the important site behavior?

Does the calibrated model fit the calibration data?

4.3 System Parameters Derived from Modeling of Site Characterization Data

4.3.1 Derivation of Modeling Input Parameters from Physical Properties

Another relevant question to ask is, “Can existing data be used to derive needed data?” For example, can percent clay (Figure 4-3) be used to estimate hydraulic conductivity? If data conversion is used it must be checked against known conditions within the regional framework to determine if the derived data is reasonable and adequately reflects the local conditions. Neuman and Wierenga (2003) proposed an iterative approach to ground-water modeling that from a logic flow is relevant and can be used for the process of refining conceptual and numerical models.

Computer programs designed for modeling have been refined to accept greater geologic heterogeneity. By using this software to handle greater complexities, flow path models can be developed that more accurately represent conditions in the subsurface and thereby reduce uncertainty in the monitoring program. With greater confidence that the models are more accurately reflecting true conditions in the flow regimes, a higher confidence can be achieved that the data collected though the monitoring activity adequately capture the FEPs as defined by the PA.

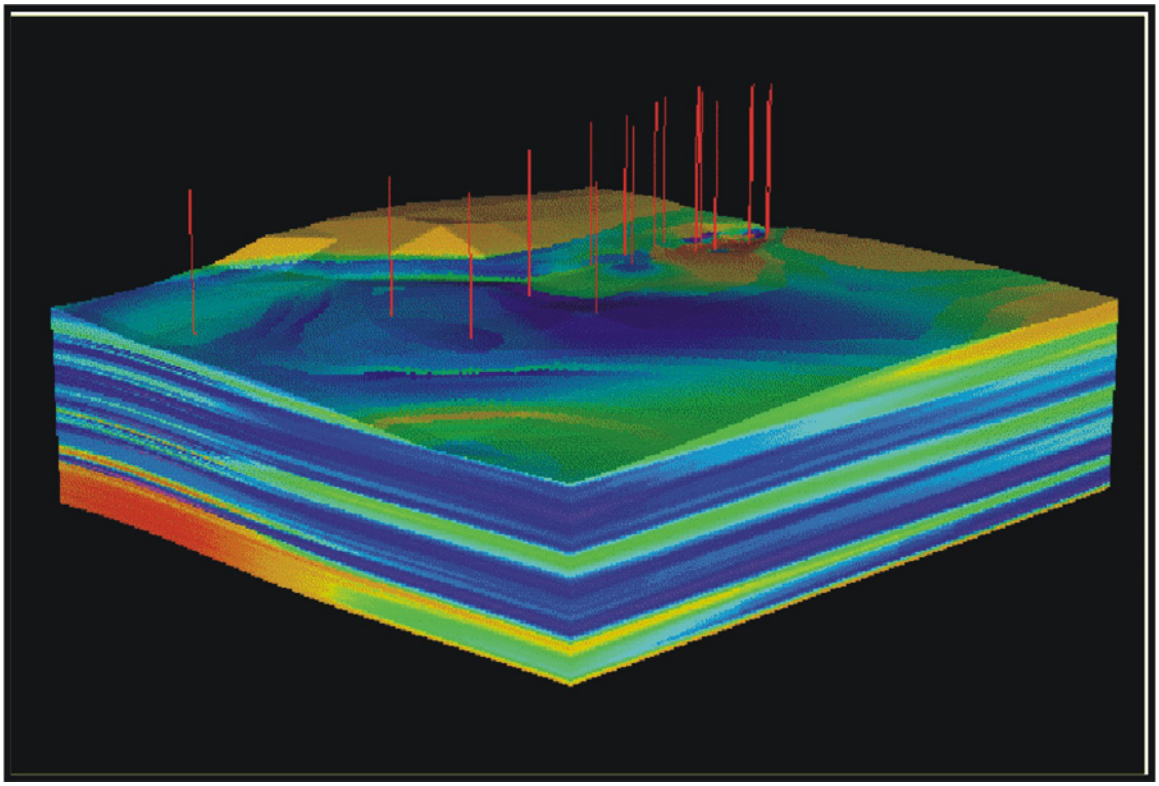


Figure 4-3 Three dimensional display showing percent clay (reds grading to sandier blues).

Through an understanding of the regional geologic/ hydrogeologic framework that constrains a given site; appropriate data can be derived to assist in bounding uncertainty and can identify data gaps to be filled. Sperry and Pierce (1995) outline a method by which hydraulic conductivity can be derived from grain shape, size and porosity.

This method uses simple regression analysis to establish a relationship between physical properties and a derived hydrologic property that is usually not measured during characterization or monitoring. Temples and Waddell (1996) used the relationship of porosity to permeability to extrapolate porosity data into hydraulic conductivity form well logs in place of traditional pump testing.

Miller et al. (2000) outlined procedures to spatially represent the hydrogeologic characteristics of a site by utilizing sequence stratigraphic concepts to map the distribution of lithofacies constraining uncertainty in geologic properties that control fluid flow in the subsurface (Figure 4-4). Software developed by Roxar was used to develop a three dimensional framework of key geologic parameters. The software uses both deterministic and stochastic methods to derive a continuous solid earth model of the critical parameters for prediction of plume migration.

Using both stochastic and deterministic methods offers a practical solution to incorporate real measured data and verified derived data into aquifer models for the predicting of monitoring points. Monte Carlo simulations are the most prevalently used statistical methods to predict uncertainty of a model. The method is relatively straightforward and can be used to predict both linear and nonlinear properties that are critical to flow and transport models, which are the basis for the selection of monitoring points both spatially and temporally. Neuman and Wierenga (2003) outline the logic and the statistics behind using this method for model development and quantifying the uncertainty associated with this approach. Data derived form this type of analysis can assist in decision making about the adequacy of monitoring relative to the PA.

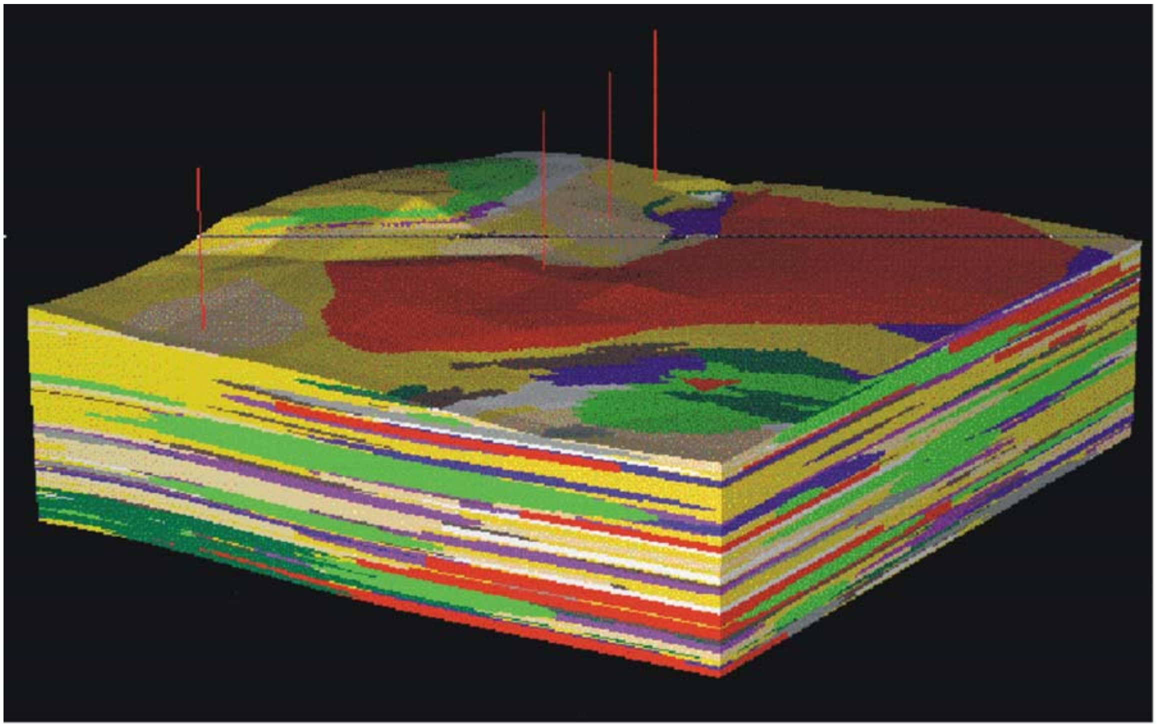


Figure 4-4 Model showing complex lithofacies interpretation.

Several computer codes (such as Plumefinder, Deschaine, 2004) use various statistical methods to predict plume configuration emanating from waste sites. These models are only as good, however, as the information input. Most of the input data used for these predictions are based on data collected from characterization and monitoring. We therefore consistently return to the validity and accuracy of the CSM as the basis for the identification of appropriate FEPs, ground water model development and the subsequent monitoring program to confirm the assumptions that establish the bounding conditions identified as relevant in the PA. Generically derived probability distributions of key parameters such as soil moisture, hydraulic conductivity, or porosity can be given a higher confidence thorough Bayesian updating. Since we know that geology controls the distributions of certain properties such as porosity and permeability rather than these being associated with random events, we can use existing data to analyze and estimate spatial trends using geostatistics. If trends are present, data can be evaluated and reinterpreted to improve confidence in its distribution. Most of this type of analysis has been pioneered by the petroleum industry (Yarus and Chambers, 1994).

4.3.2 Data Analysis Pointing to Needed CSM Revision

In most cases plotting the data followed by visual inspection will suggest whether there are obvious things to be checked. Figure 4-5 illustrates water table levels and heads in an underlying confined unit at the DOE Savannah River Site. The data points out the abnormal water level from the confined aquifer (Falls et al 1997 and Price et al. 1991). Figure 4-6 shows contoured water levels for the lower aquifer, and illustrates the concept of a *bull's-eye* in contoured data.

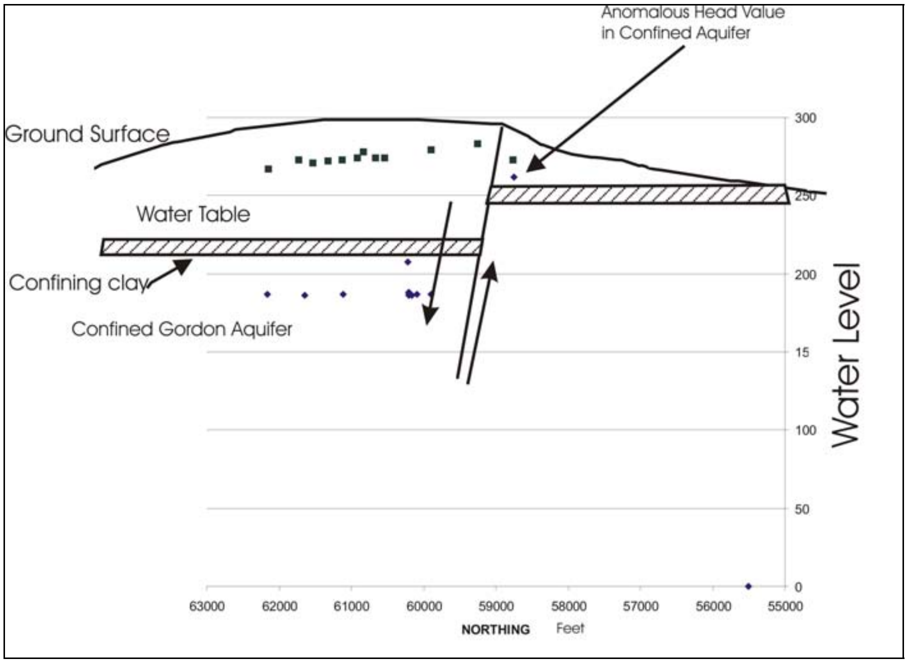


Figure 4-5 Pen Branch example (water level units reported in ft above msl)

In Figure 4-5, all well data have been projected onto a north-south plane. The water table is above 250 ft msl in all wells. Pressure heads in the underlying confined unit range between 180 and 210 ft, except for one well at the right of the figure where the head is 268 ft. Geologic study revealed that a fault displaces strata in such a way that the usually confined unit is connected to the water table across (north of) the fault.

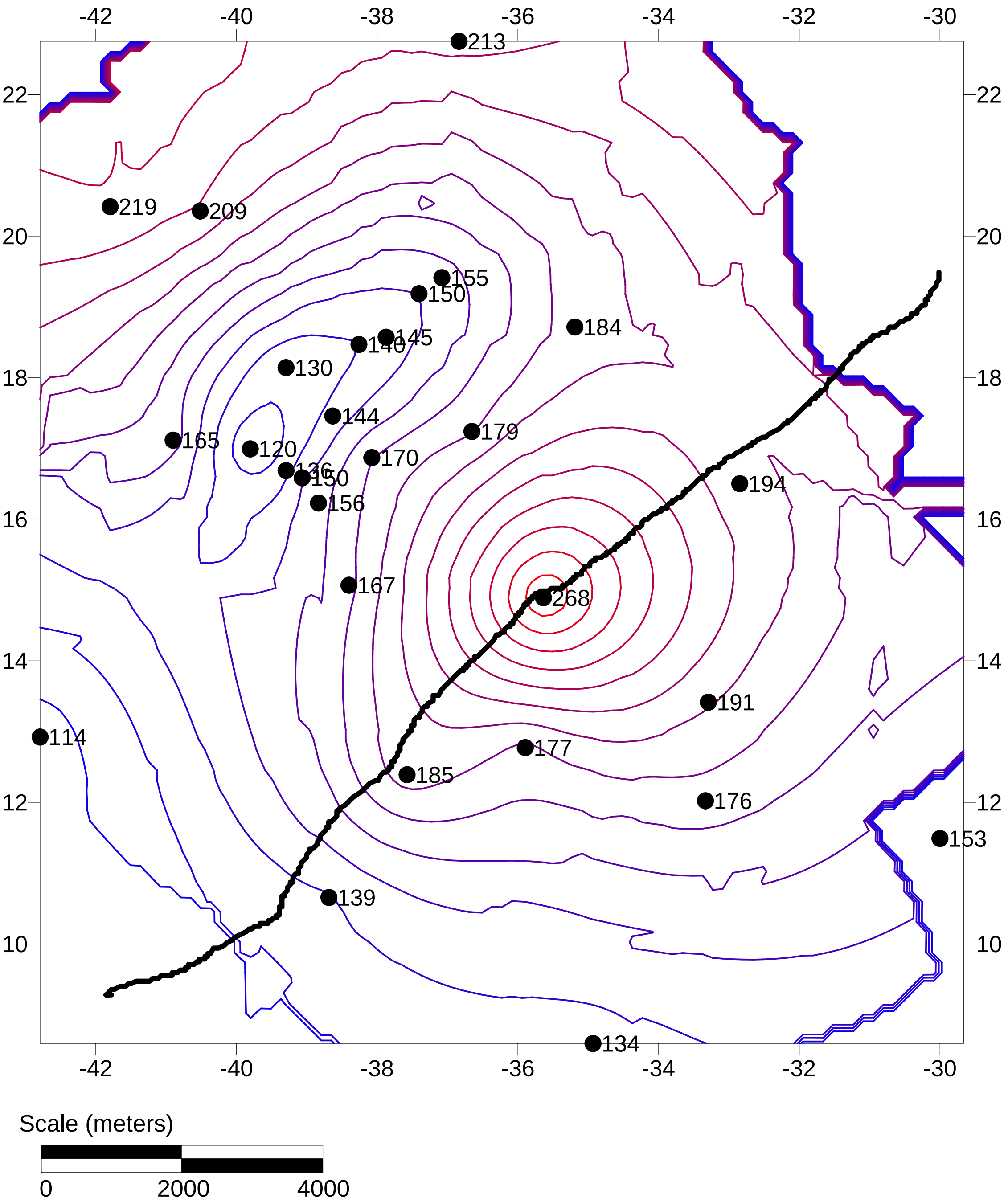


Figure 4-6 Bull's-eye in contoured data

When the anomalously high water level was first noted, it was attributed to bad well construction, and the suspect data were deleted from a regional contour map. However, it was an error to delete the result simply because it did not fit with the rest of the data. An evaluation of other associated data may reveal the anomalous information is indicative of a previously unrecognized situation. Detailed geologic study later revealed the fault and suggested a connection between the water table and the deeper water-bearing zone. By extension, it can be inferred that similar connection exists along the trend of the regional fault, and that shallow waters can flow freely into the deeper aquifer anywhere along the fault. The anomalous water level is a DSI pointing to what would become a critical issue if a new facility were planned for the area.

This leads to the concept of critical monitoring points. A new geologic model including the regional fault has been developed. The hydrologic implications of this geologic model can be tested by selecting well locations along the fault, or perhaps by testing at existing wells.

A second example of conceptual model development leading to revision of a monitoring well layout involves an unlined waste site located near the top of a hill. Several borings defined the water table as shown in Figure 4-7. Then, following standard procedures, one well was placed up-gradient and three down-gradient of the waste site. Well installation involved augering until returns were wet, then waiting for a water level to stabilize inside the hollow stem to establish a current static water table level. After the water table was determined, a well was set so that the 15 ft screened zone penetrated the water table by 10 ft. The wells were then sampled and only the down-gradient wells showed contamination, as would be expected based on this original CSM.

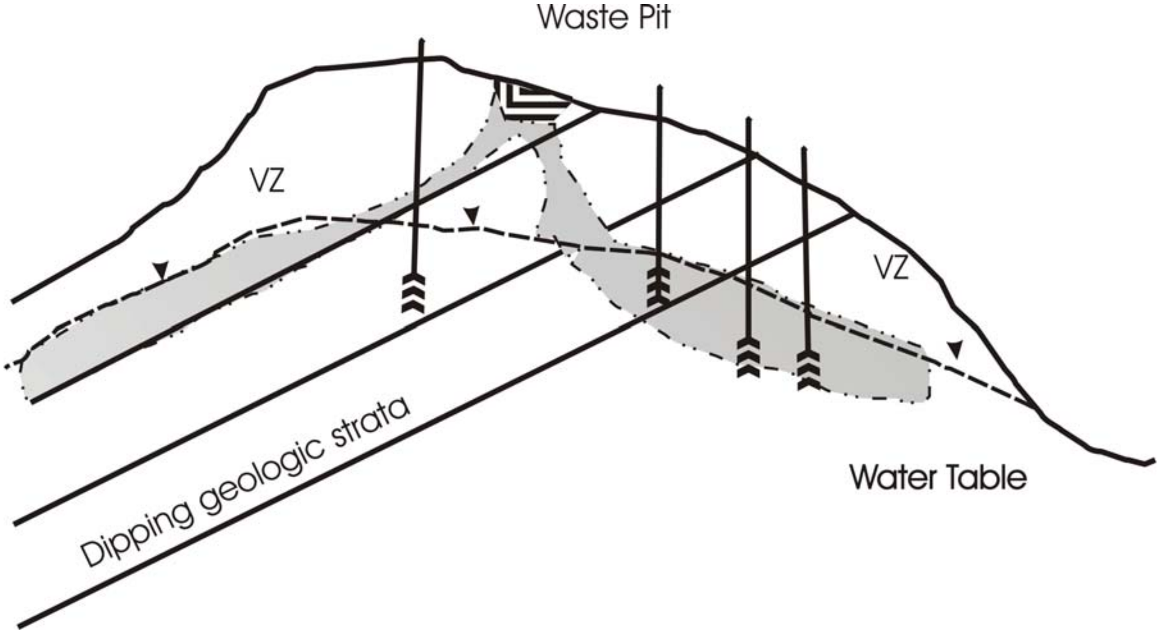


Figure 4-7 Critical monitoring points. The dashed lines indicate the water table and the shaded areas represent the contamination plume.

