ROADMAP TO LONG-TERM MONITORING OPTIMIZATION

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1.0 INTRODUCTION

1.1. BENEFITS OF OPTIMIZATION OF LONG-TERM MONITORING PROGRAMS

Costs for groundwater monitoring during remediation represent a significant, persistent, and growing burden for the private entities and government agencies responsible for environmental remediation projects, especially as remedies are determined and implemented.

The U.S. Environmental Protection Agency (U.S. EPA) (2004a) defines monitoring as

> "… The collection and analysis of data (chemical, physical, and/or biological) over a sufficient period of time and frequency to determine the status and/or trend in one or more environmental parameters or characteristics…directly related to the management objectives for the site in question."

Long-term monitoring (LTM) is defined here as monitoring conducted after some active, passive, or containment remedy has been selected and put in place, and is used to evaluate the degree to which the remedial measure achieves its objectives (e.g., removal of groundwater contaminants, restoration of groundwater quality, etc.). It usually is assumed that after a site enters the LTM phase of remediation, site characterization is essentially complete, and the existing monitoring network can be adapted, as necessary, to achieve the objectives of the LTM program (Reed *et al*., 2000). However, site characterization networks often are not perfectly suited for LTM, because they were installed with a different purpose – to define the nature and extent of the problem when there were many unknowns about the site.

In some cases, the money spent on LTM yields incomplete information on the performance of the remedy. In other situations, money spent on monitoring yields more information than is necessary to make decisions about the operation of the remedy or the progress toward closeout. LTM optimization (LTMO) offers an opportunity to improve the cost-effectiveness of the LTM effort by assuring that monitoring achieves its objectives with an appropriate level of effort. The optimization may identify inadequacies in the monitoring program, and recommend changes to protect against potential impacts to the public and the environment. LTMO may also reduce costs. This is especially true as the remedy progresses, monitored parameters become more predictable, and the extent of contamination diminishes. Decreases in monitoring frequency, locations, and analytical requirements can result in substantial cost savings, and such reductions can be implemented in ways to maintain adequate understanding of the site conditions to make site decisions.

Optimization techniques have been applied to the design of monitoring networks for site characterization, detection monitoring, and compliance monitoring (Loaiciga *et al.*, 1992). In practice, however, optimization techniques are most often applied to LTM programs, as these programs typically provide well-defined spatial coverage of the area monitored, and have been implemented for a period of time sufficient to generate a relatively comprehensive monitoring history. In addition, optimization of a long-term monitoring program can provide significant benefits, due to the typically long time periods and relatively high cost of LTM programs.

Optimization of LTM programs need not be limited to the subsurface and can extend to the monitoring performed for the operation of the above-ground treatment processes. In fact, optimization of this monitoring can be done quickly and relatively easily, and has potentially has significant cost-saving implications. Though this is not the focus of this document, it should be considered as part of an LTMO effort.

1.2. PURPOSE

The primary goals of this Roadmap are to assist site managers in:

- Understanding the steps involved in conducting a LTMO,
- Determining whether a monitoring program could benefit from a LTMO assessment,
- Identifying potential strategies for applying optimization techniques and evaluating which are appropriate for a program, and
- Accessing more information and resources about LTMO tools, methods, and approaches.

1.3. SCOPE

This roadmap focuses on optimization of established long-term monitoring programs for groundwater. Tools and techniques discussed concentrate on methods for optimizing the monitoring frequency and spatial (three-dimensional) distribution of wells (i.e., *physical* program optimization). Other LTMO methods focusing on areas such as the list of analytes, the sampling and analytical methods, and data management are important items for consideration, but are not detailed in this document.

The LTMO techniques discussed here can be described as qualitative or quantitative or some combination of these techniques. Qualitative LTMO evaluations rely on the use of professional judgment to assess the adequacy of the monitoring network and sampling frequency, whereas quantitative LTMO approaches use numerical and statistical approaches to recommend changes. There are advantages to both. The general approaches are discussed further in Section 2.4 (Determine the Type of Evaluation) and specific processes and tools are introduced in Section 2.5 (Select the LTMO Methods/Tools).

2.0 STEPS INVOLVED IN LONG-TERM MONITORING OPTIMIZATION

This section presents the seven steps involved in LTMO. These seven steps are detailed in Sections 2.1 through 2.7. Figure 2.0.1 presents a flowchart of the LTMO steps, along with the associated Roadmap sections and key considerations for each phase of the evaluation.

1. Clearly Define and Document the Current Monitoring Program.
Define monitoring objectives, parameters/constituents measured, sampling and analytical methods, frequency and location of sampling, and monitoring program costs. In addition, ensure that the monitoring program meets both Federal and State regulatory requirements. This information is used to establish the baseline conditions of the monitoring evaluation to be completed during the LTMO.

2. Examine Existing Data.
Determine the amount, types and quality of data available to discover data gaps and decide what types of analyses will be feasible. Ensure that the data are defensible, come from reputable sources, and meet the purpose for which they were collected.

3. Determine If the Site Is a Candidate for a Detailed LTMO.
Establish whether the site meets minimum threshold criteria for LTMO. The potential success of implementing LTMO recommendations can be greatly enhanced by introducing and discussing the idea of optimization with site managers and stakeholders early in the LTMO process.

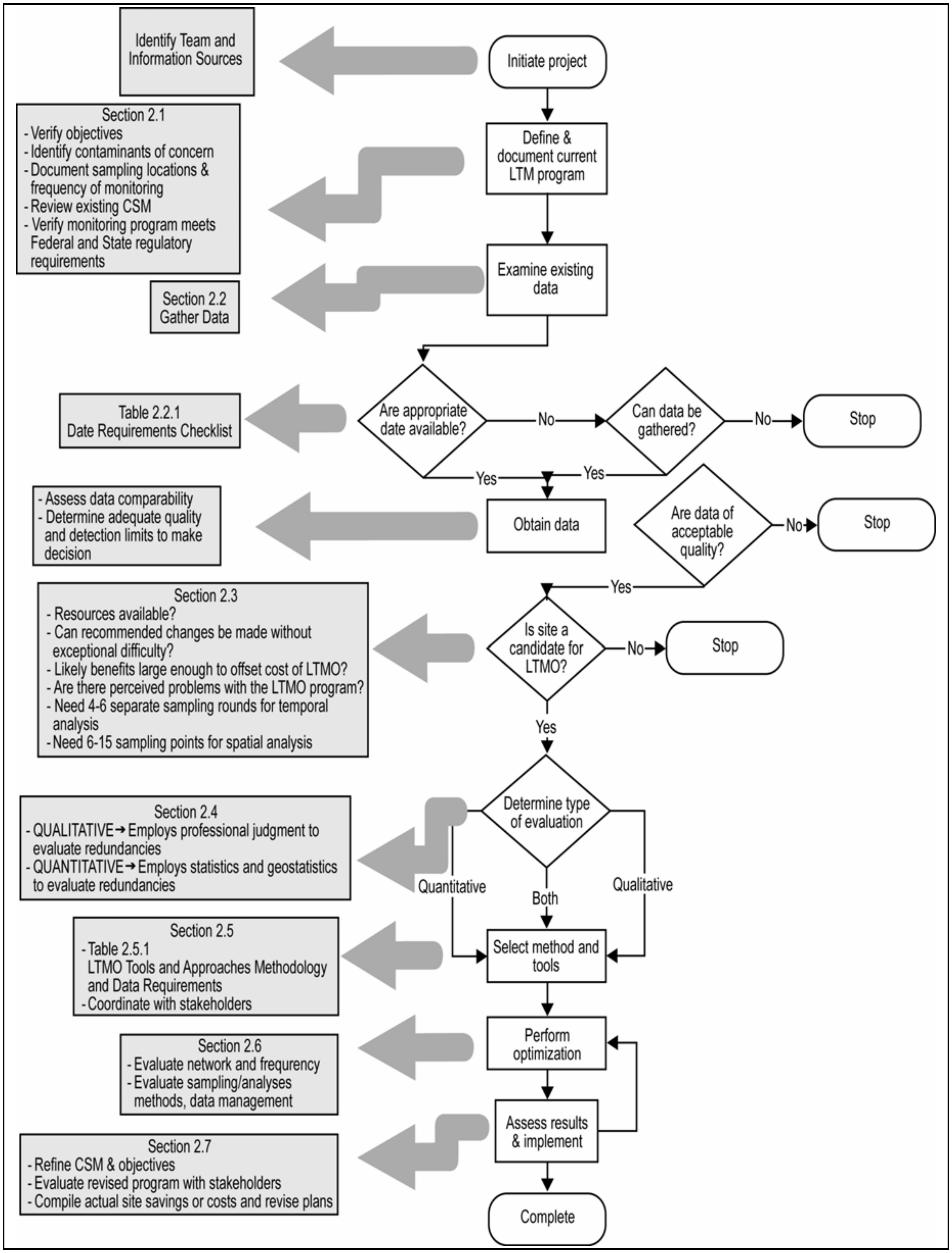
4. Determine the Type of Evaluation.
Evaluate whether a stand-alone qualitative evaluation or a qualitative evaluation, with supporting quantitative temporal and/or spatial statistical analysis, is appropriate for the site.