4.3.2.1 Incongruity with current model predictions

A soil gas survey was conducted of a large area around the waste site to help search for contaminant discharge points. Surprisingly, a significant soil gas anomaly indicated movement of a chlorinated solvent in the assumed up-gradient direction from the waste site. Further geologic study indicated that strata dipped in the up-gradient direction (left on Figure 4-7).

This strongly suggested that contaminants moving downward from the waste site were deflected along dipping beds to reach the saturated zone to the left, and to bypass the up-gradient well. This was later confirmed with additional monitoring wells.

This waste site also provides an example where discarded data were later determined to be critical to model development. Pumping tests were performed to produce data for incorporation into a ground water flow model. Existing dedicated pumps were used to pump the wells at about 10 to 15 gpm. Drawdown was measured to the nearest 0.1 inch with a minimum detection limit of 0.1 inch. About 15 wells were tested. The hydraulic conductivity was reported as averaging 400 gpd/ft^2, but several wells had no values reported because the field data *were not subjected to interpretation*. Closer inspection of the report revealed that the data were not interpreted because no drawdown could be detected! Even the simplest calculation at the minimum 0.1 inch detection limit would have yielded a conductivity of a minimum of 15,000 gpd/ft^2. (SRS Internal Memorandum, V. Price to Tracy Killian, 1986)

In this case, careful reading of the report revealed this huge error of interpretation was missed by reviewers and by the project engineer with responsibility for the site. The explanation for the extreme variation in conductivity observed is clear when the site geologic setting is understood. Figure 4-8 is a cross-section through a typical barrier bar depositional setting from the recent SC / GA coast (Ruby, 1981). Oyster beds and shell lags are interbedded with beach sands and back-barrier tidal flat clays and fine sands. These interbedded carbonates have a documented history in the literature of being highly leached after burial. This is similar to the geologic setting of the waste site area, but Figure 4-7 does not include detailed geology. Eocene oyster beds at that site have been leached to the point that they are highly transmissive.

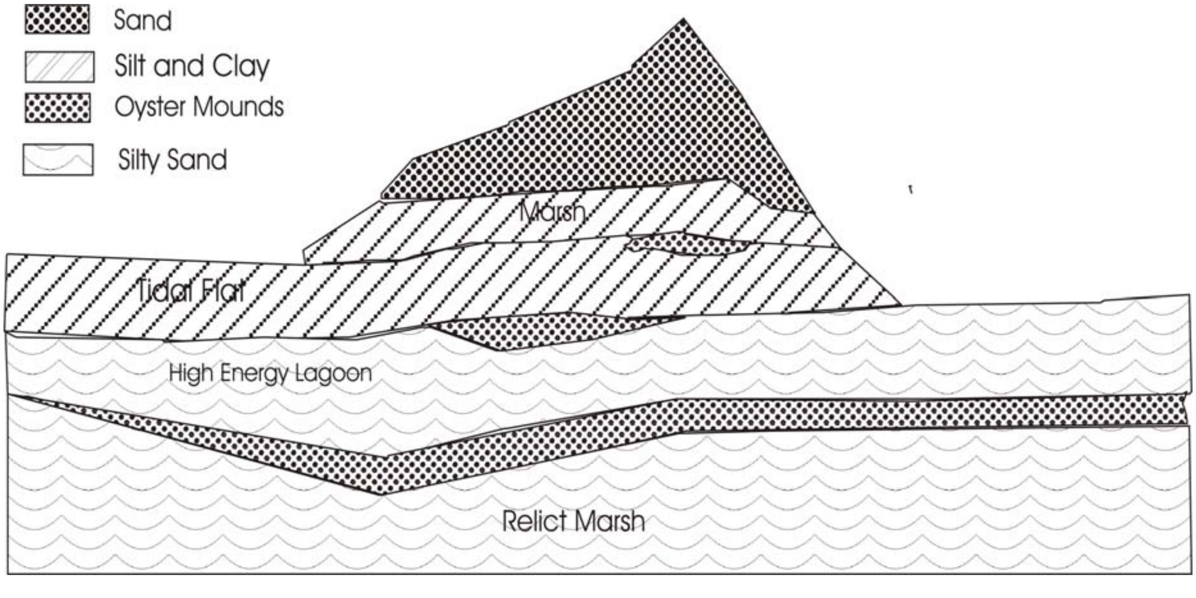


Figure 4-8 Geologic model from Ruby (1981) showing cross-section through a barrier bar system

4.4 Evaluate and Refine Conceptual Site Models

The key step for a successful modeling of ground water flow and reactive solute transport modeling is to identify a most probable CSM from the constructed alternate CSMs. Current inverse models usually can only adopt one of these alternate conceptual models at one step, which may lead to statistical bias and underestimation of uncertainty (Neuman, 2003). Trial and error is the most common method for conceptual model identification and it is usually performed using qualitative criteria. CSMs that fail to reproduce measured data are regarded as inappropriate. Quite often, this allows one to be left with a single CSM (Dai et al., 2004a; Dai et al., 2005).

However, in some cases, several models match the observation data equally well. In such cases, we need some quantitative criteria for model identification. A comprehensive strategy for constructing alternative conceptual-mathematical models of subsurface flow and transport, selecting the best among them, and using them jointly to render optimum predictions under uncertainty has been developed by Neuman and Wierenga (2003) and Meyer et al. (2004). They proposed a Maximum Likelihood Bayesian Model Averaging (MLBMA) method to accomplish this goal. In Appendix C, the MLBMA method is applied to develop conceptual models for ground water flow and reactive transport, to identify essential hydrogeological and geochemical processes and to estimate related parameters.

Proper Performance Confirmation Monitoring (PCM) will result in a database that can be used to identify and test alternative conceptual models, and to evaluate conceptual and numerical model assumptions and results. For example, if the PA's ground water transport calculations are based on a certain pH range, then pH would be monitored to detect any changes. If the site PA assumes 10% soil water content, and a rainfall or snow melt event causes a large exceedance from this value as shown by unsaturated zone monitoring, this information would need to be considered for revising the CSM and PA.

Monitoring data should be continuously updated in the CSM and analyzed for outliers or transient events indicating potential conditions outside the envelope established in the PA, and suggesting a need to update the CSM. Traditional approaches to monitoring assume a static CSM. Our process (Figure 1-1) proposes to establish the idea that the CSM is dynamic, constantly being revisited with new information, particularly monitoring data. The CSM should constantly be updated and compared to FEPs in the PA to determine if conditions outside the PA envelope are detected.

4.5 Data Management and Model Visualization

Geologic, hydrogeologic and contaminant transport models can require analysis and representation of large amounts of data. The model should also be able to represent the uncertainties in both the data and the modeled results. In addition the typical model is required to integrate many different types of information ranging from boring logs to geophysical studies and laboratory derived parameters. Also, in order to maintain the model credibility and transparency, documentation of Quality Control and Quality Assurance information must be provided. In order to manage the information associated with the models and to communicate the model results to both specialists and non-specialists in an efficient way, data management and model visualization become key considerations. This is particularly true as the sophistication and complexity of the models increase.

Geologic modeling software should be selected that will produce a geologic model of sufficient detail to meet the requirements discussed in the previous sections. The most powerful commercial modeling software has been produced for the petroleum or mining industry, and some of these packages have integrated fluid flow modeling modules. Most of them will allow data fusion by accepting seismic and other geophysical data, geologic core logs, and geophysical logs. Stochastic and geostatistical methods are used to integrate the data to best represent geology and hydrologic variables such as permeability. A sample of one of the many such software packages is illustrated in Figure 4-9. Utilization of these packages greatly improves the speed of evaluation while at the same time reduces uncertainty by the use of multiple data sources. This process would be difficult if done without the aid of a computer.

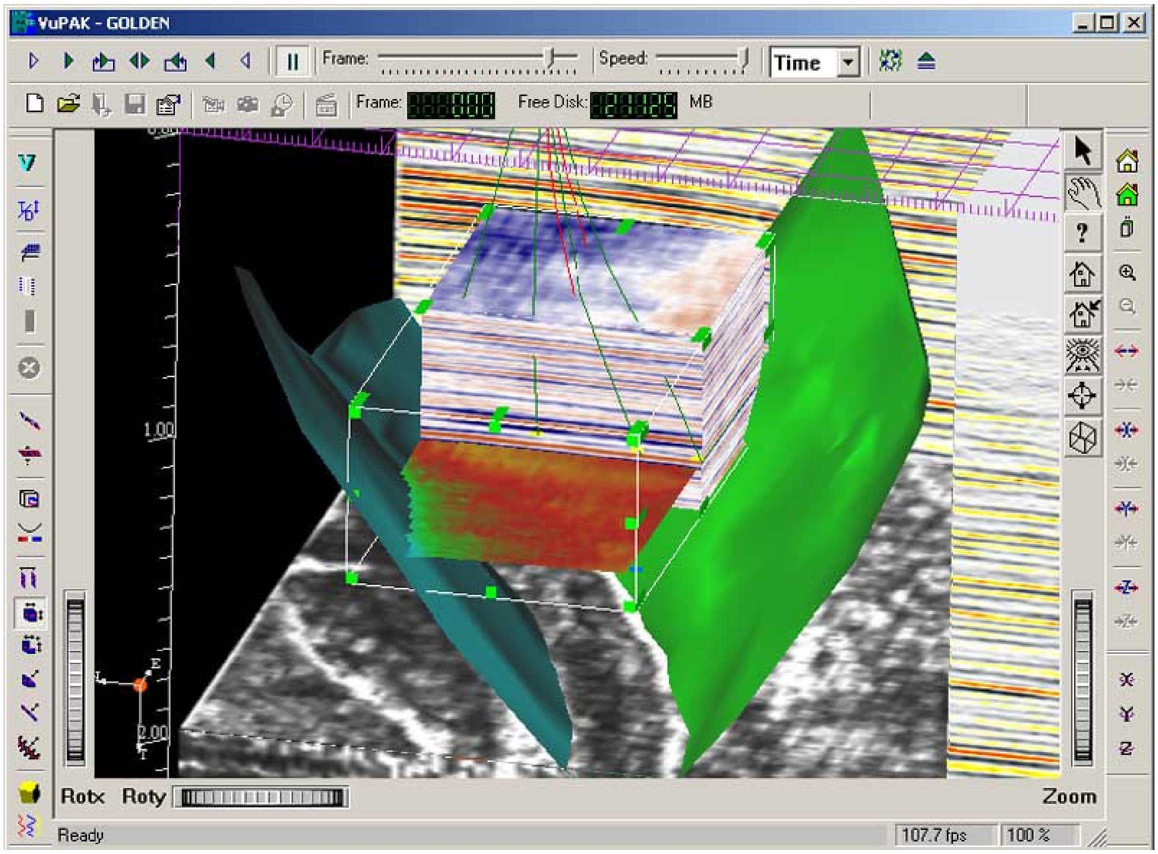


Figure 4-9 Sample for 3-D (solid) model from Kingdom Suite

The CSM could be built in a commercial modeling/visualization package such as Petra and Groundwater Modeling System (GMS). Visualization helps the modeler (as well as managers and other stakeholders) understand the interrelationships of site, facility, and plume geometries as well as their associated uncertainties. Displaying ground water data in a quasi-3-dimensional format makes it much easier to see areas of interest that require the placement of critical monitoring points.

Figure 4-10 is one frame taken from a visualization of radioactivity distribution at a tank farm. Three-dimensional computer contouring alone indicates no significant contamination at the base of the modeled volume. Visualization reveals to the operator that the hot wells do not extend to the base of the volume, whereas the cold wells do extend deeper, and control contouring at that depth. There is still a real possibility that contamination extends below the depth of measurement at the hot locations. This also calls into question the contouring method, which is probably on a plane-by-plane basis, rather than truly in 3-D. Also an area to the right of the plume does not contain any monitoring points. This area could be a candidate for placement of a monitoring point to reduce uncertainty in contaminant concentration.

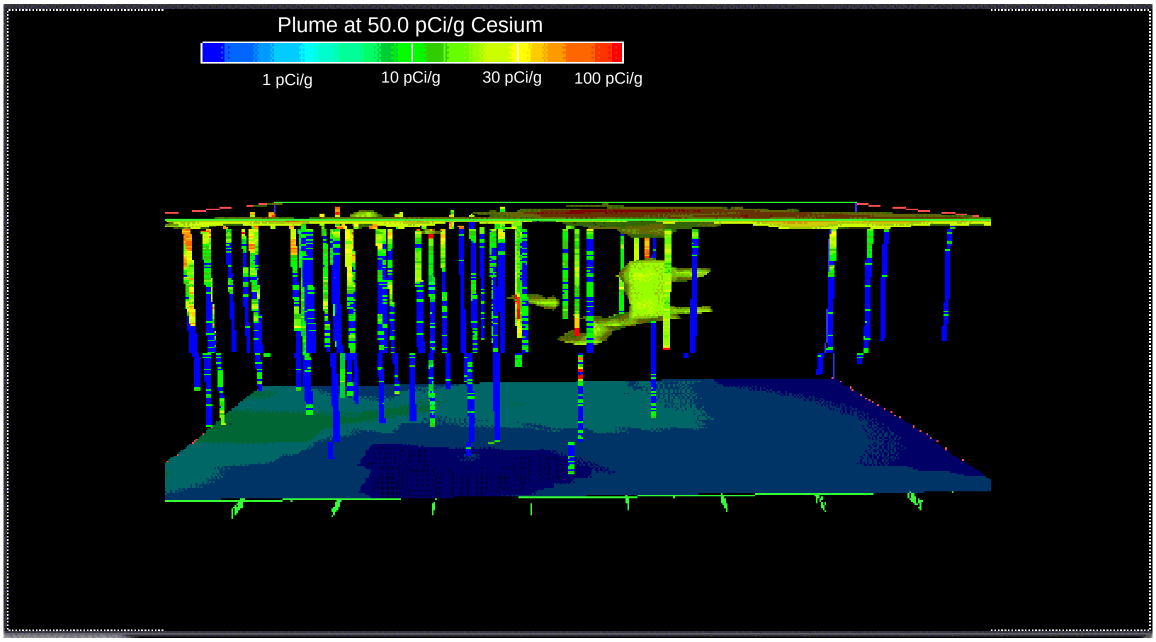


Figure 4-10 Quasi 3-D contouring and solid rendering of Cs in soil. Note that hot wells do not extend to the base of the modeled volume.

4.5.1 Data Management

In order to facilitate efficient analysis and communication of the data obtained by the monitoring network, any monitoring program should incorporate a Data Management System (DMS). The DMS should contain provisions for efficient data storage and retrieval, in addition to incorporating techniques for data analysis, and Quality Control. Closely associated with these techniques are data querying tools that allow the data to be easily accessed by the analysis, reporting and modeling software used by the decision rule evaluation and PA model. In addition, the DMS should integrate and provide methods to communicate the results of the monitoring plan and decision rules in a clear and concise way to concerned parties such as management or stakeholders. The decision rules can be programmed in a relational database so that, as new data are added, the project manager is quickly apprised of the meaning of the data in the context of site-specific requirements.

The provisions in the DMS for data storage and retrieval potentially range from simple spreadsheets for small-scale data-poor intensive monitoring programs to large scale integrated databases. In most cases however, the DMS will be implemented in a commercially available relational database that will readily accommodate geologic, hydrologic, geophysical, and geochemical data. This can include geochemical data, 3-D seismic data, maps, well logs, periodic sampling data, and data analysis reports. Database software such as Oracle or Access makes custom data sets easy to design and program.

Since the data and subsequent analyses will serve as the basis for all of the technical and many of the managerial decisions, the degree of confidence in the data is crucial to both the decision makers and the stakeholders. The data must be in a format that is accessible and understandable to all that are involved in the PA process. This is a necessity if the data are to withstand the scrutiny demanded by the PA acceptance process. This requirement immediately brings to focus the advantages of storing and managing the data in a relational database. Data querying tools can easily retrieve the data in any standard format. Many modeling and reporting tools can be implemented on top of a database structure so that the data can be directly accessed. This capability potentially leads to many efficiency gains. For instance, since the DQO process provides that detailed analysis techniques be associated with the decision rules, and these rules are formulated in a precise analytical way, in many cases the evaluation of the decision rules could be automated. Also this makes automated standardized report generation and GIS updates possible, as data and analytical results become available in the DMS.

In summary, depending upon the needs of the decision rule and PA modeling process, the DMS will need to be able to import data into a variety of software packages, including statistical analysis, geologic process models, geophysical interpretation packages, ground water flow and transport models, GIS and others. Thus it is critical that the database structure be well designed and robust.

4.5.2 Modeling and Visualization Software Used in the Development of this Document

Several software packages used during the preparation of the test cases detailed in Volume II are listed below. This listing is not comprehensive and is not an endorsement of any of this software. Some additional software is discussed in Volume II case studies.

- **ArcGIS (with 3D Analyst and Spatial Analyst)** - Standard GIS application, ArcGIS is useful for analysis, mapping and data presentation. When used in conjunction with the 3D Analyst package, it is also good for 3-D visualization. The Spatial Analyst raster GIS allows complex environmental modeling directly within the GIS environment, including ground water contaminant transport advection and dispersion modeling (Tauxe, 1994).

- **Global Mapper -** A tool for manipulating maps. Allows correction of problems with existing maps, or merging of several maps from different coordinate systems into one map with a single set of coordinates. Has an easy to use interface for geo-registering aerial photographs, or other images. Can be used to overlay several different types of maps in translucent format.

- **GMS** - Provides complete integration of numerous modeling programs (MODFLOW, RT3D, etc…) and 3-D visualization. We typically use GMS for visualization and modeling. Data and interpretations are loaded from other programs (excel, or Petra), and then modeling programs such as MODFLOW and RT3D are run.

- **GoldSim** – Systems analysis simulation software. GoldSim is an object-oriented graphical probabilistic systems analysis program. It is most useful in the context of the Strategy for constructing PA models, with inputs based on process model results where indicated. Being natively probabilistic, GoldSim is ideal for modeling where uncertainty and sensitivity analyses are of interest, and was used for developing a hypothetical probabilistic radiological PA for demonstration purposes.

- **HydrogeoAnalyst (HGA)** - HGA provides true 3-D solid contouring capabilities, which was utilized in the evaluation presented in Chapter 4 of Volume II. None of our other available software provides true 3-D contouring capabilities. True 3D gridding allows the production of solid models for visualization. This is very different from pseudo-3D perspective views. It also serves to directly link a database system (designed around environmental data) to GIS mapping capabilities.

- **Microsoft Access** - Widely used database system for data compilation and storage.

- **Microsoft Excel** - Spreadsheet program used for both the organization of data and for simple modeling and data analysis. Also provides good graphing capabilities and some statistical tools. The same functionality is also found in **OpenOffice Calc**, an open source spreadsheet.

- **Petra** – Petroleum industry software used for data storage as well as for geologic interpretation of well log and seismic data. Petra can also be used with the Petraseis module to interpret seismic data, and incorporate the results with your well interpretations. After geologic model development, the interpreted layers are exported as grid files, and imported into GMS for modeling. Also use Petra for contouring data, and making maps.

- **R** – An open source statistical programming language. This was used for development of sensitivity analysis for the results of the GoldSim model.

- **RockWorks** - Suite of various geologic based tools. It has a spread-sheet like format for storing and organizing data, and has mapping capabilities.

- **SAS** - High end statistical analysis package.

- **Surfer** (Golden Software) Contouring and basic GIS functions

4.5.3 Data Analysis

Many of the data analysis methods will have been specified or developed as part of the DQO development process. However, a fundamental requirement is that data analysis methods be able to distinguish between the natural variability in the data and the actual response in the parameter being evaluated. In the case where a monitoring hypothesis is being applied, an appropriate statistical method can help to resolve these types of issues (see Chapter 8 of Volume II for discussion of some specific techniques). The selection of the statistical approach should be tied to the monitoring objectives, hypotheses, and decision rules (EPA, 2004). The specific type of statistical tests will depend upon the data type and collection methods, and the desired level of decision error. Many of these issues are addressed as part of the DQO process.