5. Select the LTMO Methods/Tools.
Assess and select the LTMO methods and tools available to optimize the monitoring program.

6. Perform the Optimization.
Apply the selected tools and methods to develop recommendations for the monitoring program’s optimal well distribution and sampling frequency.

7. Assess and Implement the Results.
Check the reasonableness of the LTMO results, confirm stakeholder buy-in, and implement the recommendations.

Figure 2.0.1 LTMO Steps Flowchart, Associated Key Points, and Corresponding Roadmap Sections



2.1 CLEARLY Define and Document Current Monitoring Program

It is necessary that the primary elements of the existing monitoring program be clearly defined and documented prior to determining if a LTMO evaluation of the program is appropriate, or before conducting a LTMO effort. In some instances, the components of the current LTM program may not have been clearly defined or documented (e.g., in a formal monitoring plan). If the current plan is not well defined, a LTMO evaluation may facilitate the development of an appropriate plan. This section highlights the monitoring program components to be defined to establish the program baseline conditions, including objectives, monitoring constituents, sampling location and frequencies, and level of effort. These aspects are investigated and evaluated as a preliminary effort to assess the potential value of a LTMO effort and to support the LTMO effort if it is deemed appropriate. Furthermore, the relationship between the monitoring program and the current conceptual site model (CSM) should be identified. The CSM may be described in site sampling plans, risk assessments, or other documents.

2.1.1 Components of a Monitoring Program

The U.S. EPA (2004a) defines six steps that should be followed in developing and implementing a groundwater monitoring program:

1. Identify monitoring program objectives,
2. Develop monitoring plan hypotheses, consistent with the CSM,
3. Formulate monitoring decision rules,
4. Design the monitoring plan:
    - Identify the volume and characteristics of the earth material targeted for sampling,
    - Select the target parameters and analytes, including field parameters/analytes and laboratory analytes,
    - Define the spatial and temporal sampling strategy, including the number of wells necessary to be sampled to meet program objectives, sampling methods, and the schedule for repetitive sampling of selected wells, and
    - Select the wells to be sampled.
5. Conduct monitoring, evaluate and characterize the results, and
6. Establish the management decision.

In this paradigm, a long-term monitoring program is founded on the current understanding of site conditions as documented in the CSM, and monitoring is conducted to validate (or refute) the hypotheses regarding site conditions that are contained in the CSM. The conceptual site model is a mental construct (though sometimes documented in a chart or schematic) of the means by which contaminants were introduced into the environment and the fate and movements of the contaminants in liquid, dissolved, vapor, or solid phases from the release to points at which the contaminants are extracted for treatment or at which people or ecological receptors can be exposed to them. Thus, monitoring results are used to refine the CSM by tracking spatial and temporal changes in site conditions through time. All monitoring program activities are undertaken to support a management decision (e.g., assess whether a selected response action is/is not achieving its objectives). The following sections discuss aspects of the monitoring program that need to be researched prior to considering LTMO.

2.1.2 Document/Refine LTM Program Objectives

Designing an effective groundwater quality monitoring program involves selecting a set of sampling sites, suite of analytes, and sampling schedule based upon one or more monitoring program objectives (Hudak *et al*., 1993). Therefore, it is critical that the objectives of monitoring be developed and clearly articulated prior to initiating a monitoring program (Bartram and Balance, 1996), or during the process of evaluating and optimizing an existing program. Because site conditions, particularly in saturated media, can be expected to change through time, the objectives of any LTM program should be revisited and refined as necessary during the course of the program.

An effective LTM program will provide information regarding contaminant migration and changes in chemical suites and concentrations through time at appropriate locations, thereby enabling decision-makers to verify that contaminants are not endangering potential receptors, and that remediation is occurring at rates sufficient to achieve remedial action objectives (RAOs) in a reasonable timeframe. Thus, the two primary objectives of LTM programs can be expressed as follows:

- Evaluate the long-term temporal state of contaminant concentrations at one or more points within or outside of the remediation zone, as a means of monitoring the performance of the remedial measure (*temporal objective*), and
- Evaluate the extent to which contaminant migration is occurring, particularly if a potential exposure point for a susceptible receptor exists (*spatial objective*).

The design and optimization of a monitoring program therefore considers existing receptor exposure pathways, as well as exposure pathways arising from potential future use of the groundwater. These general objectives are often expressed formally in a decision document (e.g., Record of Decision [ROD] or monitoring plan) as a series of site-specific objectives, tailored to a particular LTM program. The LTM objectives should have been discussed with and endorsed by the project stakeholders early in the development of the LTM program. If the objectives of the LTM program have not been clearly articulated, they should be developed and accepted by all stakeholders prior to the initiation of an LTM optimization effort. It also may be necessary to clearly articulate or refine the monitoring decision(s) that the monitoring program is intended to support (e.g., "The response action is/is not achieving the objectives established for the response action"), and the decision rules used to evaluate the results of monitoring, as they apply to the decision (e.g., "decreases in contaminant concentrations near the source area of 50% or more are an indication that the response action is achieving its objectives").

2.1.3 Identify Parameters/Constituents To Be Monitored and Methods for Measuring Them

Target parameters and analytes typically will include those constituents that are known or suspected to be contaminants of concern (COCs) at a particular site. COCs usually are identified in a decision document (e.g., ROD) for that site. Target analytes also may include constituents or parameters that are not necessarily related to the occurrence of contaminants, but which provide information regarding hydrogeologic or geochemical conditions affecting the fate of identified COCs (e.g., oxidation/reduction potential as an indicator of *in-situ* degradation of organic chemicals) or the performance of a selected remedy (Makeig, 1991). The process of determining COCs is important early in the optimization process. Data analyses that can help identify pertinent COCs include quantifying statistics such as frequency of detects, frequency of detects exceeding environmental criteria, and frequency of detects across distinct sampling locations (i.e. how many wells are showing detects and over how much space). Emphasis should be given to constituents that are also more toxic and mobile.

Usually, several different sampling and/or analytical methods for detecting or measuring a particular parameter or constituent are available. The method that is selected for an LTM program is that method which provides sufficient precision and accuracy to satisfy program data quality objectives (DQOs) and also the stated objectives of the monitoring program, at the lowest cost or with the least level of effort. A LTMO will be dependent on the suitability and comparability of the historical data collected. The LTMO itself may assess the issues of optimal sampling and analytical methods further and develop recommendations for changes (see section 2.6.2).

2.1.4 Document Sampling Locations and Frequency of Monitoring

Designing an effective long-term groundwater monitoring program involves locating monitoring points and developing a site-specific strategy for groundwater sampling and analysis in order to maximize the amount of information obtained to effectively address the temporal and spatial objectives of monitoring, while minimizing incremental costs.

Hydrogeologic units are part of the basic framework of a CSM; thus, the volume of earth material targeted for groundwater monitoring should be defined in terms of hydrogeologic units. The number of wells sampled, and the locations selected for sampling, depend primarily on the known or anticipated spatial variability in groundwater conditions and quality (which, in turn, depends to a large degree on the differences among hydrogeologic units), because if spatial variability is great, it is a good idea for a larger number of wells to be sampled to assess that variability (Franke, 1997). Criteria used to identify wells that are suitable for inclusion in an LTM program are program-specific, and are related primarily to the locations in three dimensions (with respect to contaminant sources and potential receptor locations) of individual wells, and the purposes for which a well was installed (e.g., a well installed strictly as a monitoring point may be suited for purposes for which a groundwater extraction well is not suitable) (Franke, 1997).

Sampling frequency also is an extremely important consideration in the design of a monitoring program – if samples are not collected frequently enough, some of the temporal variability in groundwater quality and conditions may be missed, and potentially important information will be lost. On the other hand, if samples are collected more frequently than necessary, some of the information obtained will be redundant (Zhou, 1996). Therefore, prior to initiating a LTMO evaluation, it is recommended the frequency of sample collection at each monitoring point be documented, along with the rationale for sampling at each location.

2.2 EXAMINE EXISTING DATA

While the monitoring program objectives establish the baseline and "big picture" considerations for a LTMO, the data availability and format determine the feasible type(s) and level of detail of the evaluation. Successful application of any LTMO approach to the site-specific evaluation of a monitoring program is directly dependent upon the amount and quality of the available data. For example, a site with insufficient data collection or poor quality data could potentially benefit from a qualitative LTMO that recommends an improved sampling plan; however, a more sophisticated qualitative and quantitative analysis requires a certain amount of historical data. For any approach, the process of becoming familiar with the pertinent characteristics of a site, identifying those data appropriate for the intended application, and transferring those data to the appropriate format (even if the data are available in an electronic database), can be time-consuming and labor-intensive, and represents a significant up-front investment of time and resources. For instance, many LTMO tools are "data driven" and the effort to develop and cleanup the datasets prior to the tool application can often be more than 75% of the overall effort to accomplish the optimization.