4.5.3.1 Trend Analysis

Trend analysis is used to evaluate the magnitude and direction of change in the monitored PIs over time. In order for a trend analysis to be valid, sufficient data over the time period of interest must be obtained. In quality control programs trend analysis charts are called Shewhart Charts.

Trend analysis can be used to determine how the parameters of interest are progressing toward their predicted values, and in some cases be used to predict parameter response to a change in conditions based on a previous response to a similar change, such as a large rainfall event. In some cases, trend analysis could be used to refine the PA model, or to modify site operations.

Trend analysis can be used in resolving the issue of apparent outliers and anomalies. If a data point exhibits a divergence from the trend of the expected parameter values, this should trigger an investigation. There are three distinct outcomes resulting from this investigation:

1) revision of the conceptual site model that will be used to update the PA model,
2) removal of a specific reading due to collection/recording errors, or
3) removal of the data point and all associated data.

In short, trend analysis can be a valuable tool in PA model confirmation and evaluating model assumptions. More discussion is included in Chapter 8 of Volume II.

4.5.3.2 Data Scaling

The objective of up-scaling is to use information collected in detail to develop another data set that is representative of a given property at a larger scale. This process must be performed correctly in order to preserve the critical property of the detailed set in the larger scale version.

The problem is one of grid size and the appropriate spatial and/or temporal averaging of parameter values. Even with current processor speeds and computer memory, there is still insufficient computational capacity to perform modeling at the resolution of most input data. Well logs, for example, are typically sampled at 0.5 feet or less. For calculation purposes it is necessary to reduce the data volume to some manageable amount of data. This is achieved by creating a coarser grid and by assigning appropriate physical property or state values to the coarser grid elements.

This grid coarsening should be accomplished in a manner that preserves the character of the original data density (Mansoori, 1994). For parameters that can be treated as additive, such as porosity or saturation, simple arithmetic means can be used. More complex parameters like permeability or hydraulic conductivity require a more refined method. King (1989) outlines a method of up-scaling permeability data using grid replacement.

4.5.4 Data and Decision Rule Reporting and Communication

The ultimate reason for the existence of the DMS is to provide input to the decisions based on rules engineered in the DQO process and to communicate the results of the evaluation of these rules. However, in order for management and stakeholders to understand the ultimate consequences of the decision and the rule makeup, it is desirable that the DMS also be able to communicate other important information about the PA. This would include:

- features, events, and processes associated with the CSM to include assessment of model uncertainties,
- how the monitoring network interfaces with the CSM,
- general features and characteristics of the monitoring data and how it relates to the CSM, and
- general features and characteristics of the analytical results and how they relate to the CSM.

The conceptualization of the information associated with the items listed above can be quite complex. Most engineers and scientists have been trained and are experienced in conceptualizing this type of information from rudimentary inputs such as tables of coordinates or geologic cross sections. In most instances this requires synthesizing a three- or four-dimensional image from one- or two-dimensional input media. In order to make this process more efficient for management and stakeholders the DMS should implement capability to communicate this information in a fully three or four dimensional sense with associated visualization. The cost and requirements for operating resources of modern software for three- and four-dimensional imaging are well within the limits of most personal computers and would be an inconsequential budgetary item to most projects.

5 Performance Confirmation Monitoring System Design: What, Where, When, and How to Monitor

This Section describes how to translate the information learned through, data analysis, CSM development, and Performance Indicator selection into an operational Performance Confirmation Monitoring plan. Monitoring network design is directly determined by the requirements for data acquisition systems used to make meaningful measurements of identified and selected PIs for testing of PA modeling assumptions. The details of the monitoring network design are determined by the characteristics of the data and the requirements imposed by the DQOs and decision rules.

In general, the objective of monitoring network design is to choose monitoring locations and frequencies that meet DQOs while minimizing cost. Also, in certain instances it may be necessary for the network design to incorporate provisions to characterize background levels in addition to the ability to measure the levels of the relevant PI at locations where the system performance is being evaluated.

The performance confirmation monitoring system design process is outlined in Figure 5-1.

What to monitor is determined from the preliminary list of PIs and DSIs through a down selection process. The down selection should be on the basis of risk implications determined by the application of established decision rules.

Where to monitor: Monitoring locations are selected to optimally reduce the level of uncertainty in the CSM. Keep in mind that the overarching goal is to develop an accurate understanding of the natural system to reduce risk.

When to monitor: Monitoring times or frequency will be determined by site conditions, and perhaps by regulations. Examples are given in Volume II of variability that would not be captured in a quarterly or even a monthly monitoring program, and of changes in contaminant concentrations and trends caused by rainfall events. Based on the conceptual site model, triggering events may set a monitoring plan into action. For example snow melt might release water into a contaminated vadose zone and require monitoring at the water table.

How to monitor: The selection of monitoring devices will be controlled by the PI selected, the location where the device is to be placed, the performance requirements defined through the DQO process, and by the overall site conditions. Qualified experts must be employed for the selection, application, and interpretation of subsurface measurement technologies.

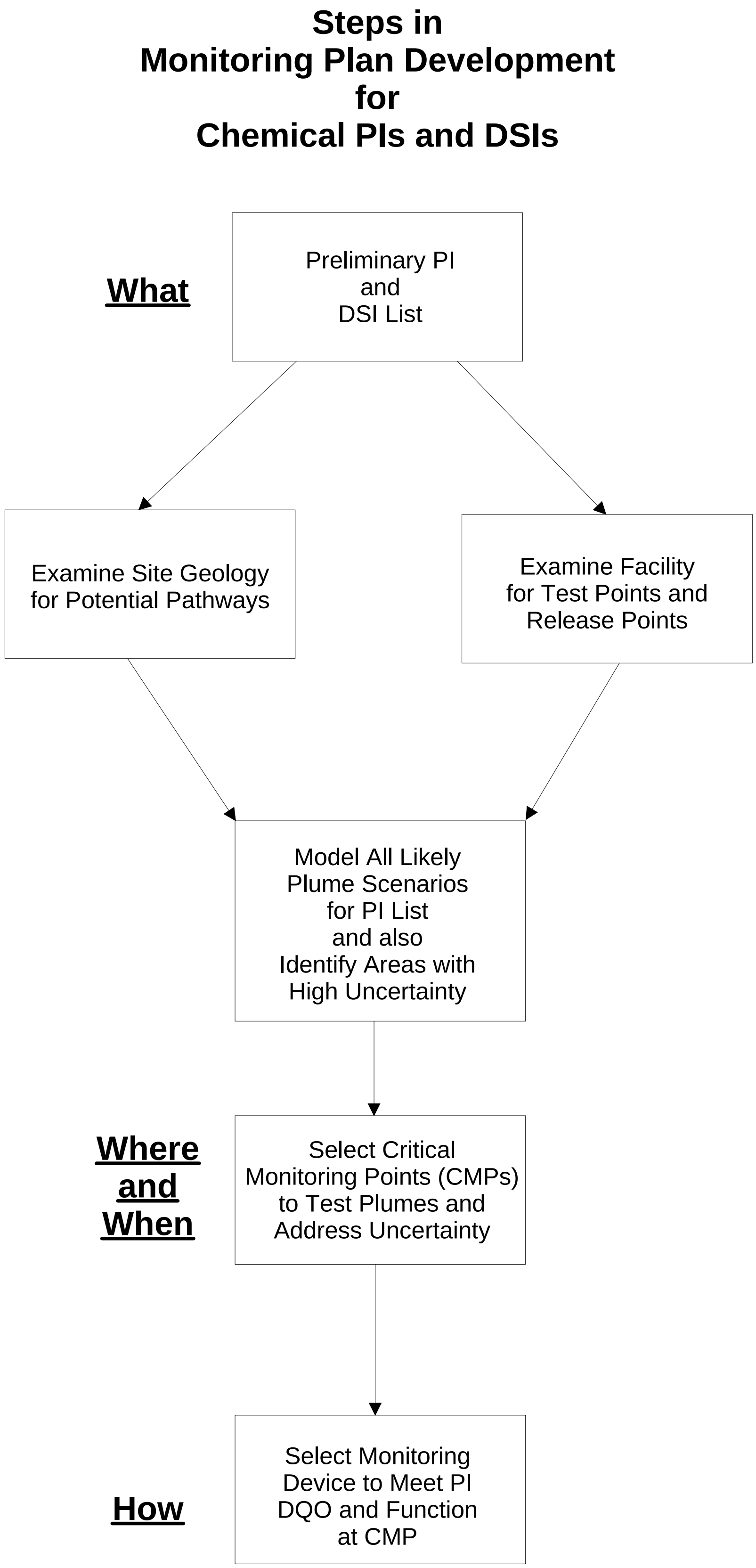


Figure 5-1 Steps in Monitoring Plan Development

5.1 Network Design for Performance Indicators

Generally, a monitoring strategy would be to sample for the presence of the PI, either continuously or at specified intervals ("when"), in pathways associated with its mobility at monitoring point locations ("where to monitor") selected so that detection of the constituent, if present, is as certain as possible. Note that the success in the implementation of this strategy requires that the uncertainties in the existence, location, geometry, and transport characteristics of the constituent mobility pathways be well known. This knowledge is the essence of the connection between site characterization and monitoring network design.

The site characterization and CSM must be robust enough so that all risk-related pathways are identified and located so that monitoring locations can be effectively identified. Also, the pathway transport properties need to be quantified well enough that the sampling time intervals can be effectively determined. Emphasis should be placed on sampling at locations in which the CSM exhibits large uncertainties in pathway characterization. In practice this Strategy would be implemented by analyzing the possible source locations for the constituent associated with the PI, and modeling the locations for potential plumes for these sources using the flow and transport model developed in the CSM.

When selecting how to monitor for a particular constituent, the accuracy and precision of techniques should be considered (to ensure that the DQOs are satisfied), as well as cost and ease of implementation. The AES 2003 report included a review of measurement devices. This is a very actively developing field, so a review of new devices and their applicability is necessary.

5.2 Design and Implementation of Unsaturated-Saturated Zone Monitoring Networks for Ground Water Constituents

Once the chemical constituent identified with the PI has reached the water table, transport of constituents in solution or suspension may be monitored through direct sampling of ground water. This is normally done through permanent wells, but can be done with direct-push technologies also (e.g. 'geo-probe', and CPT).

In a uniform isotropic world, ground water is monitored by establishing the slope of the water table and placing one well up-gradient, one well to each side, and one well down-gradient of a site. Generally, flow is assumed to be horizontal, and down the water table gradient. These conditions are probably never truly realized in nature especially at the scale of a waste disposal site. They are nevertheless, and unfortunately, implicit in many designs of ground water monitoring systems.

The assumption of uniform aquifer properties might be appropriate for a water resource study. Normally, water production wells are screened across all productive zones of an aquifer, so the quality and quantity of water produced follow properties of the entire productive thickness. Thus, at the scale of a regional aquifer, horizontal flow to producing wells may, in such cases be a reasonable assumption.

At the scale of a typical site, however, local subsurface heterogeneity controls the shape and extent of any plume emanating from the waste site and controls the zone of capture of monitoring wells. Furthermore, vertical flow may be important (Hubbert, 1940). Design of monitoring systems at the scale of a waste facility or decommissioned nuclear site must therefore incorporate consideration of facility design and site characteristics.

5.2.1 Unsaturated Zone

Bodvarsson et al. (2000) presents a detailed review of flow and transport in the unsaturated zone. They tabulate all important flow and transport processes, each of which presents a challenge or an opportunity for monitoring. They note that heterogeneity in the unsaturated zone is poorly understood, and may confound modeling efforts. From a strategic standpoint, a modeling strategy will have to be sufficiently robust to overcome the issues of heterogeneity and variability of properties.

In the unsaturated zone, the monitoring objective is frequently detection of water. This can be done with tensiometers or with various geophysical methods that measure soil electrical properties related to moisture content. Chapter 4 of Volume II mentions the use of thermocouple psychrometers to measure soil moisture in the vadose zone at the Amargosa Desert Research Site.

A great deal of NRC-supported research has focused on unsaturated zone monitoring in arid climates. Work at the Maricopa site (Young et al. 1999a & b) has evaluated trenches, islands, boreholes, and geophysics for monitoring. Borehole and surface geophysical methods offer flexibility because instrumentation can be maintained or replaced, and boreholes can be advanced to depth, or can be angled beneath a waste site.

Work at the Apache Leap Tuff, the Las Cruces Trench, and other sites has been reported in NRC, open literature and INTRAVAL Project reports. Larsson et al. (1997) reported that data from the Las Cruces Trench were valuable for testing modeling against field results.

5.2.2 Saturated Zone

Location of wells in the saturated zone is an important component of designing a monitoring network for any waste site. The most effective monitoring network design for any given site is heavily dependent on the type of media through which the ground water will travel (i.e. sand, sands and clays, fractured bedrock, karst, fractured chalk).

Spruill and Candela (1990) propose that two different approaches be used to design a monitoring network depending on the type of information required. In some cases one may be looking for quantification of typical concentrations in a given area and in other cases looking for potential problem areas. In this reference a method is introduced to determine the sample size necessary to describe any selected quantile, and kriging was used to determine the minimum number of wells necessary to retain spatial information. However, this geostatistical technique generally requires larger sample sizes than networks designed by traditional techniques.

Ben-Jemaa and Marino (1994) have applied statistical tools to determine the number of wells and samples necessary to characterize properties of the aquifer and the water it yields. It might be possible to use this method for estimating a range of constituent concentrations from samples of a regional aquifer, then to spot probable anomalous values in data from a given well. This approach should work at the scale of an aquifer because resolution of local water-bearing zones is not needed.

In Volume II, Chapter 3, we recommend that monitoring purposes be integrated into process water systems. Instead of one high-capacity well, a number of lesser capacity wells close to the facility are recommended. These are pumped more or less continuously so that each develops a zone of capture much more extensive than that of a monitoring well that is only pumped a few times a year. In this way, leaks that might ordinarily go undetected for years as a narrow plume passed between monitoring wells would be detected by the active monitoring system. In the event of detection the well can be taken out of service for process (or drinking) water, but still pumped as a plume control well until a remediation plan is fully developed.

Selection of monitoring points at the site or facility scale must be based on understanding details of site hydrogeologic features or controls. Without this detail, statistical approaches will give false guidance.

5.2.3 Soil Gas and Volatile Fluids

Many chemicals may move without the assistance of water. These include mercury, iodine, tritium, radon, argon, krypton and other waste components such as organic liquids and their vapors. Soil gas can be sampled and analyzed in a number of ways, and the term *soil gas* is often applied to any soil constituents that got to where they are found in the form of a vapor.

In a regulatory context, soil gas can be used to identify contaminated areas, but cannot directly quantify contaminants in regulated media such as drinking water. Soil gas surveys are broadly divided into free gas and soil-adsorbed –vapor methods. Actual soil, or an absorbent buried for some period, e.g., two weeks, can be removed to a lab or portable analytical device. Free gas can be tested with portable devices, or transported for laboratory analysis. Both approaches are used as screening techniques to identify areas for further study.

Implementation of a soil gas survey generally begins with a grid-based sampling plan with additional locations near potential contaminant sources such as pipes or trenches. Data turnaround is normally a matter of hours so that confirmation and infill sampling can be done if constituents of interest are detected. Access methods vary from truck-mounted probes to hand-pushed or hammered probes or augers to spades. Simple methods may work as well as expensive methods.

In a case example discussed in Section 4.3.2, above, soil gas provided information leading to revision of a CSM, and later placement of additional wells.

5.3 Monitoring Network Assessment

The general adequacy of a monitoring network design may be assessed by consideration of the following points:

1. Do monitoring networks sample at appropriate locations and frequencies to provide a high degree of confidence that chemical constituents associated with the PIs will be

detected if present? In practice this means that the network must sample at locations identified in all plume scenarios defined in the CSM and simulations based on the CSM. The sampling frequency at these locations must also be commensurate with the transport rates for the chemical constituent as determined by the flow and transport model.

2. Do network sample locations and intervals accommodate areas of high uncertainty in the flow and transport model?

3. Does the network design provide for identification of background levels if necessary for identifying elevated levels of the constituent associated with the PI?

The use of visualization software allows the project manager to develop insights into the observed or predicted 3-D relationships between the facility, site geology, and plume geometries. Visualization of modeling output can be used to determine areas where there is a high degree of uncertainty in plume mapping or site characterization. This visualization also reveals the placement of MPs in the context of site, facility, and contaminant FEPs. For example tritium plumes are represented in 3D renderings in the Brookhaven Chapter of Volume II.

5.4 Demonstrating Site Performance With Respect to Site Performance Objectives

Each engineered facility has design requirements, derived from release restrictions, which specify limits of releases to the environment. These requirements become objectives to be achieved. A CSM is developed, and release scenarios modeled as part of the PA process. Whether or not the objectives are being met is determined through Performance Confirmation Monitoring.

The purpose of material in this document is to aid NRC in their effort to demonstrate that a licensed nuclear site or facility is behaving within the expected limits as described by the performance assessment.

5.4.1 Site Performance Confirmation

Much of the discussion above addresses this topic. MPs and PIs are selected to verify that the site is performing as designed or modeled, and within acceptable limits.

5.4.2 Remediation Confirmation

Performance Confirmation Monitoring can also demonstrate that natural attenuation or remediation is occurring according to expectations. Although remedial expectations and, consequently, appropriate performance monitoring analyses are site specific in nature, reduction in contaminant concentrations to specified levels is generally expected for most selected remedies (Pope et al., 2004). Data analyses useful in evaluating progress toward contaminant reduction objectives include evaluation of temporal trends in contaminant concentrations or mass, comparisons of observed contaminant distributions with predictions or required milestones, and in some cases, comparison of calculated attenuation rates with the range of rates required to meet remedial objectives within the required time frame. Evaluations of adequate progress toward restoration objectives are difficult due, in large measure, to subsurface variability and to a lesser extent, measurement variability. This will often necessitate use of multiple lines of evidence (e.g., temporal trends and estimates of contaminant mass loss as discussed in Pope et al., 2004) and relatively dense monitoring networks to reduce uncertainty to acceptable levels.

The remedial action objective of attaining permitted standards throughout the plume should be demonstrated before monitoring is terminated to ensure that the required standards are actually achieved (Pope et al., 2004). The techniques for determining compliance with remedial action objectives under a natural attenuation remedy are similar to those used for determining compliance following application of other remediation methods. The demonstration of the attainment of cleanup objectives should include sufficient verification monitoring (*e.g.,* three to five years) once the standards are met to evaluate the effects of natural variations in site conditions, based on objective statistical analyses of the data. Statistical methods useful in these evaluations include analyses of temporal trends in contaminant concentrations and comparisons with the specified concentration standard. Guidance regarding verification of compliance with cleanup objectives is provided in Cohen *et al.* (1994) and EPA (1992a).

5.5 Selection of Monitoring Points: Where and When to Monitor

There are uncertainties inherent in all PA models. Poor understanding of site hydrogeology may lead to inappropriate monitoring point selection. Transient events such as rainfall or snow-melt, long-term climate, and infiltration rates may change drastically over time, making previous computer modeling obsolete and decreasing the validity of data gathered from sampling points devised based on original site assumptions.

Heterogeneity in general was noted above as a challenge for modelers. PA model parameters that are important to risk include spatially distributed parameters such as chemical properties used to model transport (absorption coefficients, or transmissivity) and physical properties such as moisture content or pressure distributions. These types of parameters are not related to mobile constituents; consequently the main issue in the monitoring network design is no longer related to pathways but to spatial heterogeneity.