Table 2.2.1 presents priority and useful information, potential data sources and the associated purpose of the data required to conduct a LTMO. The first step in the analysis would be to get a general feel for the types and formats of data available in order to determine if a LTMO analysis is possible (Section 2.3). If an LTMO is deemed appropriate, then more rigorous data gathering and processing can take place. Ideally, the available site and monitoring data listed in Table 2.2.1 can be used to revisit the comprehensive CSM over time, which should include extent and nature of the plume as well as the hydrogeologic conditions. The data collected must be evaluated as it is gathered to make site decisions in a timely fashion. This would include periodic qualitative review of the LTM program. In addition, other available information can be used to characterize important institutional considerations. It is important to involve site personnel, site managers, and stakeholders in the LTMO process, as they can provide essential information about regulatory issues, political issues, and other qualitative information that drives monitoring priorities but might not be available in other information sources.

Along with acquiring and processing the data, it is important to evaluate the data in terms of quality and comparability. The defensibility and usability of the data should be verified. This is important when the data are obtained from multiple sources, and is especially true when preparing to assess temporal trends. For example, detection limits of sampling results can be examined to see if they change over time and/or if they are adequately low to enable effective decision making.

Table 2.2.1 Data Requirements Checklist

Data Needed	Potential Data Source(s)	Purpose
Priority Information		
Current monitoring program description	– Monitoring program plan – Recent monitoring report	Establish baseline conditions, purpose of monitoring program, rationale for monitoring wells, and sampling and analytical methods
Well locations and coordinates	– Database – Well construction information – – Site maps	Determine spatial distribution of monitoring points
Analytical data and COC sampling results	– Database – Monitoring reports – Site investigation reports	Define concentrations of COCs in space and time, Confirm primary COCs, Verify data quality
Potentiometric surface configuration – groundwater flow direction, velocity, and gradient	– Recent monitoring report – Document providing facility and site information (e.g., CSM, remedial investigation [RI] or RCRA facility investigation [RFI] report, or similar) – Database	Evaluate direction and rate of groundwater movement and contaminant migration
Hydrogeologic conditions	– Document providing facility and site information (e.g., RI/RFI or similar document) – CSM – Hydrogeologic testing results	Identify geologic or other controls on occurrence and movement of groundwater and dissolved COCs
Well completion intervals and hydrogeologic zone	– Database – Well construction diagrams – Drilling logs	Determine depth of sample collection in groundwater system and potential hydrogeologic and stratigraphic zones
Cleanup goals and regulatory limits	– ROD – Decision document – RI/RFI	Establish cleanup limits and areas of concern requiring monitoring
Potential receptor and compliance point locations	– RI/RFI – ROD – Site map – Site visit	Identify areas and/or migration directions of concern, e.g., nearby public supply wells
Useful Information		
Logistical/policy considerations	– Site personnel – Stakeholders	Identify regulatory/public priorities and potential for program implementation
Site features (roads, building, rivers, property boundaries)	– Site map—AutoCAD drawings or GIS layers (in real coordinates, if possible) – Site visit	Create spatial context for monitoring program, Develop base map of site for LTMO reporting
Water levels through time	– Database – Historical monitoring reports	Identify dry wells, Evaluate seasonal effects

Data Needed	Potential Data Source(s)	Purpose
Geochemical data	– Database	Identify natural attenuation parameters
Wells with NAPL present	– Database, historical monitoring reports	Identify data values that potentially should be excluded from the analysis
Current program costs, including analytical, field mobilization, sample collection, data management and reporting, and waste management	– Laboratory invoices – Project budget, schedule, and labor projections for monitoring projects – Site personnel; professional judgment	Establish a baseline and quantify potential cost changes based on optimization results

2.3 Determine if Site is a Candidate for a Detailed LTMO Evaluation

The decisions regarding whether to conduct a LTMO evaluation, which approach to apply, and the degree of regulatory-agency involvement in the LTMO evaluation and implementation of optimization recommendations are made on a site-specific basis. Factors to be considered in deciding whether to proceed with a LTMO evaluation include:

- The projected level of effort necessary to conduct the evaluation,
- The resources available for the evaluation (e.g., quality and quantity of data, staff having the appropriate technical capabilities),
- The anticipated degree of difficulty in implementing optimization recommendations,
- The potential benefits (e.g., projected savings in cost or level of effort) that could result from an optimized monitoring program, and
- Perceived problems with the current LTMO program on the part of the project team or stakeholders.

Experience suggests that optimization of a monitoring program should be considered for most sites where the LTM programs are based on monitoring points and/or sampling frequencies that were established during site characterization, or for sites where more than about 20 samples are collected and analyzed on an annual basis. Because it is likely that monitoring programs can benefit from periodic evaluation as environmental programs evolve, LTM program optimization also should be considered periodically, rather than being regarded as a one-time event. The periodic assessment of remedy effectiveness, such as a CERCLA five-year review, offers a good framework in which to perform LTMO.

In general, overall site conditions should be relatively stable before LTMO is conducted, and no major changes in remediation approaches should be occurring or anticipated in the next year or two. LTMO should be part of any system-wide optimization effort for sites at which response-action decisions are being validated or refined (e.g., during periodic remedy-performance reviews). The implementation of recommendations from optimization of the LTM program should be considered in light of the other recommended adjustments to the remediation. If there are major changes in the subsurface aspects of the remediation, the LTMO recommendations may be best implemented after the other remedial measures have been implemented and evaluated.

Successful application of any LTMO approach to the site-specific evaluation of a monitoring program is directly dependent upon the amount and quality of the available data. Minimum data requirements include:

- Results from **four to six** separate sampling events (to support a temporal analysis),
- Results collected at **six to 15** separate monitoring points (to support a spatial analysis)., and
- An adequate CSM, describing site-specific conditions (e.g., direction and rate of groundwater movement, locations of contaminant sources and potential receptor exposure points - Section 2.1.1).

If a CSM does not exist, the team conducting the LTMO should develop one based on the available site characterization data. A potential recommendation of the LTMO may be to gather the necessary additional data to refine the CSM. In addition, it is extremely beneficial to delineate the extent of contaminants in the subsurface at the site before the monitoring program can be optimized, though the process of LTMO may help identify data gaps and the need for additional monitoring. The certainty in results of a temporal or spatial analysis increases with an increased number of sampling events or monitoring points, respectively. The minimum numbers of events or points mentioned above must be considered in light of the spacing in time or space and the time period and area over which the data were collected. The data should not be highly clustered in time or space and should span the scope of the problem (e.g. over years or the footprint of the groundwater plume).

2.4 DETERMINE THE TYPE OF EVALUATION

2.4.1 General Considerations in LTMO

Historically, most monitoring programs have been designed and evaluated based on qualitative insight into the characteristics of the hydrologic system using professional judgment (Zhou, 1996). Groundwater systems by nature are variable in space and through time, and it may be difficult to account for much of the existing variability using quantitative techniques (Ward *et al*., 1990). All approaches to the design, evaluation, and optimization of effective groundwater monitoring programs must acknowledge and account for the dynamic nature of groundwater systems, as affected by natural phenomena (e.g., changes in groundwater levels and the resulting rates or directions of groundwater movement) and anthropogenic changes (e.g., changes in nearby pumping, introduction and movement of contaminants) (Everett, 1980). This means that in order to assess the degree to which a particular program is achieving the temporal and spatial objectives of monitoring (Section 2.1.2), a LTMO evaluation should address the temporal and spatial characteristics of groundwater-quality data. Temporal and spatial data may be most rigorously evaluated using temporal and spatial-statistical techniques, respectively.

However, there may be other considerations that are best addressed through qualitative evaluation. Therefore, an LTM program can be evaluated and optimized using qualitative or quantitative approaches. Because it is possible to consider numerous factors simultaneously in a qualitative evaluation, this usually is considered to be the primary approach for evaluating an LTM program, with the results of temporal or spatial-statistical evaluations used to support the results of a qualitative evaluation. Even if the focus of the LTMO is a rigorous quantitative analysis, a qualitative review of the results is recommended to assess the impacts of site hydrogeologic characteristics and stakeholder considerations.

If attenuation or removal of contaminant mass is occurring in the subsurface as a consequence of natural processes or operation of an engineered remedy, attenuation or mass removal will be apparent as a:

- Decrease in contaminant concentrations through time at a particular sampling location,
- Decrease in contaminant concentrations with increasing distance from chemical source areas, and/or
- Change in the suite of chemicals through time or with increasing migration distance.

Conversely, if a persistent source is contributing contaminants to groundwater, or if contaminant migration is occurring, this may be apparent as an increase in contaminant concentrations through time at a particular sampling location, or as an increase in contaminant concentrations through time with increasing distance from contaminant source areas.

2.4.2 Considerations in Qualitative Evaluation

In a qualitative evaluation, the numbers and locations of wells and frequency of sample collection are examined in the context of site-specific conditions. This is done to ensure that the program is capable of generating information regarding contaminant migration and changes in chemical concentrations through time and to ensure that the objectives of the monitoring program (Section 2.1) are satisfied. Additional considerations such as the list of analytes, sampling method(s), analytical methods, and mechanisms used for data management and reporting can also be assessed during the qualitative evaluation (Section 2.6.2). The relative performance of the monitoring program is assessed from calculations and judgments made without the use of quantitative methods (Hudak *et al*., 1993). Sampling locations are evaluated by considering contaminant behavior and hydrogeologic and other conditions within, and at locations distal from the source(s) of contaminants (e.g., Schock *et al.*, 1989). The ultimate configuration of the monitoring program, including the location of wells and frequency of monitoring, is subject to the investigator's understanding of:

- The properties and behavior of the groundwater system,
- The ways in which these properties influence the movement and fate of contaminants, and the resultant contaminant distributions, and

- What constitutes an "optimal" monitoring program, given the monitoring objectives, probable contaminant migration pathways, receptor exposure points, and travel times.