Where to monitor for these indicators is mainly dependent on having adequate sampling density in locations where these parameters are important to the flow and transport risk, for example risk associated constituent pathways and hydrologic confining units. The sampling density in these locations should be enough to drive down the uncertainty in the spatial correlation of these parameters to acceptable levels so that a high degree of confidence will result from the flow and transport modeling. This can be determined by various statistical methods. The monitoring wells are usually assigned in the following critical locations:

1) Source areas, within and immediately down-gradient of source area;
2) Transmissive zones with highest contaminant concentrations or hydraulic conductivity;
3) Fringe portions and boundary of the plume;
4) Areas representative of contaminated and uncontaminated geochemical settings;
5) Areas supporting the monitoring of site hydrogeology; or

6) Regulatory points of compliance.

The predicted time-series trends of the contaminant concentrations provide most of the information for us to determine the monitoring frequency or time intervals. The most appropriate frequency is determined based on the predicted rate with which contaminant concentrations change due to ground water flow and natural attenuation processes, the degree to which the causes of this variability are known, the types of evaluations to be performed, the locations of possible receptors, and the remedial action objectives for the site. In situations where the hydrologic, geochemical and contaminant trends are stable and the CSM is verified by existing monitoring data, reductions in sampling frequency may be warranted. In situations where the variability is high, increases in monitoring frequency may be warranted. More frequent monitoring of ground water elevations may be warranted, particularly during the establishment of baseline conditions, to improve the characterization of ground water flow patterns.

The other factors for determining monitoring frequency include the relevance of PIs and the information redundancy. If a PI is not expected to significantly influence the performance evaluations in a site, then monitoring frequency for that PI could be greatly reduced or even eliminated. If over a period of several years data trends are stable, a reduction in monitoring frequency may be warranted. In Volume II of this document, examples are presented to illustrate pitfalls of premature reduction or termination of sampling, as well as to demonstrate when monitoring points may be abandoned.

In addition to considerations associated with uncertainties related to heterogeneities of the model parameters, the PA model assumptions and uncertainties may also be evaluated by analysis of congruity, as discussed in Section 3.2.3. This analysis is mainly concerned with evaluating the CSM for consistency relative to new or unconsidered information. The monitoring network design in this case is mainly concerned with making sure that new information is obtained when available and that the congruity review occurs on a timely basis.

A feedback loop must exist so that new information obtained from the monitoring network is used to refine the CSM and to continually optimize the network itself. Details are dependent on the type of new information, but may consist only of a periodic review and assessment by qualified experts. For instance new information about features in the locally surrounding geology resulting from nearby characterization or monitoring activities need to be evaluated to ensure that they validate the existing CSM.

5.6 Selection of Monitoring Devices: How to Monitor

Selection of an appropriate monitoring device will de driven by what the PI is and what property of the PI is best measured. For example, early detection of leakage of conductive fluid would best be accomplished using electrical methods. These devices measure directly the electrical conductivity of a volume of soil. With minimal assumptions, this measured parameter can be easily converted to the PI of interest, i.e. soil moisture. The important issue, from a strategic standpoint, is that the resulting data collected by a monitoring device address the issue of interest.

Given the constraints of the engineered facility, what is the best type of device to gather the needed data? Given the physical features of the site, what devices can be used to make the desired measurements of critical FEPs? If subsurface emplacement is required a number of access technologies are available as well as guidance for their application.

The AES (2003) report included a review of measurement devices. This is a very actively developing field, so a review of new devices and their applicability must be done periodically. EPA/625/R-93/003a (EPA, 1993) is an extensive desk reference guide to sampling and monitoring devices. The discussion below is not intended t give thorough coverage of all devices and methods, but should give the reader a general overview of methods. Because each monitored location is unique to some degree, experts should be consulted to select the best available technology for the specific application.

Monitoring Devices fall into several general categories: devices that directly measure a primary or secondary PI and those that measure some associated property that can be converted to an estimate of a PI parameter. These two general types of monitoring devices can be further divided into how the device collects the data and whether the data to be collected is in the vadose zone or the saturated zone. Listed below are some examples of monitoring devices. How these devices are deployed is strictly a function of the PI and the location.

5.6.1 Saturated Zone Sampling

Once a contaminant has reached the water table, transport of the constituents in solution or suspension may be monitored through direct sampling of ground water.

Many States and Federal agencies have issued guidance for well installation that covers most well construction issues. For years the standard guide for well drilling and installation was The Johnson Water Well Manual, which has been replaced by Driscoll, 1986. These sources contain details of well materials, installation, pumps, and testing.

United States Geological Survey (USGS), State, and EPA guidance documents also exist and were referenced in AES (2003). A USGS reference (Lapham et al., 1997) describes the supporting documentation, or metadata, that should be collected during well installation or other types of borings.

There is extensive literature on saturated zone sampling for hydrologic and chemical data including EPA, U.S. Army Corps of Engineers (USACE), DOE, and State guidance documents. It includes permanent and temporary (e.g., penetrometer) methods. The reader is referred to Sara (1994) and Driscoll (1986).

5.6.2 Geophysical Methods

Geophysical methods can be thought of in two broad categories, those which require access to the subsurface through wells or direct push methods and those which are non-invasive and are applied from the surface. In the first category are geophysical logs such as resistivity and radiation logs.

Devices requiring direct access to the subsurface by wells (including piezometers) or direct push methods:

- geophysical logs,
- *in situ* chemical probes, and
- sensors for many elements or compounds.

Geophysical methods measure an associated property which can then be extrapolated to the PI of interest. Geophysical methods and what each technique measures are described in a large number of textbooks. One of the best for environmental (shallow) applications is Telford, Geldart, Sheriff, and Keys (1976). Annual publications of the Symposium on the Application of Geophysics to Engineering and Environmental Problems(SAGEEP) record new applications of geophysics to environmental problems. EPA published a guidance document (EPA, 1993) that has fact sheets or short descriptions of almost any conceivable subsurface monitoring and characterization technique including geophysical methods.

Sara (1994) has an excellent summary of geophysical techniques and several figures that illustrate which geophysical techniques are best for which applications. In general, geophysical methods are intended to supplement other methods.

While geophysical methods can be applied without any subsurface data, interpreting the results is improved if independent information on geologic strata, properties, or structures can be obtained. For example, a single well can provide sonic velocities for seismic interpretation, or layer thicknesses and electrical conductivity for electrical or electromagnetic methods.

Kowalsky et al., 2006, report on combining geophysical and hydrological data for improved subsurface characterization. They illustrate time-lapse (4D) methods to detect changes in subsurface plumes. Several books specifically related to geophysical methods in hydrogeology are available.

Geophysics can be used to provide information between boreholes or to quantify some physical property where access is an issue for boreholes, such as under impermeable covers. Table 5-1 presents commonly applied geophysical methods.

Table 5-1. Summary of Possible Applications of Surface and Cross Borehole Geophysical Methods for Site Characterization.

Surface/ Crosshole Method: Application	Resistivity	EM Induction	GPR	Seismic Reflection	Crosshole Seismic	Seismic Refraction	Gravity	Magnetics
Depth to Water Table	2	2	4	2	0	4	1	0
Fresh/Salt Water Interface	4	4	2	1	0	2	0	0
Depth to Bedrock	4	4	4	4	0	4	4	2
Gross Hydrostratigraphy	4	4	4	4	1	4	1	1
Detailed Hydrostratigraphy	2	3	4	4	4	1	1	0
Significant Fault Detection	4	4	4	4	4	4	4	4
Cavity Detection	2	1	3	2	3	0	2	1
Porosity, Permeability Estimation	3	3	3	3	3	1	1	0
Water Content Estimation	3	3	3	1	0	1	1	0
Contaminant Detection	3	3	3	1	3	0	0	0
Detection of Buried Metallic Objects	2	4	4	2	1	0	1	4
Landfill Delineation	4	4	4	2	2	2	2	4
Depth of investigation – a function of design and equipment selected	Shallow to km	Shallow to km.	Shallow 0-20m	Shallow to km	Between wells	Shallow to km		Surface to km
Resolution – often a function of design of data acquisition	10	10	Good	By design	By design - fuzzy	Good	Low	10

Key:
0 = not considered applicable
1 = limited use
2 = used, or could be used, but not the best approach or has limitations
3 = excellent potential but not fully developed
4 = generally considered an excellent approach, techniques are well developed
10 – resolution approx 10% of depth
Modified from Looney and Falta, 2000, Volume I, p223

5.6.3 Vadose Zone Devices

Water samplers for the unsaturated zone have long been used in agricultural research to evaluate nutrient and pesticide movement in soils. Listed below are some of the monitoring devices currently being used to:

measure soil water content and distribution

- neutron probes
- time domain reflectometry
- frequency domain reflectometry
- electrical resistance sensors
- tensiometers
- thermocouple psychrometers
- heat dissipation sensors or thermal conductivity sensors
- microgravimeters

measure constituents

- soil gas
    - mercury
    - iodine
    - tritium
    - radon, argon, krypton, etc.
    - organic vapors
- gamma (radiation) detectors

5.6.4 Other Monitoring Devices

Surface water sampling may provide a method of locating preferred pathways of ground water. For example, sampling along a seep line, or of shallow subsurface water along a creek edge (where upwelling is expected) may provide more information than sampling the flowing stream. Current-operated integrating samplers are available for streams. Stream flow may drive a paddle wheel that turns gears to periodically add a sample of the stream water to a container. Samples are retrieved and analyzed to detect contaminants seeping into the stream.

Once PIs have been identified, then appropriate measurements, measuring devices and access technology must be selected. While we again iterate through the PA, facility and site, the analysis assumes that the PIs are chosen, and that instrumentation or measurement type is now the focus.

This process is interactive and iterative, involving representatives of all parts of the total process. The modelers need to be involved during the design of the sampling and analysis plan to make sure that information crucial to the model is collected during site characterization.

5.7 Modify and Optimize Monitoring System

As part of the data analysis process, opportunities exist to increase the efficiency of the monitoring system, both in terms of data quality and savings realized. Applying an optimization technique to analyze an existing well network can potentially reduce the number of wells that need to be sampled and possibly the sampling frequency, while increasing the detection and delineation of contaminant plumes. On the other hand, some techniques (Ross and Vieux, 2000) can reveal inadequacies in the existing design and indicate the need for a greater well density to improve the monitoring performance.

Optimization methods can be used as the technical basis for a regulatory permit modification (Tuckfield et al., 2001). This is necessary when the long term use of a monitoring well has set a precedent for its continued use, whether it contributes to an understanding of the overall system or not.

The optimization methods used to analyze the network design vary. Some employ a geostatistical method of kriging (Journel and Huijbregts, 1978, Ben-Jemaa et al., 1994, Spruill and Candela, 1990), some use geological setting analysis (Nativ et al., 1999) combined with geostatistics (Tuckfield et al., 2001), and others use a combination of multiple criteria decision analysis combined with geostatistics (Woldt and Bogardi, 1992). In this last method there exists the opportunity to consider the performance and cost-effectiveness of different designs.

We caution against the use of statistical methods to justify elimination of monitoring wells. In complex hydrogeological systems (and they all are) wells assigned to the water table aquifer may actually be screened in several water-bearing zones. Head differences might be trivial, but transport pathways might be complex.

Chapters 2, 3 and 8 of Volume II include discussions of deleting wells from a monitoring network. Chapter 2 of Volume II provides an evaluation for the Charleston Naval Weapons Station showing how application of the strategy provides for the revision of the monitoring well network to increase the monitoring system performance and reduce uncertainty.

6 Conclusion

Performance Assessment modeling of a site may make predictions of potential contaminant levels many millennia into the future. Yet, the lifetime of a monitoring program may be measured in decades at most. For this reason, a strategic approach must be applied that ensures that the facility is, in fact, behaving as expected and within limits described by the performance assessment and that there is high confidence that it will continue to do so.

Risk or performance assessments are based on a sufficiently accurate understanding of flow and transport in the subsurface. It is most important to determine what things to measure and where and how to measure them in a short period of time so that the long-term predictions can be most accurate.

The discussions and recommendations of the preceding pages are intended to help guide a site manager in a logical way toward an effective ground water monitoring system. A logical or strategic approach to system design, including what, where, when, and how to monitor, is the best path toward reducing uncertainty regarding system performance.

Although the high level logic of the approach is simple, a great deal of specialized knowledge is required for implementation of the logic. The Strategy requires application of tools from geology, hydrogeology, geochemistry, geophysics, statistics, computer simulations and access and sampling technologies. An objective in this document has been to present enough information in each area for a responsible party to appreciate the need for expertise in each area. Our recommendation is that the Strategy be implemented with the assistance of a team of technical experts.

The DQO process can be a powerful tool supporting goal setting and evaluation of whether goals are achieved. Unfortunately the first step in the DQO process is unwritten. The first step is to assemble a really good technical team to write the DQOs. Poorly written DQOs can result in poor goals and poor execution. This differs a bit from the MBO process in which all stakeholders are asked to contribute ideas and which involves less critical thinking. The strength of MBO results from its inclusiveness.

Ultimately a manager, together with relevant stakeholders or regulators will make decisions based on ground water data. Following a logical approach, including application of the DQO process, will allow increased confidence in decisions, and reduce the risk of reaching the wrong decision.

References

Advanced Environmental Solutions, LLC. *A Review of Ground-Water Monitoring Issues, Strategies, and Technologies.* Washington, DC. May 30, 2003. U.S. Nuclear Regulatory Commission, ADAMS accession no. ML072740153

Andraski, B.J., et al. "Importance and Use of Plants in Evaluation Water Flow and Contaminant Transport in Arid Environments." *Eos Trans. AGU, Fall Meet. Suppl., Abstract H52A-0836.* Vol. 83. No.47. 2002.

Ben-Jemaa, F. and M.A Marino. "Multivariate Geostatistical Design of Ground-Water Monitoring Networks." *Water resources Planning and Management.* Vol.120 No. 4: 505-522. 1994.

Bevin, K.J. *Prophecy, Reality, and Uncertainty in Distributed Hydrological Modeling.* Advance Water Resource. pp. 16, 41-51. 1993.

Bevin, K.J. *Uniqueness of Place and Non-Uniqueness of Models in Assessing Predictive Uncertainty.* Computational Methods in Water resources XIII. Bentley et al. Balkema, Rotterdam: The Netherlands. pp. 1085-1091, 785-792. 2000.

Bevin, K.J., and J. Freer. "Equifinality, Data Assimilation, and Uncertainty Estimation in Mechanistic Modeling of Complex Environmental Systems Using the GLUE Methodology." *Journal of Hydrology*. pp. 249, 11-29. 2001.

Blanchard, B.S., and W.J. Fabryky. *Systems Engineering and Analysis, Third Edition.* Prentice Hall International Series in Industrial and System Engineering. 1998.

Bodvarsson, G., et al. *Flow and Transport Modeling of the Vadose Zone.* 2000.

Brooks, R.H. and A.J. Corey. *Hydraulic Properties of Porous Media.* Hydrol. Fort Collins, CO: Colorado State University. Paper 3. 1964.

Brooks, R.R. "Biogeochemical Methods of Prospecting." *Australian Mining.* Vol. 60: 81-83. 1968.

Carrera, J. and S.P. Neuman. "Estimation of aquifer parameters under steady-state and transient conditions: 2. Uniqueness, stability, and solution algorithms." *Water Resource Res.* Vol. 22. No2: 211-227. 1986.

Chamberlain, T.C. *The Method of Multiple Working Hypotheses*. Science. pp. 754-759. (1890) 1965.

Cohen, R.M., et al. EPA/600/R-94/123. "Methods for Monitoring Pump-and-Treat Performance." EPA, Office of Research and Development :Ada, Oklahoma. 1994 http://www.epa.gov/r10earth/offices/oea/gwf/issue20.pdf

Cooley, R.L. “Some new procedures for numerical solution of variably saturated flow problems.” *Water Resource Res*. Vol. 19 No.5: 1271-1285. 1983.

Craig, R.W. and R.L. Reed. ISGS/WRIR-89-4025. “Geohydrology of Rocks Penetrated by Test Well USW-h6, Yucca Mountain, Nye County, Nevada.” pp. 48. 1989.

Dai, Z., et al. *Evaluating Conceptual Site Models with Multicomponent reactive Transport Modeling, Abstract and Poster*. New Orleans, Louisiana: AGU 2005 Joint Assembly. 2005.

Dai, Z. and J. Samper. “Inverse problem of multicomponent reactive chemical transport in porous media: Formulation and applications.” *Water Resource Res*. Vol.40, W07407, doi: 10.1029/2004WR003248. 2004.

Dai, Z., et al. “Transport in heterogeneous sediments with multimodal conductivity and hierarchical organization across scales.” *Journal of Hydrology*. Vol.294 No 1-3:68-86. 2004a.

Dai, Z., et al. “Estimating Parameters for Hierarchical permeability Correlation Models.” *Aquifer Characterization, Eds. J. Bridge and D. Hyndman.* SEPM Publishers. No. 80: 41-54. 2004b.

Dershowitz, W.S., et al. DOE/PC/91008-5 (DE98000469). “Fractured Reservoir discrete Feature Network Technologies.” DOE: Oklahoma. 1998.

Driscoll, F.F. *Ground Water and Wells*. Johnson Division. 1986.

Dunn. “Bibliography of Uranium biogeochemistry.” *Misc. Rept. Miner. Resour.* Saskatchewan. Vol. 80 No.4: 59. 1980.

Environmental Protection Agency. EPA/230/R-92/014. “Methods for Evaluating the Attainment of Cleanup Standards, Volume 2: Ground Water.” U.S. EPA, Office of Policy, Planning, and Evaluation, Environmental Statistics and Information Division. Washington, DC. 1992a.
http://www.epa.gov/superfund/health/conmedia/gwdocs/per_eva.htm

EPA. *Ground-Water Monitoring: Draft Technical Guidance.* Washington, DC: U.S. EPA. 1992b.

EPA. EPA-625/R-93/003a “Subsurface Characterization and Monitoring Techniques, A Desk reference Guided, Volume 1: Solids and Ground Water Appendices A and B.” EPA:Washington, DC. 1993.

EPA. EPA QA/G-4HW, EPA/600/R-00/007. “Data Quality Objectives Process for Hazardous Waste Site Investigations.” EPA: Washington, DC. pp. 1-143. 2000.

EPA. OSWER Directive No. 9355.4-28. “Guidance for Monitoring at Hazardous Waste Sites: Framework for Monitoring Plan Development and Implementation.” 2004.

EPA. *Compacted Clay and ET Landfill Covers Compared in Humid Climate*. Technology Innovation Program, Publication and Studios, Technology News and Trends. May 2006. http://www.clu-in.org/products/newsltrs/tnandt/view.cfm?issue=0506.cfm

Erdman, J.A. and G.H. Harrach. "Uranium in Big Sagebrush from Western U.S. and Evidence of Possible Mineralization in the Owyhee Mountains of Idaho." *Journal of Geochemical Exploration.* Vol.14 No.1:83-94. 1981.

Falls, W., et al. *Geology and Hydrogeology of Cretaceous and Tertiary Strata, and Confinement in the Vicinity of the U.S. Department of Energy Savannah River Site, South Carolina and Georgia.* Water-Resources Investigations Report. U.S. Geology Survey, SC. 1997.

Gee, G.W., et al. PNNL-13712. "Installation of a Hydrologic Characterization Network for Vadose Zone Monitoring of a Single-Shell Tank Farm at the U.S. Department of Energy Hanford Site." Pacific Northwest National Laboratory: Richland, Washington. 2001.