These factors will influence the locations and spacing of monitoring points, and the sampling frequency. All monitoring points that are sampled periodically in conjunction with the LTM program under consideration should be included in a qualitative evaluation. Multiple factors can be considered in developing recommendations for continued monitoring, additional monitoring, or cessation of monitoring at each monitoring point or well. In some cases, a recommendation may be made to continue monitoring at a particular well, but at a less frequent interval than at present. Typical factors considered in developing recommendations to retain, add, or remove a well from the monitoring program are summarized in Table 2.4.1; typical factors considered in developing recommendations for monitoring frequency are summarized in Table 2.4.2. These tables are meant to assist in understanding the nature of qualitative analysis so a decision can be made regarding the appropriateness of this approach to a site. These tables can also be of use in guiding the actual performance of qualitative analysis.

Table 2.4.1 Qualitative Monitoring Network Optimization Decision Logic

Reasons for Retaining or Adding a Well in a Monitoring Network	***Reasons for Removing a Well From a Monitoring Network***
Well is needed to further characterize the site or monitor changes in contaminant concentrations through time.	Well provides spatially redundant information with a neighboring well (e.g., same constituents, and/or short distance between wells).
Well is important for defining the lateral or vertical extent of contaminants.	Well has been dry for more than two years, and there is no expectation for the water levels to recover in the foreseeable future.
Well is needed to monitor water quality at a compliance point or receptor exposure point (e.g., sentinel well for municipal wells).	Contaminant concentrations are consistently below laboratory detection limits or cleanup goals.
Well is important for defining background water quality.	

Table 2.4.2 Qualitative Monitoring Frequency Decision Logic

Reasons for Increasing Sampling Frequency	***Reasons for Decreasing Sampling Frequency***
Groundwater velocity is high.	Groundwater velocity is low.
Change in concentration would significantly alter a decision or course of action.	Change in concentration would not significantly alter a decision or course of action.
Well is close to source area or operating remedy.	Well is far from source area or operating remedy.
Whether concentrations will change significantly over time cannot be predicted, or there is no ready explanation for recent irregular or contradictory data.	Concentrations are not expected to change significantly over time, or contaminant levels have been below cleanup objectives for some period of time.

A qualitative evaluation is complete when recommendations regarding retention in, or removal from, the program and the frequency of sample collection have been generated for every sampling location (well) in the monitoring program, and other broader program considerations (Section 2.6.2) have been assessed and documented. Qualitative approaches to the evaluation of a monitoring program range from relatively simple to complex, but often are subjective. Furthermore, the degree to which the LTM program satisfies the spatial and temporal objectives of the program may not be easily evaluated by qualitative methods.

2.4.3 Considerations for Quantitative Analysis of Temporal Trends

Temporal data (chemical concentrations measured at different points in time) provide a means of quantitatively assessing conditions in a groundwater system (Wiedemeier and Haas, 1999), and evaluating the performance of a groundwater remedy and its associated monitoring program.

The temporal objective of LTM (evaluate contaminant concentrations in groundwater through time; Section 2.1.2) can be addressed by identifying trends in contaminant concentrations, by identifying periodic fluctuations in concentrations, or by estimating long-term average ("mean") values of concentrations (Zhou, 1996). Concentration trends, periodicity, and long-term mean concentrations typically are evaluated using statistical methods. In particular, tests for trends, including the Student's t-test (Zhou, 1996), regression analyses, the Mann-Kendall test (Gibbons, 1994), and Sen's (1968) non-parametric test for the slope of a trend, are widely applied (Hirsch *et al.*, 1991). The frequency of sampling necessary to achieve the temporal objective of monitoring then can be based on trend detection, accuracy of estimation of periodic fluctuations, or accuracy of estimation of long-term average concentrations. Other quantitative methods use a different means for temporal analysis. They may recommend a sample frequency based on an analysis of the portion of historical concentration trends that can be reconstructed when sampling events are iteratively removed from the monitoring system. The minimum frequency of past sampling events that can indicate the same general concentration trend as has been observed is used as a basis for the recommended future sample frequency.

Decisions regarding sampling frequency are made using a simulation approach or a rule-based approach. In a simulation approach, a computer model is used to simulate the movement of contaminants in the environment, and the optimal frequency of sampling at a particular monitoring point is estimated based on the rate of change in contaminant concentrations calculated by the model. In a rule-based approach, a decision rule is established and is used together with the results of the trend, periodicity, or average-concentration evaluations to select the sampling frequency at a particular monitoring location. For example, a decision rule may state that if a trend of increasing contaminant concentrations in groundwater is identified at a monitoring point near a potential receptor exposure point, an increase in the frequency of sampling at that location is warranted.