Guzowski, R.V. SAND89-7149. "Preliminary Identification of Scenarios that May Affect the Escape and Transport of Radionuclides from the Waste Isolation Pilot Pant, Southeastern New Mexico." Sandia National Laboratories: Albuquerque, New Mexico. 1990.

Guzowski, R.V. SAND93-7100. "Preliminary Identification of Potentially Disruptive Scenarios at the Greater Confinement Disposal Facility, Area 5 of the Nevada Test Site." Sandia National Laboratories: Albuquerque, NM. 1993.

Hartman M.J., L.F. Morasch, and W.D. Webber. *Hanford Site Groundwater Monitoring for Fiscal Year 2002*. PNNL-14187. Richland, Washington: Pacific Northwest National Laboratory. 2003.

Hooten, M.M. and T.G. Myles. *Biotic Processes Relevant to Near-Surface Pedoturbation and Contaminant Transport in Alluvial Soils of the Nevada Test Site*. Los Alamos, New Mexico: Neptune and Company. December 2006. http://www.neptuneandco.com/pubs/Rev_Final_Biotic_Trans_Soils_NTS.pdf

Hill, M. C. *Methods and Guidelines for Effective Model Calibration*. U.S. Geological Survey, Water-Resources Investigations Report 98-4005.1998.

Hoeting, J.A., et al. "Bayesian model averaging: A tutorial." *Statist. Sci.*. Vol. 4 No.4: 382-417. 1999.

Hossner, L.R., et al. *Literature Review: Phytoaccumulation of Chromium, Uranium, and Plutonium in Plant Systems.* ANRCP-1998-3. 1998.

Hsieh, P.A. and A.M. Shapiro. "Hydraulic characteristics of fractured bedrock underlying the FSE well field at the Mirror Lake Site, Grafton County, New Hampshire, in Morganwalp, D.W., and Aronson, D.A. eds., U.S. Geological Survey Toxic Substances Hydrology Program—Proceedings of the technical meeting, Colorado Springs, Colorado, September 20-24, 1993." *U.S. Geological Survey Water-Resources Investigations Report 94-4015*. Vol. 1: 127-130. 1996.

Hubbert, M.K. "The Theory of Ground-Water Motion". *Journal of Geology*. Vol. 48 No.8 Part 1:781-944. 1940.

International Atomic Energy Agency (IAEA). *Hydrogeological Investigation of Sites for the Geological Disposal of Radioactive Waste*. Vienna: IAEA. 1999.

IAEA. IAEA-TECDOC-1372. "Safety Indicators for the Safety Assessment of Radioactive Waste Disposal." IAEA:.Austria. 2003.

Idaho National Engineering and Environmental Laboratory (INEEL). INEEL/EXT-02-01209. "RWMC Performance Assessment / Composite Analysis Monitoring Report - FY-2002." INEEL: Idaho. 2002.

James, Scott C., Sandia National Lab, Personal Communication, 2007. The figure shown here was also presented in James and Umari, Saturated Zone Anisotropy Near the C-wells Complex, a paper presented at the Geological Society of America annual meeting, November 2003.

Journel, A.G., and Ch.J. Huijbregts. *Mining Geostatistics*. Academic Press. 1978.

Kashyap, R.L. "Optimal choice of AR and MR parts in autoregressive moving average models." *IEEE Trans. Pattern Anal. Mach. Intel. PAMI*. Vol. 4 No.2: 99-104. 1982.

King, P.R. *The Use or Renormalization for Calculating Effective Permeability: Transport in Porous Media*. Vol. 4: 37-58. 1989.

Lapham, W.W., F. D. Wilde, and M.T. Koterba. *Guidelines and Standard Procedures for Studies of Ground-Water Quality: Selection and Installation of Wells, and Supporting Documentation*, U.S. Geological Survey Water Resources Investigations Report 96-4233. VA.1997.

Larsson, A., et al. *INTRAVAL Project: To Study Validation of Geosphere Transport Models for Performance Assessment of Nuclear Waste Disposal, Phase 2, Summary Report*. Nuclear Energy Agency, Organization for Economic Cooperation and Development. 1997.

Long, P.E. and S.B Yabusaki. PNNL-16385. "Evaluating the Efficacy of Uranium Bioremediation in the Subsurface: Technical Bases and Performance Indicators." Letter Report to the Nuclear Regulatory Commission. pp. 62. 2007.

Mansoori, J. *A Review of Basic Upscaling Procedures: Advantages and Disadvantages, in Yarus and Chambers*, eds. Stochastic Modeling and Geostatistics. AAPG Computer Applications in Geology. No. 3: 65-74. 1994.

Meyer, P.D., et al. NUREG/CR-6843. "Combined Estimation of Hydrogeologic Conceptual Model and Parameter Uncertainty." p42, prepared for U.S. Nuclear Regulatory Commission. Washington, DC. 2004.

Miller, R. B., J.W. Castle, and T.J. Temples. "Deterministic and Stochastic Modeling of Aquifer Stratigraphy." *Groundwater*. Vol. 38, No. 2. SC. 2000.

National Academy of Sciences (NAS). *Research Needs in Subsurface Science*. Washington, DC: National Academy Press. 2000a.

NAS. *Natural Attenuation for Ground-Water Remediation*. Washington, DC: National Academy Press. 2000b.

NAS/NRC. *Improving Operation and Long-Term Safety of the Waste Isolation Pilot Plant.* Washington, DC: National Academy Press. pp.142. 2001.

Nativ, R., E. Adar, and A. Becker. "A monitoring network for ground water in fractured media." *Ground Water*. Vol. 37: 38– 47. 1999.

Neuman, S.P. "Maximum likelihood Bayesian averaging of uncertain model predictions." *Stochastic Environ. Res. and Risk Assess*. Vol. 17: 291-305. 2003.

Neuman, S. P and P.J. Wierenga. NUREG/CR-6805. "A Comprehensive Strategy of Hydrogeological Modeling and Uncertainty Analysis for Nuclear Facilities and Sites." Arizona: University of Arizona. 2003.

Nielsen, D. M. *Practical Handbook of Ground-water Monitoring*. Michigan: Lewis Publishers. 1991.

Nuclear Regulatory Commission (NRC). NUREG-1573. "A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities." NRC:Washington, DC. 2000.

NRC. NUREG-1569. "Standard Review Plan for In Situ Leach Uranium Extraction License Applications." NRC:Washington, DC 2003a.

NRC. NUREG-1620, Rev. 1. “Standard Review Plan for the Review of a Reclamation Plan for Mill Tailings Sites Under Title II of the Uranium Mill Tailings Radiation Control Act of 1978.” NRC:Washington, DC. 2003b.

NRC. *Liquid Radioactive Release Lessons Learned Task Force Report* (NRC Document Accession # ML062650312,). NRC:Washington, DC. 2006a.

NRC. NUREG/CR-6884. “Model Abstraction Techniques for Soil-Water Flow and Transport.”. NRC:Washington, DC. 2006bOrganisation for Economic Co-operation and Development (OECD). “Features, Events and Processes (FEPs) for Geologic Disposal of Radioactive Waste.” Nuclear Energy Association: Paris. 2000.

Ponke, D., *Implementing the Graded Approach Process at the Department of Energy Facilities*. 2002.

Pope, D.F., et al. EPA/600/R-04/027. “Performance Monitoring of MNA Remedies for VOCs in Ground Water.” Technique Report for Office of Research and Development. U.S. Environmental Protection Agency. p74. April, 2004.

Popper, K. *Conjectures and Refutations: The Growth of Scientific Knowledge*. New York: Harper & Row.1963.

Price, V., W.C. Fallaw, and J.B McKinney. WSRC-RP- 91-96, ESH-EMS-90171. “Geologic Setting of the New Production Reactor Reference Site within the Savannah River Site (U).” 1991.

Pruess, K., et al. “Fluid Flow, Heat Transfer, and Solute Transport at Nuclear Waste Storage Tanks in the Hanford Vadose Zone.” *Vadose Zone Journal*. Vol.1:68-88. 2002.

Radian International. *Guide to Optimal Groundwater Monitoring*. Prepared for the Naval Facilities Engineering Service Center in Port Hueneme, CA. January 2000.

Ross, R. R and B.E. Vieux. “A Probabilistic Method for Estimating Monitoring Point Density of Containment System Leak Detection.” *Ground Water*. Vol. 38, No. 4: 533-540. July-August 2000.

Rossi, C. and J.R. Nimmo. “Modeling of soil water retention from saturation to oven dryness.” *Water Resources Research*. Vol.30: 701-708. 1994.

Ruby, C. H. *Clastic Facies and Stratigraphy of a Rapidly Retreating Cuspate Foreland*. Cape Romain, South Carolina: University of South Carolina.1981.

Sara, M. N. *Standard Handbook for Solid and Hazardous Waste Facility Assessments*. Florida: Lewis Publishers. 1994.

Shaw, T., USACE, Seattle District Joint Services Environmental Management Conference & Exposition Denver, CO March 2006, EPA, http://www.epa.gov/correctiveaction/workshop.htm, RCRA Corrective Action Workshop on Results-Based Project Management, June 10, 1999.

Sperry, J. M. and J.J. Peirce. *A Model for Estimating the Hydraulic Conductivity of Granular Material Based on Grain Shape, Grain Size, and Porosity*. North Carolina: Duke University. 1995.

Spruill, T.B. and L. Candela. "Two Approaches to Design of Monitoring Network." *Ground Water*. Vol. 28, No. 3: 430-442. 1990.

Sun, N-Z. *Inverse Problems in Groundwater Modeling.* Netherlands: Kluwer Academic Publishers. pp. 364. 1994.

Taplin, R.H. "Robust likelihood calculation for time series." *J. Roy. Statist. Soc. Ser.* Vol. B 55: 829-836.1993.

Tauxe, J.D. *Porous Medium Advection-Dispersion Modeling in a Geographic Information System*. Center for Research in Water Resources Technical Report No. 253, Bureau of Engineering Research. Austin, Texas: The University of Texas. May 1994.

Telford, W.M., et al. *Applied Geophysics*. Cambridge: Cambridge University Press.1976.

Temples, T.J. and M.G. Waddell. *Application of Petroleum Geophysical Well Logging and Sampling Techniques for Evaluating Characteristics*. Vol. 34, No. 3. 1996.

Tuckfield, R.C., et al. *Using Geosciences and Geostatistics to Optimize Groundwater Monitoring Networks at the Savannah River Site.* Tennessee: U. S. Department of Energy. 2001.

Tukey, J.W. "The Future of Data Analysis." *Annals of Mathematical Statistic*. Vol. 33: 1-67. 1962.

van Genuchten, M. Th. "A closed-form equation for predicting the hydraulic conductivity of unsaturated soils." *Soil Science. Soc. American. Journal.* Vol. 44:892–898. 1980.

Wagner, B.J. and S.M. Gorelick. "Optimal ground water quality management under parameter uncertainty." *Water Resource. Res.* Vol. 23, No.7: 1162-1174. 1987.

Wagner, B.J. "Simultaneous parameter estimation and contamination source characterization for coupled ground water flow and contaminant transport modeling." *Journal of. Hydrology*. Vol. 135: 275-303. 1992.

Walker, R.G. *Facies Model*. Toronto, Canada: Geological Association of Canada. 1984.

Williams, J.D. *The Compleat Strategyst*. New York: McGraw-Hill. p. 234. 1954.

Woldt, W. and I. Bogardi. "Ground Water Monitoring Network Design Using Multiple Criteria Decision Making and Geostatistics." *Water Res. Bull.* Vol. 28 No.1:45-62. 1992.

Wood, T.R., et al. INEEL/Ext-99-0984. "Deficiencies in Vadose Zone Understanding at the Idaho National Engineering and Environmental Laboratory." 2000.

Westinghouse Savannah River Company (WSRC). WSRC-RP-2000-00326, Rev. 0. "Composite Analysis Monitoring Plan for the E-Area Low-Level Waste Facility and the Z-Area Saltstone Disposal Facility." WSRC. 2000.

Wyatt, D.E. and Temples, T.J. "Ground-Penetrating Radar Detection of Small-Scale Channels, Joints and Faults in the Unconsolidated Sediments of the Atlantic Coast Plain." *Environmental Geology.* Vol. 37, No. 3. 1996.

Yarus, J.M. and R.L. Chambers. *Stochastic modeling and geostatistics: principles, methods, and case studies*. Tulsa, Oklahoma: American Association of Petroleum Geologists. p.379. 1994.

Young, M.H., et al. NUREG/CR-5694. "Results of Field Studies at the Maricopa Environmental Monitoring Site, Arizona." NRC: Washington, DC. 1999a.

Young, M.H., et al. NUREG/CR-5698 "Comparing Monitoring Strategies at the Maricopa Environmental Monitoring Site, Arizona." NRC: Washington, DC. 1999b.

Bibliography

ASTM, 2002, *Standard Guide for Risk-Based Action Applied to Petroleum Release Site*, ASTM E1739-95.

Atwood, C. L., et al. NUREG/CR-6823, SAND2003-3348P. "Handbook of Parameter Estimation for Probabilistic Risk Assessment." Sandia National Laboratories, Albuquerque, New Mexico.2003.

Bailey, L.E.F., and D.E Billington. *Overview of the FEP Analysis Approach to Model Development*, NIREX Science Report S/98/009.1998.

Beardsley, C., et al. WSRC-TR-98-00191. "Groundwater Sampling Reduction at the Savannah River Site." Westinghouse Savannah River Company, Aiken, SC. 1998.

Black, P.K., et al. "Assessing the Probability of Inadvertent Human Intrusion at Nevada Test Site Waste Management Sites: Final Report." U.S. Department of Energy, Report Number DOE/NV-593-Vol. 1. 2001.

Carle, S. F., M. Zavarin, and G.A Pawloski. *Geostatistical Analysis of Spatial Variability of Mineral Abundances and Kd in Frenchman Flat*. NTS, Alluvium, Draft Report, NNSA/NV.2002.

Compton, R. R. *Manual of Field Geology*. John Wiley & Sons. pp. 1-378.1962.

Coward, M. P., T.S Daltaban, and H. Johnson. *Structural Geology in Reservoir Characterization*. The Geological Society, London.1998.

Curtis, G.P. NUREG/CR-6871. "Documentation and Applications of the Reactive Geochemical Transport Model RATEQ." U.S. Geological Survey.2005.

Daniel, D. E. *Surface Barriers: Problems, Solutions and Future Needs*. In- Situ Remediation: Scientific Basis for Current and Future Technologies. Washington: Battelle Press. pp. 441-487. 1994.

Davis, J.A. and G.P Curtis. NUREG/CR-6820. "Application of Surface Complexation Modeling to Describe Uranium (VI) Adsorption and Retardation at the Uranium Mill Tailings Site at Naturita, Colorado." Nuclear Regulatory Commission.2003.

Department of Environmental Protection (DEP). *Groundwater Monitoring Guidance Manual*. Pennsylvania Department of Environmental Protection.2001.

DeSchaine, L.M. *Mathematical Simulation and Optimization of Subsurface Environmental Contamination Events*. Chalmers University of Technology.2003.

Department of Energy (DOE). *Summary Report of Performance Monitoring Workshop*. Office of Environmental Cleanup Technologies. 2005.

Environmental Protection Agency (EPA). EPA/600/R-04/027. "Performance Monitoring of MNA Remedies for VOCs in Ground Water." National Risk Management Research Laboratory, Office of Research and Development, Cincinnati, OH. 2004a.

EPA. EPA/542/R-04/013. "Survey of Technologies for Monitoring Containment Liners and Covers." Office of Solid Waste and Emergency Response, Washington DC. 2004b.

EPA. OSWER 5102G, EPA 542-R-04-001b. "*Demonstration* of Two Long-Term Groundwater Monitoring Optimization Approaches."2004.

EPA. EPA 542-R-05-003. "Roadmap to Long-Term Monitoring Optimization." 2005.

Fayer, M.J., et al. PNL-5604. "Model Assessment of Protective Barrier Designs." Prepared for the Department of Energy.1985.

Gregg, D.O. "An Analysis of Ground-Water Fluctuations Caused by Ocean Tides in Glynn County, Georgia." *Ground Water*. Vol. 4, No 3.1966.

Harbaugh, J. W., J.H Doveton, and J.C Davis. *Probability Methods in Oil Exploration*. New York: John Wiley& Sons, Inc. 1977.

Hogan, J.F., F.M Phillips, and B.R Scanlon. *Groundwater Recharge in a Desert Environment – The Southwestern United States*. American Geophysical Union. Washington, DC. 2004.

Horton, D.G., S.P Reidel, and G.V Last. PNNL-11958, Rev. 2. "Monitoring Guidance for Vadose Zone Monitoring of Liquid Waste Disposal Facilities for the Hanford Groundwater Project." 1999.

International Atomic Energy Agency (IAEA). *Safety Assessment for Near Surface Disposal of Radioactive Waste*. No. WS-G-1.1. International Atomic Energy Agency, Vienna. 1999.

IAEA. *Scientific and Technical Basis for the Near Surface Disposal of Low and Intermediate Level Waste*. Technical Report Series, No. 412. International Atomic Energy Agency, Vienna.2002.

INCORE. *Integrated Concept for Ground water Remediation.* Contract No. EVK1 CT-1999-00017. 1999.

Kotra, J.P., et al. *Branch Technical Position in the Use of Expert Elicitation in the High-Level Radioactive Waste Program*, NUREG-1563, U.S. Nuclear Regulatory Commission, D.C. 1996.

Last, G. V., et al. PNNL-34515. "Use of Process Relationship Diagrams in Development of Conceptual Models." Pacific Northwest National Laboratory. 2001.

Last, G.V., et al. "A Comprehensive and Systematic Approach to Developing and Documenting Conceptual Models of Contaminant Release and Migration at the Hanford Site.*" Journal of Stochastic Environmental Research and Risk Assessment.* 2004.

Leroy, L.W. *Subsurface Geologic Methods*. 2nd Edition. Colorado School of Mines, CO. 1951.

Looney, B. WSRC-RP-2002-00077. "Technical Targets – A Tool to Support Strategic Planning in the Subsurface Contaminants Focus Area." Westinghouse Savannah River Company, Aiken, SC. 2002.

Mackin, P.C., et al. NUREG/CR-6733. "A Baseline Risk-Informed Approach for In Situ Leach Uranium Licensees." 2001.

McDonald, M.G. and A.W Harbaugh. *A Modular Three-Dimensional Finite- Difference Ground-Water Flow Model: U.S. Geological Survey Techniques of Water- Resources Investigations*. Book 6, Chap. A1, p. 586.1988.

Meyer, P.D., G.W Gee., and T.J. Nicholson. PNNL-13091, NUREG/CR-6656. "Information on Hydrologic Conceptual Models, Parameters, Uncertainty Analysis, and Data Sources for Dose Assessments at Decommissioning Sites." Pacific Northwest National Laboratory, Washington. November 1999.

Meyer, P.D. and R.Y Taira. NUREG/CR-6695, PNNL-13375. "Hydrologic Uncertainty Assessment for Decommissioning Sites: Hypothetical Test Case Applications." Pacific Northwest National Laboratory, Washington. 2001.

Meyer, P.D., M.L. Rockhold, and G.W Gee. *Uncertainty Analyses of Infiltration and Subsurface Flow and Transport*, PNNL-11705, NUREG/CR-6565. September 1997.

National Academy of Sciences (NAS)/NRC. *Rock Fractures and Fluid Flow*. Washington, D.C: National Academy Press. pp. 1-557. 1996.

National Academy of Sciences (NAS)/NRC. *Conceptual Models of Flow and Transport in the Fractured Vadose Zone.* Washington, D.C: National Academy Press. pp. 1-365. 2003.

NEA. *The Handling of Timescales in Assessing Post-closure Safety.* ISBN 92-64-02161-2. 2004.

Nicholson, T. J. and V. Price. "Development of an integrated ground-water monitoring strategy for supporting performance assessments of nuclear facilities." *Eos Trans. AG.* Vol. 84 No.46, Fall Meet. Suppl. 2003.

NRC. NUREG/CP-0177, PNNL-13654. "Proceedings of the Environmental Software Systems Compatibility and Linkage Workshop." Nuclear Regulatory Commission. 2000a.

Nuclear Regulatory Commission (NRC). NUREG-1724. "Standard Review Plan for the Review of DOE Plans for Achieving Regulatory Compliance at Sites with Contaminated Ground Water Under Title I of the Uranium Mill Tailings Radiation Control Act." Nuclear Regulatory Commission.2000b.

NRC. *Land Disposal of Radioactive Waste*. 10 CFR 61, Nuclear Regulatory Commission, Subpart C - Performance Objective. pp. 167. 2003.

Pachepsky, Y., et al. *Letter Report: Task 3 - Develop Test Plan for Testing and Confirming Model Abstraction Techniques*. U.S. Nuclear Regulatory Commission. 2003.

Reed, P.M. *Cost Effective Long-Term Groundwater Monitoring Design Using A Genetic Algorithm and Global Mass Interpolation*. Master's Thesis, University of Illinois at Urbana-Champaign. 1999.

Saltelli, A.S., S. Tarantola, and K/ P.-S Chen. *"About the Use of Rank Transformation in Sensitivity Analysis of Model Output."* Reliability, Engineering, and System Safety. pp. 50, 225-239. 1999.

Sobol, I.M. *"Sensitivity Analysis for Nonlinear Mathematical Models."* Mathematical Modeling & Computational Equipment. pp. 1, 40-414. 1993.

U.S. Department of Agriculture. NUREG/CR- 6729. "Field Studies for Estimating Uncertainties in Ground-Water Recharge Using Near-Continuous Piezometer Data." U.S. Nuclear Regulatory Commission: Washington D.C. 2001.

White, G.J, et al. NUREG/CR-5615, EGG-2604. "Low-Level Radioactive Waste Disposal Facility Closure." 1990.

Wilson, J.L., and W.R Linderfelt.. *Groundwater Quality in Pumping Wells Located Near Surface Water Bodies*. New Mexico Institute of Mining and Technology. New Mexico Water Resources Research Institute. 1991.

Wood, T.R. *Impact of Surface Water Recharge on the Design of a Groundwater Monitoring System for the Radioactive Waste Management Complex, Idaho National Engineering Laboratory*. Proceedings of the Annual Symposium on Engineering Geology and Geotechnical Engineering. April 1990.

Zheng, C. and P.P Wang. *MT3DMS: A Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems; Documentation and User's Guide*. University of Alabama. U.S. Army Corp of Engineers, SERDP-99-1. 1999.

.

Appendix A: Existing Guidance for Traditional Monitoring

Guidance documents that cover some aspects of environmental monitoring have been issued by several different governmental agencies and other entities. In most cases the guidance is regulatory driven, though some describe the use of monitoring as a tool, such as for decision making. Presented here are summaries of the sections that pertain to monitoring. This includes many of the regulatory driven guidance documents affecting NRC regulated facilities and those that pertain to other hazardous waste sites and disposal facilities.

10 CFR 20, Subparts E and F

Subpart E: The NRC issued radiological criteria for license termination in July 21, 1987. The general provisions and scope include:

(a) The criteria in this subpart apply to the decommissioning of facilities licensed under Parts 30, 40, 50, 60, 61, 63, 70, and 72 of this chapter, and release of part of a facility or site for unrestricted use in accordance with § 50.83 of this chapter, as well as other facilities subject to the Commission's jurisdiction under the Atomic Energy Act of 1954, as amended, and the Energy Reorganization Act of 1974, as amended. For high-level and low-level waste disposal facilities (10 CFR Parts 60, 61, 63), the criteria apply only to ancillary surface facilities that support radioactive waste disposal activities. The criteria do not apply to uranium and thorium recovery facilities already subject to Appendix A to 10 CFR Part 40 or to uranium solution extraction facilities.

(b) The criteria in this subpart do not apply to sites which:

(1) Have been decommissioned prior to the effective date of the rule in accordance with criteria identified in the Site Decommissioning Management Plan (SDMP) Action Plan of April 16, 1992 (57 FR 13389);

(2) Have previously submitted and received Commission approval on a license termination plan (LTP) or decommissioning plan that is compatible with the SDMP Action Plan criteria; or

(3) Submit a sufficient LTP or decommissioning plan before August 20, 1998 and such LTP or decommissioning plan is approved by the Commission before August 20, 1999 and in accordance with the criteria identified in the SDMP Action Plan, except that if an EIS is required in the submittal, there will be a provision for day-for-day extension.

(c) After a site has been decommissioned and the license terminated in accordance with the criteria in this subpart, or after part of a facility or site has been released for unrestricted use in accordance with § 50.83 of this chapter and in accordance with the criteria in this subpart, the Commission will require additional cleanup only, if based on new information, it determines that the criteria of this subpart were not met and residual radioactivity remaining at the site could result in significant threat to public health and safety.

(d) When calculating Total Effective Dose Equivalent (TEDE) to the average member of the critical group the licensee shall determine the peak annual TEDE dose expected within the first 1000 years after decommissioning.

Subpart F: Issued in May 21, 1991, Subpart F is the regulations for surveys and monitoring:

(a) Each licensee shall make or cause to be made, surveys that—

(1) May be necessary for the licensee to comply with the regulations in this part; and

(2) Are reasonable under the circumstances to evaluate—

(i) The magnitude and extent of radiation levels; and

(ii) Concentrations or quantities of radioactive material; and

(iii) The potential radiological hazards.

(b) The licensee shall ensure that instruments and equipment used for quantitative radiation measurements (e.g., dose rate and effluent monitoring) are calibrated periodically for the radiation measured.

(c) All personnel dosimeters (except for direct and indirect reading pocket ionization chambers and those dosimeters used to measure the dose to the extremities) that require processing to determine the radiation dose and that are used by licensees to comply with § 20.1201, with other applicable provisions of this chapter, or with conditions specified in a license must be processed and evaluated by a dosimetry processor—

(1) Holding current personnel dosimetry accreditation from the National Voluntary Laboratory Accreditation Program (NVLAP) of the National Institute of Standards and Technology; and

(2) Approved in this accreditation process for the type of radiation or radiations included in the NVLAP program that most closely approximates the type of radiation or radiations for which the individual wearing the dosimeter is monitored.

10 CFR 61

The NRC has issued regulations for the land disposal of low-level radioactive waste in 10 CFR 61. While the monitoring strategy is not constrained to disposed radioactive wastes, the language in the regulation can be readily applied to decommissioned nuclear facilities as well, if they are imagined to be a specialized form of disposal. As far as PA is concerned, it doesn't matter if the inventory of radionuclides on the surface or buried below is the result of intentional waste disposal activities, or of residual and perhaps inadvertent contamination of a nuclear facility. The site characterization and modeling of material properties, both man made and natural, and of radionuclide transport is independent of these distinctions. Indeed, DOE 435.1-1, discussed in a following section, recognizes that, "For deactivated high-level waste facilities or sites that are closed as low-level waste sites, the disposal facility performance objectives [for low-level waste] should be met." [DOE G 435.1-1 II.U.(3)(a)(5)].

These regulations are oriented principally toward waste classification and the operations of a shallow land burial (SLB) disposal site, and provide only general guidance for monitoring. The regulation defines *monitoring* as "...observing and making measurements to provide data to evaluate the performance and characteristics of the disposal site." This general definition is at the core of this monitoring strategy, in that it frames monitoring in the context of evaluation of the site both in reality and in its modeled representation. Later in the text of the regulation, monitoring is assigned the more specific purpose of "...providing early warning of releases of radionuclides from the disposal site before they leave the site boundary" [§61.53(d)].

Several other references to monitoring are made in 10 CFR 61. Section 61.7(a)(2) suggests a 500-year time frame for the consideration of site characteristics. This hints at the regulation's emphasis on *modelability* [§61.50(a)(2)] and *stability* [§61.7(b)(2) and §61.44] of the site. Confidence in the stability of site characteristics throughout the modeled time window is of paramount importance. While this should be used as a criterion for selection of a new site, such conditions are by no means guaranteed at any given decommissioned nuclear facility or legacy waste site. Easily modeled sites will have straightforward monitoring plans, but those sites with more challenging conditions will require monitoring strategies involving many contingencies and allowances for various conceptual models.

Subpart B of the regulation concerns licensing, and mentions monitoring only briefly, in the context of a monitoring plan accompanying the license application. The specific technical information required includes "A description of the environmental monitoring program to provide data to evaluate potential health and environmental impacts and the plan for taking corrective measures if migration of radionuclides is indicated," [§61.12(l)]. The following section discussed technical analyses, requiring an analysis of specific environmental transport pathways, including "...air, soil, ground water, surface water, plant uptake, and exhumation by burrowing animals" [§61.13(a)]. This monitoring strategy is concerned with only one of these pathways: ground water. Presumably, additional strategies will be developed for the other pathways, which in some cases (e.g. arid sites with deep water tables) will be of much greater significance.

Post-closure monitoring is also discussed in Subpart B. Section 61.29 states "Following completion of closure authorized in §61.28 [Contents of application for closure] the licensee shall observe, monitor, and carry out necessary maintenance and repairs at the disposal site until the license is transferred by the Commission in accordance with §61.30 [Transfer of license]. Responsibility for the disposal site must be maintained by the licensee for 5 years." That said, one presumes that site monitoring will continue for a far greater period than that. Yet, curiously, the time frame of interest is not specified in 10 CFR 61.

Subpart D is entitled "Technical Requirements for Land Disposal Facilities", and includes a section (61.53) on Environmental monitoring. In §61.53(c), a longer time frame is hinted: "Measurements and observations must be made and recorded to provide data to evaluate the potential health and environmental impacts during both the construction and operation of the facility and to enable the evaluation of long-term effects and the need for mitigative measures.” The meaning of “long-term” is not defined.

10 CFR 40, Appendix A

This regulation establishes criteria relating to the siting and design of uranium tailings for permanent isolation. This involves minimizing the potential for disturbance and dispersion by natural forces of the site without ongoing maintenance.

The specific ground water protection standards set forth are defined in Criterion 5, which incorporates the basic standards imposed by the EPA in 40 CFR Part 192, Subparts D and E. The ground water monitoring to comply with these standards is required in Criterion 7.

Criterion 7 states that “At least one full year prior to any major site construction, a pre-operational monitoring program must be completed to provide baseline data on a milling site and its environs”. The operational monitoring program is required to “measure or evaluate compliance with applicable standards and regulations, to evaluate performance of control systems and procedures, to evaluate environmental impacts of operation, and to detect potential long term effects”.

The licensee is directed to establish a detection monitoring program. The main reason for this monitoring is to comply with the ground water standards set in paragraph 5B (1) by the NRC for this site. In the event that a contaminant exceeds the set standards, a corrective action program must be implemented. In that event, “the licensee shall establish and implement a corrective action monitoring program”. The monitoring program in support of the corrective action “may be based on existing monitoring programs to the extent that the existing programs can meet the stated objective of the program” (WSRC, 2000; INEEL, 2002).

NUREG-1569

The NRC has recently issued guidance on how to conduct a ground water monitoring program at an *in situ* uranium leach facility (NRC, 2003a). This includes both new facilities and those facilities applying for renewal. The intent of the document is to ensure that an excursion (i.e., an unplanned lixiviant migration) from the uranium leach zones is detected early enough to allow correction and minimize aquifer degradation. The original intent of the document was to offer guidance to the NRC staff reviewing the license application, but it offers valuable guidance to the licensee in preparing an application.

The licensee is responsible for establishing the criteria used in the number, screen length, and placement of monitoring wells, and their sampling schedule. The licensee is responsible for determining the ground water parameters that will serve as the excursion indicator constituents and their upper control limits.

The NRC staff responsible for reviewing the *in situ* leach application are directed to use American Society for Testing and Materials (ASTM) standards when applicable to ensure acceptable procedures by the applicant. In addition, the document contains numerous other specific guidelines to be used in the review process. For example, it states that at least four independent sets of baseline samples should be collected by the licensee.

Three distinct phases of monitoring are indicated, though the standard review plan section deals specifically with the operating phase.

In the pre-operational phase, ambient monitoring is used to adequately evaluate the natural spatial and temporal variations in water quality. From this, a set of water quality parameters and their upper control limits are established.

In the operational phase, detection monitoring is used to ensure the timely detection of unplanned subsurface migration (an excursion) away from the production zone, in either the horizontal or vertical direction. An excursion is defined when two or more excursion parameters in any monitor well exceed the defined upper control limits (UCLs). If an excursion is detected, corrective actions must be made and the NRC must be notified.

Remediation monitoring is conducted after the *in situ* operations if necessary. The portion of the aquifer used for active leach operations are exempted from cleanup by the EPA, however, the ground water adjacent to the leach zone must be remediated. In the remedial phase, monitoring is conducted just for the indicator constituents.

NUREG-6733

This document (Macklin et al., 2001) provides the foundation for implementing a risk-informed, performance-based (RIPB) regulatory program at *in situ* leach uranium operations. Much of this document follows the guidance set forth in the draft version of NUREG-1569, but contains specific details for corrective actions in the case of lixiviant excursions.

Along with specific actions to take in case of an excursion such as converting some injection wells to production wells to change the hydraulic gradient (which should be monitored to confirm the performance of such a corrective action), the sampling frequency for a monitor well on "excursion status" should be increased to weekly, and the number of monitored parameters may be expanded. When the excursion indicator drops below the UCL for three consecutive weekly sampling events, the excursion is considered to be corrected.

With regard to the standards for restoring the aquifer outside of the leach zone, the primary goal is to return all parameters to the average pre-extraction baseline conditions. If this goal can not be met with "reasonable" restoration efforts, a secondary goal is the maximum concentration limits (MCLs) for drinking water specified by the EPA.

In addition to local conditions (the leach field), detailed water sampling programs should be implemented to identify potential impacts on the regional ground water system. Historical results indicate though that this has not been a problem.

NUREG-1620

This recent publication (NRC, 2003b) provides guidance to NRC staff on protecting water resources when reviewing uranium tailings reclamation plans and operating license renewals/ amendments as required by Title II of the Uranium Mill Tailings Radiation Control Act of 1978 as amended. The review plan is written in a general manner to cover a variety of site conditions.

This document instructs reviewers to ensure that operations at uranium mills do not contaminate ground water and to mitigate the spread of contaminants to the public. The ultimate goal of the review process is to ensure long term compliance with 10 CFR Part 40, Appendix A.

The water resource protection review is divided into four parts:

- Site Characterization
- Ground water protection standards for the hazardous constituents
- Use of alternative hazardous chemical concentration limits
- Ground water corrective action and compliance monitoring.

In the compliance monitoring section, reviewers are instructed to "evaluate whether the ground water monitoring system is sufficient to verify the performance of the selected cleanup strategy and to monitor the long term performance of any on-site tailings disposal cells". Yet the focus here is on compliance monitoring for corrective action. In support of constructing a defensible corrective action plan, the document offers a thorough treatment of the process involved.

In contrast, there is little guidance in how to monitor for long term performance of waste units. While the techniques presented are applicable to the design and success of performance monitoring, they are not presented in this light. The reviewer would most likely need to seek other guidance documents to assess the success of such monitoring.

DOE Order 435.1

The Department of Energy (DOE) regulates many of its own radioactive waste disposal practices under Order 435.1, Radioactive Waste Management, and its associated Manual and Implementation Guide. Although the DOE regulations are not directly applicable to NRC activities, there may be useful parallels in how the two agencies conceive of monitoring.

In general terms, DOE 435.1 requires that "Radioactive waste management facilities, operations, and activities shall meet the environmental monitoring requirements of DOE 5400.1, *General Environmental Protection Program*, and DOE 5400.5, *Radiation Protection of the Public and the Environment* [DOE Manual 435.1-1 §I.1.E.(7)]. The Manual and Implementation Guide are subdivided into sections for high-level, transuranic, and low-level waste classifications, each with its own section concerning monitoring. For high-level waste, the focus of §II.T is on the operations of pretreatment, treatment, storage, and transportation facilities, rather than on disposal facilities. Implementation Guide recognizes as an issue that DOE has no extensive guidance on disposal, but follows NRC licensing requirements.

While the environmental monitoring mandated by DOE 5400.1 and DOE 5400.5 is adequate to detect after-the-fact releases of high-level waste to the environment, additional requirements are necessary to improve the detection of conditions that could provide warning of impending releases that could increase worker exposure and/or impact the environment.

An effective monitoring program is dependent on the frequency and the rigor of the monitoring operations, and the effectiveness of the systems and devices in detecting changes and abnormal conditions. Therefore, facility managers must take these factors into consideration when designing the monitoring program to ensure that the high-level waste systems are being operated according to design.

The specified parameters to be monitored are selected based on their significance for anticipating and identifying undesirable conditions and the availability of a means for monitoring them. In addition, parameters to be monitored include those to ensure the protection of public health, the environment, and workers due to releases of radioactivity in ventilation exhausts and liquid effluent streams, and from unsafe concentrations of flammable and/or explosive gases in the waste. The accuracy and precision of measurement required is dictated by the expected variations in the parameters and the level of accuracy and precision needed to identify problems. The monitoring frequency for specific parameters is likewise determined based on the possible time variation of the parameter and the response time required to take mitigating action. [DOE G 435.1-1 II.T]

Similarly, for transuranic wastes, the focus in the order is not on disposal, since that is regulated by the Environmental Protection Agency (EPA) under 40 CFR 191. Again, however, the Implementation Guide recognizes the need for monitoring:

While the environmental monitoring mandated by DOE 5400.1 and DOE 5400.5 is adequate to detect environmental releases, it was determined that due to the long storage times that occur with transuranic waste, monitoring of additional systems or parameters was needed. [DOE G 435.1-1 III.Q.(2)]

Only for low-level wastes does DOE specifically consider monitoring of disposal facilities, in §IV.R.(3), Disposal Facilities. Therein, the regulation encourages monitoring of site parameters as well as PIs (performance objectives):

a. The site-specific performance assessment and composite analysis shall be used to determine the media, locations, radionuclides, and other substances to be monitored. [This corresponds to the what and where of this strategy.]

b. The environmental monitoring program shall be designed to include measuring and evaluating releases, migration of radionuclides, disposal unit subsidence, and changes in disposal facility and disposal site parameters which may affect long-term performance.

The environmental monitoring programs shall be capable of detecting trends in performance to allow application of any necessary corrective action prior to exceeding the performance objectives.

OSWER Directive 9355.4-28

This document outlines a framework for monitoring at hazardous waste sites (EPA, 2004). A general approach is offered, as opposed to specific instructions. Its goal is to treat monitoring in a holistic manner, as opposed to merely something to satisfy a regulatory requirement.

In particular, this document is geared towards the use of monitoring in making or facilitating management decisions about the waste site. The entire monitoring program is developed in a framework called "Scientific Management Decision Points" that culminate in a decision document.

Practical Handbook of Ground Water Monitoring

This textbook (Nielsen, 1991) relates the regulatory concepts surrounding monitoring at hazardous waste sites, specifically those for RCRA (40 CFR 264.97) with the need for a holistic approach in ground water system design. It states for example, that the EPA specified minimum of one up-gradient and three down-gradient wells, will be adequate for only a very small number of sites.

It stresses the need to understand the geologic controls on ground water movement, as the degree of complexity will govern the amount of effort required to characterize the site and develop a conceptual model to guide the monitoring design. Examples of monitoring well designs in both simple and complex geologic settings are presented.

EPA/625/R-93/003a

The document (EPA, 1993) entitled *Subsurface Characterization and Monitoring Techniques* is a comprehensive list of techniques and devices available for use in a ground water and/or vadose zone monitoring program. It does not offer guidance on the design and implementation of a monitoring program, just on the accepted techniques and devices.

Optimal Ground Water Monitoring

The focus of this document (Radian, 2000) is on determining ways to design and optimize ground water monitoring programs to maximize their cost-effectiveness without compromising quality. Some of the strategies used to ensure cost effectiveness include reducing the number of monitoring points, reducing monitoring duration and frequency, and simplifying analytical protocols. Ideally, the application of these strategies is continually revisited as the monitoring program progresses.

Ground Water Monitoring: Draft Technical Guidance

This EPA, 1992b manual provides guidance to permitted hazardous waste disposal facilities in conducting RCRA ground water monitoring programs to meet the requirements of 40 CFR Parts 264 and 270. The three distinct phases of ground water monitoring are defined: detection, compliance, and corrective action monitoring. The manual describes procedures that the EPA believes are the most appropriate for designing, installing, and operating monitoring systems.

The approach favored is one that relies heavily on the development and refinement of conceptual models. Strongly emphasized is the idea that the process of developing a conceptual model is ongoing, and that it should be revisited and refined by data gained from ground water sampling over a period of time.

Appendix B: Types of Monitoring

Ambient Monitoring

Ambient monitoring typically is a short term activity conducted to determine background conditions in the ground water. The goal is to establish both natural variations and any man-made impacts to the system. The results of this monitoring will form a basis against which future monitoring results will be compared. The purpose is to establish background values for specific chemicals of concern (COCs), develop ground water trend analyses, or determine compliance.

Detection Monitoring

Detection monitoring is used at sites not believed to be releasing hazardous wastes or constituents into the ground water. This typically involves semi-annual monitoring of ground water parameters or constituents that would indicate the presence of hazardous substances. If monitoring indicates a release, analysis of all COCs is generally required, and the site or facility enters the compliance phase.

Compliance Monitoring

Compliance monitoring typically is conducted at established intervals for those constituents detected in the detection monitoring phase. In addition, this phase monitors for all COCs that are associated with the site or facility, whether or not they have been detected. Compliance monitoring can also be used to determine Performance Indicators.

Assessment Monitoring

If compliance monitoring identifies an unauthorized release into ground water, assessment monitoring is initiated to establish the nature and extent and to determine the origin of the release. Assessment monitoring can lead to a determination that sampling and/or analytical anomalies exist.

Performance Confirmation Monitoring

Performance Confirmation Monitoring (PCM) is intended to verify that the data going into and the predictions coming out of the PA are sufficiently accurate and that a facility is behaving within expected limits. The objective of monitoring in the context of this Strategy is to understand the functioning of a hydrogeologic system. It is important to note that the driver for selecting what, when, where, and how to monitor is to understand system performance rather than system compliance.

Remediation Monitoring

Ground water remediation monitoring is initiated when an unauthorized release has been detected and characterized through assessment monitoring. Remediation monitoring is usually implemented as part of a clean-up effort to determine how effective the clean-up activities are and if this effort has attained the remediation goals.

Post-Closure Monitoring

Post-closure monitoring is required for permitted facilities. Post closure monitoring is conducted to detect any changes in the ground water after the cessation of an activity. Analytes to monitor for include those that were monitored during compliance and/or remediation monitoring. Post closure monitoring also is performed to determine when remediation is complete

Appendix C: Identification of the Conceptual Site Models with Maximum Likelihood Bayesian Model Averaging Method

Maximum Likelihood Bayesian Model Averaging (MLBMA) method includes a comprehensive strategy combining the statistic analysis and numerical modeling technique to identify and select the best CSM from a group of alternate CSMs. We will introduce this method starting from Bayesian model averaging.

Bayesian Model Averaging

Hoeting et al. (1999) and Neuman (2003) presented Bayesian model averaging (BMA) by noting that if Δ is a quantity one wants to predict, then its posterior distribution given a discrete set of hydrologic and geochemical measurement data $\mathbf{D}$ is

$$p(\Delta|\mathbf{D}) = \sum_{k=1}^{N} p(\Delta|M_k, \mathbf{D})\, p(M_k|\mathbf{D}) \tag{C1}$$

where $\mathbf{M} = (M_1, \ldots, M_N)$ is the set of all models or possible geochemical processes considered, at least one of which must be valid. $p(\Delta|\mathbf{D})$ is the average of the posterior distributions $p(\Delta|M_k, \mathbf{D})$ under each model, weighted by their posterior model probabilities $p(M_k|\mathbf{D})$. The posterior probability for model M_k is given by Bayes' rule,

$$p(M_k|\mathbf{D}) = \frac{p(\mathbf{D}|M_k)\, p(M_k)}{\sum_{i=1}^{N} p(\mathbf{D}|M_i)\, p(M_i)} \quad (k = 1, 2, \ldots, N) \tag{C2}$$

where:

$$p(\mathbf{D}|M_k) = \int p(\mathbf{D}|\theta_k, \quad {}_k)\, p(\theta_k|M_k)\, \mathrm{d}\,\theta_k \tag{C3}$$

is the integrated likelihood of model M_k, θ_k is the vector of parameters associated with model M_k, $p(\theta_k|M_k)$ is the prior density of θ_k under model M_k, $p(\mathbf{D}|\theta_k, M_k)$ is the joint likelihood of model M_k and its parameters θ_k, and p (M_k) is the prior probability that M_k is the correct model or geochemical process.

The components of parameter vector θ_k include: (1) flow parameters; (2) transport parameters: molecular diffusion coefficient, longitudinal and transverse dispersivities, distribution coefficient, K_d, and total and accessible porosity (the latter may differ from total porosity when anion exclusion takes place); (3) geochemical parameters; and (4) kinetic reaction parameters such as rate constants.

Maximum Likelihood Bayesian Model Averaging

To make BMA computationally feasible, we will adopt the suggestions by Taplin (1993), Hoeting et al. (1999) and Neuman (2003) to approximate $p(\Delta|M_k, \mathbf{D})$ by $p(\Delta|M_k, \hat{\theta}_k, \mathbf{D})$, where $\hat{\theta}_k$ is the maximum likelihood estimate of θ_k based on the likelihood $p(\mathbf{D}|\theta_k, M_k)$.

Maximum likelihood estimation provides an approximate covariance matrix for the estimation errors of $\hat{\theta}_k$. So, we can determine $p(\Delta|M_k, \hat{\theta}_k, \mathbf{D})$ by Monte Carlo simulation of Δ through random perturbation of the parameters. According to suggestions of Kashyap (1982), we propose to select one among several competing models which minimizes the Kashyap Information Criterion (KIC)

$$\hat{d}_k = -\ln p(\mathbf{D}|\hat{\theta}_k, M_k) - \ln p(\hat{\theta}_k|M_k) - \frac{N_{Pk}}{2}\ln(\frac{2\pi}{N_D}) + \frac{1}{2}\ln\left|F_k(\mathbf{D}|\hat{\theta}_k, M_k)\right| \qquad \text{(C4)}$$

where, N_{Pk} is the dimension of parameter vector $\hat{\theta}_k$ associated with model M_k, N_D is the dimension of hydrologic and geochemical data D, and F_k is the normalized Fisher information matrix. Equation (C4) makes a connection between the model identification and parameter estimation. Solving it can provide information for us to make a decision on selecting a more parsimonious model with fewer parameters or selecting a more complex model with more parameters under the condition that the simulated values match well to the measurements.

Numerical Solutions

The general numerical methods to evaluate $\hat{\theta}_k$ by calibrating a deterministic model M_k against hydrologic and geochemical data **D** is described by Cooley (1983), Carrera and Neuman (1986), Wagner and Gorelick (1987), Wagner (1992), Sun (1994), Hill (1998), and Dai and Samper (2004). The approach yields a negative log likelihood criterion that includes two weighted square residual terms: a generalized sum of squared differences between simulated and observed state variables, and a generalized sum of squared differences between posterior and prior parameter estimates. Within the first term, Dai and Samper (2004) derived a two-level weighting system to balance the different type of measurements (such as hydraulic heads or pressures, total dissolved concentrations, total concentrations including liquid and solid phases, cumulative water inflows and water contents) and the concentrations of different chemical components. Such a weighting system will be incorporated into the objective function for handling the different type of measurements.

The second term in the likelihood criterion deals with prior information. Without prior information, most complex inverse problems are ill posed. Such information can be derived from available data and incorporated into the objective function. It can be also used also to provide a range of permissible values that a parameter can take within its lower and upper bounds during the optimization process. Moreover, incorporating prior information into the objective function is mathematically equivalent to taking extra measurements, may alter the numerical predominance of parameters over the measurements and thus provide the system with the ability to supply a unique set of parameter estimates. In some cases, a set of highly correlated parameters can be varied simultaneously with no significant effect in the objective function (Dai and Samper, 2004; Dai et al. 2004a, b). This can lead to nonunique parameter estimates. Sometimes nonuniqueness can even lead to numerical instability and failure of the estimation process. However, if prior information is available for at least one of the parameters, it should be included in the objective function to overcome nonuniqueness and provide stability.

The processes for identifying CSMs by maximum likelihood Bayesian model averaging (MLBMA) are plotted in the flow chart (Figure C1)

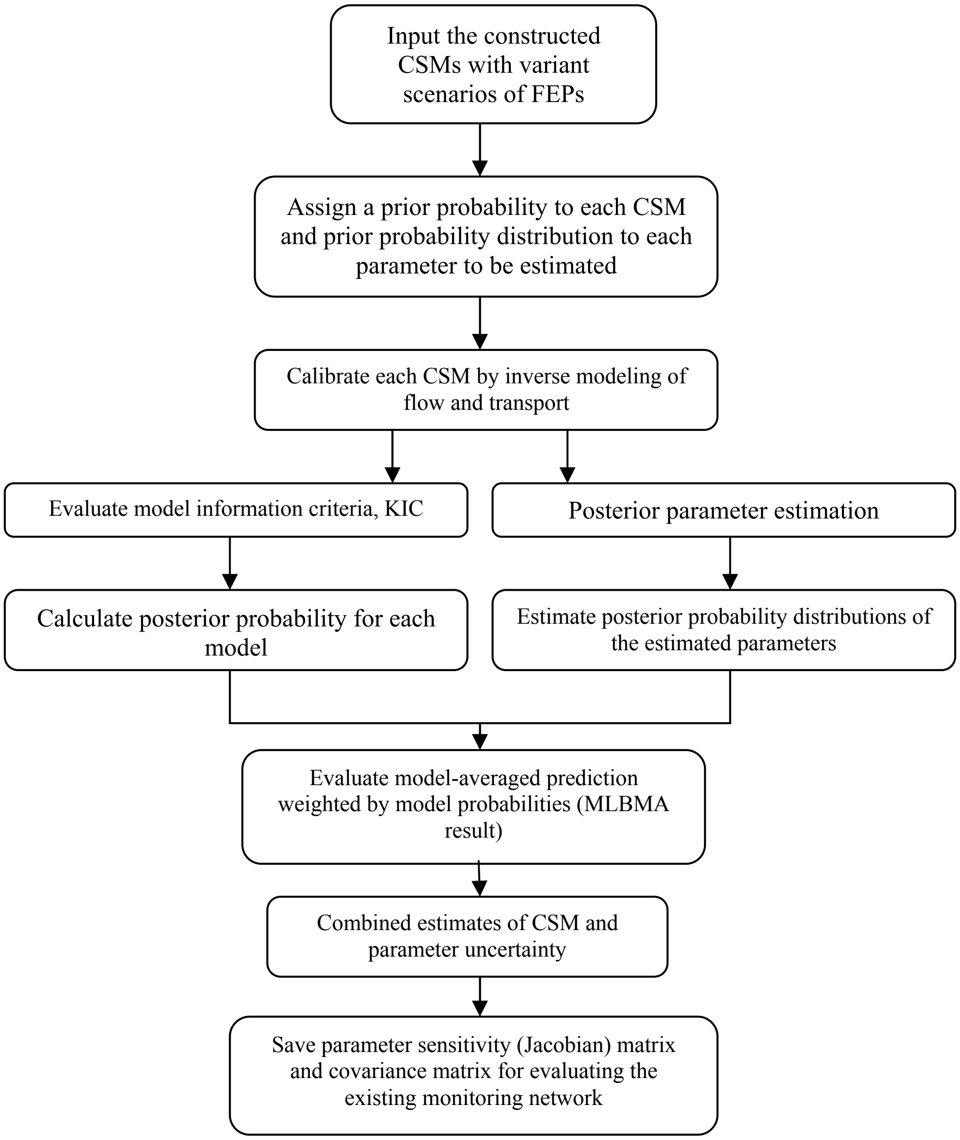


Figure C1. Identifying conceptual site model by maximum likelihood Bayesian model averaging (modified from Meyer et al., 2004).

Appendix D: Determination of Data Quality Objectives

Step 1. Problem Definition

Step one in DQO development involves developing a concise statement of the problem and a conceptual model. Other activities identified under step one are to identify team members and available resources.

Step 2. Identify the Decision

Identification of the decision involves three facets, identification of the principal study question, identifying alternative actions, and formulation of a decision statement. The principal study question in the context of Performance Assessment would depend on the exact nature of the PI or model assumption to be tested. However, a representative study question for a typical PI might be: "Does the concentration of a particular constituent in ground water indicate that the system under study is outside its performance envelope?" Or if the PA model is being evaluated: "Is the CSM consistent with information obtained from an adjacent site?"

Alternate actions specify what actions are to be taken given the answer to the principal study question. For example an action might be to refine the CSM, to gather additional data on the site, to reevaluate uncertainties to lower values, or to do nothing.

The last part of step 2 is to combine the principal study question and the alternate actions to form a concise decision statement employing an If …, Then format. For example, "If the CSM is consistent with new information, then reevaluate and lower associated uncertainties", or "If not consistent with new information then refine conceptual model with new information.

Step 3. Identify Inputs to Decision

Step three involves the implementation of the decision statement formulated in step two. This requires the identification of the kinds and sources of information that will be used to evaluate the decision statement. For most PIs this would be fairly straight forward and involve measurement of the concentration level of a constituent in ground water at some location, etc. However, this may be a more complicated question when it comes to evaluating the assumptions made in the PA model and would possibly involve a sensitivity analysis in order to determine which parameters associated with the model were important to the question.

It is also necessary to determine the basis for setting the action level associated with the "If.." part of the decision statement. Most often for a PI, the action level would be specified by a regulatory limit or exceedance of background conditions. However, in the example given above concerning the assessment of the PA conceptual model related to new information the action level may be based on the significance of the new information to the elements of the conceptual model related to the most risk.

Once the practical aspects of the implementation of the decision statement have been determined it must be ascertained if sampling and analysis methods exist or can be developed with sufficient resolution and precision to meet the requirements of the specified action level.

Step 4. Define Boundaries of the Study

Step 4 is concerned with the sampling details such as the sizes of samples necessary and the boundaries of the area to be sampled. Of particular importance in the application of performance confirmation monitoring is the duration of the sampling program. This step also involves such considerations as to practical constraints that may interfere with the sampling program. These issues become important when the specific design for sampling data is developed.

Step 5. Develop Decision Rule

In step 5 the team develops a theoretical decision rule in the form of an unambiguous "If…, Then…" statement. This rule is theoretical in the sense that it assumes no uncertainty in any of the information involved as input to the decision statement. In this statement the decision based parameter (i.e. sample mean, etc) is specified and the particular action level quantified. Detailed sample analysis methods are also specified and it is verified that the action level magnitude chosen for the decision statement is above the detection limit and resolution for the sampling methods chosen. The actual statement is formulated by combining the value of the decision parameter assuming no uncertainty with the alternative actions.

Step 6. Identify Limits on Decision Errors

Evaluation of the decision statement requires that the magnitude of some data parameter be compared to the specified action level. The measurement and modeling of all real data has associated uncertainties and these uncertainties must be dealt with in evaluation of the decision statement. These uncertainties mean that errors will be made in the decision as to exceedance of the action level. Step 6 determines a methodology for managing these decision errors. The essence of this methodology is to define a baseline CSM that is assumed to be true unless the data indicate otherwise. The critical issue to this process is to decide what probability levels are significant for abandoning the baseline condition. The significant probability level is decided based on risk as evaluated by the team.

Step 7. Optimize Design for Obtaining Data

In step 7 the details of the data acquisition system design are specified taking into account all of the issues identified in the preceding steps. The issues in step 7 are basically those involved in designing the monitoring network.

Appendix E: Radionuclides and Radiochemistry Analysis Methods[1]

The purpose of this appendix is to provide a generalized list of radionuclides that might be expected at NRC-licensed sites as fuel cycle-related contaminants. Any ground-water monitoring program at a nuclear site should test for the listed (Table 1) materials at least once per year.

Radionuclides[2]

Radionuclides, broadly, are produced in four ways. They may be natural, they may result from radioactive decay, they may be the products of nuclear fission, or they may result from activation, a process of capturing an energetic particle by a nucleus.

Naturally-occurring radioactive material, or NORM, includes uranium, thorium, and their decay series daughters. Other NORM includes potassium-40 and rare substances such as samarium-147, but these are not fuel cycle-related.

Decay

Radioactive decay occurs when atomic nuclei spontaneously disintegrate and emit particles such as electrons (beta radiation), 2-proton-2-neutron particles (alpha radiation), or neutrons, accompanied by electromagnetic energy (gamma radiation). The time for half of a material to decay is called its half-life. The shorter the half-life the more radioactive a substance is, or the more disintegration occurs per unit time.

In alpha decay, an alpha particle consisting of two neutrons and two protons leaves the nucleus. An alpha particle is the same as a helium nucleus or a helium atom without its electrons. Note that the atomic number decreases by two and the mass decreases by four. For example when U-238 decays, Th-234 is produced and one alpha particle is emitted.

In beta decay, a neutron splits into an electron and a proton, and the electron is emitted as a beta particle. Because an electron has almost no mass, the atomic number is not changed, but the number of nuclear protons increases by one. For example tritium has two neutrons and one proton, for a nuclear mass of 3 – the single proton being a characteristic of hydrogen. When tritium decays by emitting a beta particle, it is left with one neutron and two protons --- it is now helium with a mass of 3. (Most helium has a mass of 4, with two protons and two neutrons.) Note that the atomic number goes up by one, but the mass does not change.

In addition to alpha and beta particles, gamma photons resembling high-energy x-rays, may be produced. Alpha and beta particles are easily stopped by shielding, but gamma rays can travel readily through construction materials and special shielding (e.g., leaded glass, lead and steel containers) must be provided to protect personnel.

---

[1] Table 2, below, is adapted from www.gel.com. The reference is not intended as an endorsement of General Engineering Laboratories, LLC. There are a number of qualified (e.g. NELAP-certified) laboratories for mixed waste.

[2] A more thorough discussion of radionuclides in the environment, including definitions and discussion of terms may be found at : http://www.epa.gov/narel/radnet/glossary.html

Some nuclear decay involves emission of neutrons (neutron decay). Neutrons, because they have no charge, may also penetrate materials and require shielding.

The products of decay are called daughter products. Some daughters in the U-238 decay chain include Ra-226 and Rn-222, Bi-214, and finally Pb-206. Gamma rays emitted by Bi-214 provide an analytical method for U-238. These gamma rays can be detected and quantified with portable equipment.

Thorium-232 also decays through isotopes of radium and radon. These isotopes have much shorter half-lives than the corresponding U-series isotopes. In this series, Tl-208 provides a diagnostic gamma ray, and the final stable isotope is Pb-208.

Fission

The energy produced in nuclear reactors comes from the fission of the fuel, commonly U-235. In fission a nucleus splits when hit by a neutron. The split produces nuclei of lighter elements such as cesium and strontium. A small fraction of the total mass disappears and converts to energy.

U-235 spontaneously splits and emits a neutron occasionally. When the concentration of spontaneously fissioning atoms is high enough, the neutrons emitted by spontaneous fissions can hit other atoms and induce splitting. This is known as a chain reaction. The chain reaction can be controlled by limiting the ability of neutrons from one atom of U-235 to reach other atoms. This is done in solution by dilution and controlled geometry (e.g., slab-shaped tanks). In a reactor, control rods are inserted and withdrawn to control the rate of fission and hence the power production. In an emergency, materials such as cadmium nitrate can be added to the primary cooling water. Cadmium strongly absorbs neutrons and poisons the chain reaction.

Activation

In reactor environments, neutrons can be absorbed by ordinarily stable isotopes to produce radioactive isotopes. Common materials like sodium, titanium, and iron can become radioactive if exposed to a high neutron flux. The most commonly mentioned activation product is Co-60 which is produced when Co-59 absorbs a neutron.

Plutonium is produced after U-238 captures a neutron.

Radionuclides at waste sites

The EPA maintains a list of waste sites called the National Priority List, or NPL under the Superfund program. These are waste sites that have been abandoned. Not all contain radioactive material, but the following table lists radionuclides that have been identified, and the number of sites where they have been found. Fission and activation products typical of a reactor site are present in this table.

Table 1 Distribution of Radionuclides Present at NPL Sites (EPA, 1996)

Radionuclide	Half-life	Prevalence	Radionuclide	Half-life	Prevalence	Radionuclide	Half-life	Prevalence
Actinium-227	21.773 yr	2 sites	Iodine-129	15.7 million yr	3 sites	Ruthenium-106	373.59 d	2 sites
Americium-241	432 yr	4 sites	Iodine-131	8 d	1 site	Selenium-79	650,000 yr	1 site
Antimony-125	2.758 yr	1 site	Krypton-85	10.72 yr	1 site	Strontium-90	29.1 yr	11 sites
Carbon-14	5700 yr	2 sites	Manganese-54	312.7 d	1 site	Technetium-99	212,000 yr	7 sites
Cobalt-60	5.27 yr	7 sites	Nickel-63	100.1 yr	1 site	Thorium-228	1.9 yr	3 sites
Cerium-144	284.893 d	1 site	Plutonium-238	87.8 yr	10 sites	Thorium-230	80,000 yr	14 sites
Cesium-134	2.1 yr	2 sites	Plutonium-239	24,000 yr	10 sites	Thorium-232	1.41×10^{10} yr	14 sites
Cesium-135	3 million yr	1 site	Plutonium-240	6560 yr	5 sites	Tritium	12.3 yr	11 sites
Cesium-137	30 yr	10 sites	Protactinium-231	32,500 yr	1 site	Uranium-234	247,000 yr	32 sites
Curium-244	18 yr	1 site	Radium-226	1602 yr	29 sites	Uranium-235	0.71 billion yr	10 sites
Europium-152	13.516 yr	1 site	Radium-228	5.76 yr	9 sites	Uranium-238	4.51 billion yr	30 sites
Europium-154	8.593 yr	1 site	Radon-220	55.6 s	5 sites			
Europium-155	5.0 yr	1 site	Radon-222	3.825 d	23 sites			

RADIOCHEMISTRY ANALYSES

Several commercial analytical laboratories have facilities for analysis of samples for radionuclides. The following Table 2 was adapted from the web site of one such lab.

** w - water*
s/s/v/af /m - soils/sludges/vegetation/air filters/milk

Table 2. Analytical Methods

ANALYSIS	METHOD	MATRIX *see key
Americium 241	DOE EML HASL 300 4.5.4 modified	s/s/v/af/m
	RAD-A011 by Alpha Spectroscopy	w
Americium 243	RAD-A011 by Alpha Spectroscopy	w
	DOE EML HASL 300 4.5.4 modified	s/s/v/af/m
Carbon 14	RAD-A003 by Liquid Scintillation Counting	
	EPA EERF C-01	w
	EPA EERF C	s/s/v/af/m
Chlorine 36	RAD-A033	w s/s/v/af/m
Curium 242, 243/244, 245/246	RAD-A011 by Alpha Spectroscopy	w
	DOE EML HASL 300 4.5.4 modified	s/s/v/af/m
Gamma Spectrometry	Many isotopes detectable – DOE HASL-300 manual currently available at http://www.eml.st.dhs.gov/publications/procman/	
	RAD-A013 by Gamma Spectrometry	w
	EPA 901.1	af
	DOE EML HASL 300 4.5.2.3	s/s/v/m
Gross Alpha	RAD-A001 by Gas Flow Proportional Counting	w
	EPA 900.0/9310	s/s/v/af/m
	RAD-A001c by Coprecipitation	w
	EPA EERF 00-02-1	af
Gross Alpha and Nonvolatile Beta	RAD-A001 by Gas Flow Proportional Counting	w
	EPA 900.0/9310 swipe direct count	s/s/v/af/m
Iodine 129	RAD-A006 by X-ray Spectroscopy	w
	LANL EM-9	s/s/v/af/m
Iodine 131	RAD-A013 by Gamma Spectroscopy	w
	EPA 901.1	s/s/v/af/m
Iron 55	RAD-A040 by Liquid Scintillation Counting	w
	DOE EML HASL-300 (Fe-01-RC) modified	s/s/v/af/m
Lead 210	RAD-A018 by Gas Flow Proportional Counting	w
	DOE EML HASL 300 (Pb-01-RC) modified	af
	RAD-A013 by Gamma Spectroscopy	s/s/v/m
	DOE EML HASL 300	
Neptunium 237	RAD-A032 by Alpha Spectroscopy	w
	DOE EML HASL 300 modified	s/s/v/af/m
Nickel 59	RAD-A022 by X-ray Spectroscopy	w
	DOE RESL Ni-1	s/s/v/af/m
Nickel 63	RAD-A022 by Liquid Scintillation Counting	w
	DOE RESL Ni-1	s/s/v/af/m
Nonvolatile Beta	RAD-A001 by Gas Flow Proportional Counting	w
	EPA 900.0/9310	s/s/v/af/m
Plutonium 238, 239/240	RAD-A011 by Alpha Spectroscopy	w
	DOE EML HASL 300 4.5.4	s/s/v/af/m
Plutonium 241	RAD-A035 by Liquid Scintillation Counting	w
	DOE EML HASL 300 4.5.4	s/s/v/af/m
Plutonium 242	RAD-A011 by Alpha Spectroscopy	w
	DOE EML HASL 300 4.5.4	s/s/v/af/m

Polonium 208, 210	RAD-A016 by Alpha Spectroscopy	w
Polonium 209	RAD-A016 by Alpha Spectroscopy	w
	DOE EML HASL 300 4.5.4	s/s/v/af/m
Promethium 147	RAD-A020 by Liquid Scintillation Counting	w
	EPA EERF PM-01-1 (modified)	s/s/v/af/m
Radium 223	RAD-A024 by Gamma Spectroscopy	s/s/v/m
	DOE EML HASL 300 4.5.2.3	
Radium 226	RAD-A008 by Radon Emanation	w
	EPA 903.1 modified	af
	RAD-A013 by Bismuth Ingrowth and Gamma Spectroscopy	
	DOE EML HASL 300 4.5.2.3	s/s/v/af/m
Radium 228	RAD-A009 by Gas Flow Proportional Counting	w
	EPA 904.0 modified/9320	af
	RAD-A013 by Actinium Ingrowth and Gamma Spectroscopy	
	DOE EML HASL 300	s/s/v/af/m
Radon 222	RAD-A007 by Liquid Scintillation Counting	w
	SM 7500-Rn B (modified)	
Selenium 79	RAD-A031 by Liquid Scintillation Counting	w
	NERC ORD	s/s/v/af/m
Strontium 89	RAD-A004 by Gas Flow Proportional Counting	w
	EPA 905.0 modified	s/s/v/af/m
Strontium 90	RAD-A004 by Gas Flow Proportional Counting	w
	EPA 905.0 modified	s/s/v/af/m
Strontium 89 & 90 (Total Radiometric Strontium)	RAD-A004 by Gas Flow Proportional Counting	w
	EPA 905.0 modified	s/s/v/af/m
Technetium 99	RAD-A005 by Liquid Scintillation Counting	w
	DOE EML HASL 300 (TC-01-RC)	s/s/v/af/m
Tellurium 125m	RAD-A031 by X-ray Spectroscopy	w
	NERC ORD	s/s/v/af/m
Thorium 228, 230, 232	RAD-A012 by Alpha Spectroscopy	w
	DOE EML HASL 300 4.5.4 modified	s/s/v/af/m
Thorium 229	RAD-A012 by Alpha Spectroscopy	w
	DOE EML HASL 300 4.5.4 modified	s/s/v/af/m
Thorium 234	RAD-A013 by Gamma Spectroscopy	w
	EPA 901.1	s/s/v/af/m
Total Activity	RAD-A041 by Liquid Scintillation Counting	w/s/s/v/af/m
Total Alpha Radium	RAD-A010 by Gas Flow Proportional Counting	w
	EPA 900.1, EPA 903.0, 9315	af/s/s/v/m
Total Uranium	RAD-A023 by Laser Kinetic Phosphorimetry	w
	ASTM D5174	s/s/v/af/m
Tritium (H-3)	RAD-A002 by Liquid Scintillation Counting	w
	EPA 906.0	s/s/v/af/m
Uranium 232	RAD-A011 by Alpha Spectroscopy	w
	DOE EML HASL 300 4.5.4 modified	s/s/v/af/m
Uranium 233/234, 235/236, 238	RAD-A011 by Alpha Spectroscopy	w
	DOE EML HASL 300 4.5.4 modified	s/s/v/af/m

Appendix F: Introduction to Systems Engineering Basics

The terms “systems engineering” and “systems analysis” are applied in many fields and with many meanings. Fundamentally, however, the concepts refer to a structured approach to design or analysis of some system.

Broadly, a system is any portion of the universe isolated for study. A system may include sub-systems and components, each of which has a function in the overall system.

The structured approach can begin with establishing requirements of a system to be designed and constructed. The approach can also begin in reverse by dividing a complex system into subsystems and components. An engineered system will have a function that it is required to perform. There may be some latitude in the system requirements, for example a home heating system might be required to operate within a 5-degree range, whereas an eye surgeon’s laser might be required to operate with almost zero tolerance. These are performance requirements. A waste site might be required to retain 90% of its soluble contaminants for 100 years. It could be designed for zero leakage and perform at a very small actual leakage that still meets the performance requirement.

A system to be designed might be an airplane. Generally a customer specifies the overall performance requirements of the system. These could include speed, range, cargo and or passenger load, weaponry, and so forth. They could also include factors in the external environment such as altitude and weather, water landing and take off, short runways, etc.

Then a design team would determine what subsystems would be needed to meet these requirements, and in more detail, what were the components of the subsystems and materials of the components. From this design, models would be built, including physical and computer models. Simulations in test chambers or mathematical abstractions would test the models. Prototypes would be built and tested to determine whether the customer’s requirements were met.

For each component there would be some performance requirement, a contribution to meeting the overall performance requirement.

An analysis of the system would determine what components were capable of seriously degrading the overall system performance. For example, an engine oiling subsystem might contain a critical pump.

Here is where performance monitoring comes in. Critical components should be monitored to determine whether they are meeting the specified operating requirements. Oil pressure could be measured to ensure that the oiling subsystem was performing as needed.

Once in the customer’s hands, the operator – in our example, the pilot – would need to be aware of fuel reserves, cabin pressure, engine temperature, oil pressure, hydraulic pressures, etc. Automatic alarms could be designed to alert the operator to a decline in system performance below some safety factor.

The systems approach is applied in many disciplines, and is in fact implicit in any attempt to study natural systems. A textbook on forest ecology may not mention systems analysis, but understanding of the interactions between bugs, bunnies, grass, trees, rain, streams and so forth is an exercise in systems analysis. Once these interactions are understood, first qualitatively, then through measurements, they can be simulated with computer models. Once simulated, the consequences of some perturbation, such as deforestation, or introducing a predator, can be estimated and any attendant risk quantified. In this way, risk-informed decisions can be made about some course of action.

But – let's throw in a very large word of caution. Even in an engineered system it is hard to predict how well all the components and subsystems will function together. Problems appear in testing, and some components are redesigned before production is begun. In complex natural systems it is sheer folly for us to think we understand all the components and subsystems in a quantitative way.

We can test each component. For example, 100 motors could be run continuously until they fail. The first failure, last failure, and the mean time of failure can be recorded. This information can be used to establish the probability that a motor will fail after some number of hours. The same can be done with bearings, tires, brakes, and so forth. Sometimes the occurrence rate for some event can only be guessed using expert opinions. The failure probability of all components or subsystems can be combined into a failure prediction model for the final system. This approach is that of a probabilistic risk assessment, or PRA.

Some natural processes operate too slowly or infrequently for us to take much note of them. We know to design components for earthquakes – at least on a probabilistic basis. The thought process of systems analysis must be applied in designing or evaluating a monitoring program.

For further reading see:

Blanchard, B.S., and Fabryky, W.J. *Systems Engineering and Analysis, Third Edition.* Prentice Hall International Series in Industrial and System Engineering. 1998.

Appendix G: Management by Objectives

Management by Objectives (MBO) is an enterprise planning paradigm that can be thought of as having several stages of increasing detail. The first stage is to articulate the purpose of the enterprise. The second stage is to articulate high-level goals for the enterprise. The next level of detail is to develop an understanding of the steps that must be undertaken to reach each goal.

The concept can be applied at any level within an organization – or even at home to plan a vacation. Most of us think in these terms whether we list goals and objectives on paper or not.

Purpose

The purpose can also be called the mission. A lot of lip service has been paid to mission, vision, and principles – we will focus only on mission.

The others generally fail in execution and become statements endorsing motherhood, patriotism, and regular church attendance – worthwhile, but not contributing to critical thinking about the enterprise. That may be because they are passed down from the top, and have no meaning at the level at which work is accomplished. They should be distilled from the objectives. The purpose is analogous to the needs definition that drives the systems engineering process.

Goals

Here we begin to focus on elements of the enterprise that fit together to make the whole. For example – if our purpose is to make automobiles, then a goal would be to make good ones, another goal might be to sell many. We might divide our enterprise into divisions based on the goals, and the goals of the enterprise might become the purpose of these subdivisions. In the systems engineering paradigm, we are defining subsystems.

Objectives

These are definable milestones on the road to reaching a goal and are developed for each goal. These must be understood in any organization at the operational level. In systems engineering, we are reaching the component level.

Objectives may be best defined by brainstorming involving all levels of the enterprise. In a restaurant, the cook, the wait staff, the cashier, and the dishwasher should be involved in developing and ranking a list of objectives.

A manager might have a goal of building a culture where all personnel embrace the goals of the enterprise. Getting personnel involved in setting goals and defining objectives for the enterprise should be an objective for the manager's path to institutional unity.

In systems engineering we are at the component level, but the analogy is not complete. Objectives are milestones along a path to reaching goals.

Pathways

There may be many roads to reach a goal. Each will have milestones, and some may branch or cross. Choosing the optimal pathway becomes an exercise in game theory. At each crossroads, there may be opportunity costs. This is best understood by reading Frost's poem that begins "Two roads diverged in a yellow wood…"

The classic book on enterprise strategy is Williams, 1954. The book introduces concepts of win-win strategies to optimize the outcome of decisions that must be made in any enterprise.

Strengths, Weaknesses, Opportunities and Threats

Once objectives are defined one must determine whether one has the resources to reach them. Resources is used here as a broad term to include the overall business environment. The Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis should be conducted in a brainstorming setting by all with a stake in or knowledge of reaching the objective.

Ultimately a manager will decide how or whether or when to proceed on a given pathway. The SWOT analysis should provide a thorough checklist of issues that must be analyzed to reach a decision.

Strengths may lie in personnel, budgets, previous experience, strategic location, available equipment, subcontractors, or other factors developed in a stakeholder meeting, traditions that give one a competitive edge should also be included. Weaknesses are generally in the same categories as strengths. Opportunities, in addition to those strictly related to the targeted objective, could include secondary targets, new markets or collateral benefits.

Threats include opportunity costs, competition, enemy gun emplacements, foreign labor rates*, injury from dangerous equipment or processes, risks deriving from failure to achieve the target. Risks could include fines from regulators. SWOT analysis may identify critical issues that must be addressed before an objective can be achieved. (* In the 1980s, market analyses for the future of copper prices included such things as projected demands and current inventories – but did not predict that Peruvian workers would go to the mines to produce copper at any price rather than face unemployment.)

Summary

The MBO concepts can be applied at any level of an activity. For ground-water monitoring, the purpose is to provide assurance that a facility is operating in a safe manner with respect to any public or environmental risk through ground-water pathways.

Goals would include: to understand the risk sources, the ground-water pathways, controls on flow and transport; and to develop integrated conceptual and computer models of the system. Predictions from the models would help set other goals and objectives.

Objectives would be methods to develop and feed the predictive model with characterization and monitoring data. The data would allow refinement of the models and thus contribute to understanding and assurance.

A SWOT analysis or something analogous should be undertaken and reviewed regularly.

Reference

Williams, J.D., 1954, The Compleat Strategyst, McGraw-Hill, New York, 234p.

NRC FORM 335
(9-2004)
NRCMD 3.7

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER
(Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)

NUREG/CR-6948, Vol 1

2. TITLE AND SUBTITLE

Integrated Ground-Water Monitoring Strategy for NRC-Licensed Facilities and Sites: Logic, Strategic Approach and Discussion

3. DATE REPORT PUBLISHED

MONTH	YEAR
November	2007

4. FIN OR GRANT NUMBER

Y6020

5. AUTHOR(S)

Van Price, Tom Temples, John Tauxe, Rex Hodges and Ronald Falta

6. TYPE OF REPORT

Technical

7. PERIOD COVERED *(Inclusive Dates)*

February 2003 - September 2007

8. PERFORMING ORGANIZATION - NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*

Advanced Enivironmental Solutions, LLC
407 West Main Street
Lexington, SC 29072

9. SPONSORING ORGANIZATION - NAME AND ADDRESS *(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*

Division of Fuel, Engineering and Radiological Research
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES

T.J. Nicholson, NRC Project Manager

11. ABSTRACT *(200 words or less)*

This document presents a logical framework for assessing what, how, where and when to monitor underground water in order to ensure that a licensed nuclear site or facility is behaving within the expected limits as described by the performance assessment. The Strategy is implemented as an iterative process beginning with analysis of any existing site and facility characterization and monitoring data, any existing conceptual site model (CSM), in this case generally a hydrogeologic model, and any existing risk assessment or PA model. The iterative nature of the Strategy results in a graded approach to development or evaluation of a monitoring program. Through analysis, an initial assessment of what, how, when, and where to monitor to evaluate system performance is made. Performance Indicators include chemicals, hydrogeologic attributes, and other features, events, or processes (FEPs) that may significantly influence contaminant flow and transport. These PIs may be directly measurable in a monitoring program or may be derived from compilations and interpretations of data. The integrated strategy benefits are:

- Characterization allows development of CSM;
- CSM allows modeling / simulation;
- Modeling allows prediction;
- Monitoring allows refinement; and
- Refinement allows confidence.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

conceptual site model
geophysics
ground water
hydrogeology
monitoring
Performance Assessment
Performance Indicator
risk
tritium
visualization

13. AVAILABILITY STATEMENT

unlimited

14. SECURITY CLASSIFICATION

(This Page)

unclassified

(This Report)

unclassified

15. NUMBER OF PAGES

16. PRICE