2.4.4 Considerations for the Quantitative Spatial Analysis of Monitoring Networks

Spatial techniques that can be applied to the design and evaluation of monitoring programs fall into several categories – simulation, geostatistical, and analytical approaches (Minsker, 2003). Simulation approaches fit historical data to computer models and simulate the evolution of contaminant plumes. Geostatistical and analytical methods use only historical data to interpolate contaminant concentrations throughout the region of interest and, in some cases, in multiple periods of time. Geostatistical methods typically use kriging, while analytical methods apply other interpolation methods, such as Delaunay triangulation.

Once a plume model is created using one of these approaches, it can then be incorporated into a numerical optimization algorithm that uses formal mathematical techniques to derive an optimal monitoring network configuration (e.g., Reed et al., 2000). Alternatively, ranking methods can be used to select monitoring configurations using "rules-of-thumb" rather than formal optimization. Monitoring points that are identified as contributing relatively little information to the program, based on a spatial evaluation, are candidates for removal from the program.

More significantly, if areas having significant uncertainty in contaminant concentrations are identified in the spatial evaluation, it may be necessary to install and sample additional monitoring points in these areas. This is especially true where the uncertainty exists near the limits of the plume and near potential receptors (American Society of Civil Engineering [ASCE], 1990a and 1990b).

2.4.5 Other Considerations

A site manager desiring to optimize a LTM program may not possess the technical capabilities necessary to complete a qualitative, temporal, or spatial evaluation. In this circumstance, it may be necessary to seek outside expertise (e.g., a contracted or in-house specialist) to provide the necessary capabilities. Although this may necessitate additional expenditures, in addition to completing the required technical evaluation(s), an individual or firm not otherwise directly involved in the LTM program can also provide an independent and possibly fresh and more objective review of aspects of the LTM program, or of the overall environmental program. This can be a distinct advantage if disincentives exist for an incumbent contractor responsible for the LTM program to optimize or otherwise change aspects of the program.

The concepts discussed are geared toward the subsurface monitoring networks, but could also apply to the collection of data from points within above-ground treatment systems. In this case, the frequency of sampling and locations of sampling within the treatment "train" can be modified to more efficiently meet the needs of sampling.

2.5 SELECT THE LTMO METHOD(S)/TOOL(S)

There is no definitively "right" way to conduct a LTMO; multiple guidance documents, tools, and standardized methods and approaches which utilize qualitative, temporal, and/or spatial-statistical methods have been applied successfully to a range of sites.

Application of any approach to an existing LTM program can be used to generate recommendations for changes in sampling frequency, and in the numbers and locations of monitoring points that are sampled. Whatever approach is used should be applied within the framework of a clearly articulated decision structure that has been accepted by all stakeholders. As a consequence of structural differences in approaches to the evaluation and optimization of monitoring programs, the results generated by any optimization approach should be expected to differ slightly from the results generated by other approaches; however, the results of any optimization approach should be defensible, if the decision logic on which the approach has been based is sound. The most significant advantage conferred by any optimization approach is the fact that they are used to apply consistent, well-documented procedures, which incorporate formal decision tools, to the process of evaluating and optimizing monitoring programs.

2.5.1 LTMO Guidance Documents

The primary available LTMO guidance documents are discussed briefly below. Additional information about these guidance documents, additional guidance references, and full web page addresses are presented in the Appendix.

- *Naval Facilities Engineering Service Center (NFESC) Guide to Optimization Groundwater Monitoring, January 2000*

  This guide includes information on how to both design new monitoring programs and optimize existing programs. It covers a broad range of issues including physical program optimization (e.g., frequency and location), analytical & field protocols and data management and reporting, and includes a summary of several optimization case studies.

- *Air Force Center for Environmental Excellence Long-Term Monitoring Optimization Guide, Version 1.1, October, 1997*

  This guide includes information on developing a LTM work plan, collecting data and documenting the existing LTM program, optimization strategies, and evaluation of cost savings.

2.5.2 LTMO Tools & Standardized Approaches

The specific optimization approach selected for a given site depends on several factors, including the amount and type of existing data, available resources, and size of the monitoring program. A significant number of monitoring programs have been optimized using various LTMO methods at a range of sites. Current academic research tends to consider primarily numerical simulation and formal optimization approaches, while "readily available" tools and approaches tend to focus more on rule-based algorithms and professional judgment. The ASCE monograph "Long-Term Groundwater Monitoring, The State of the Art" (2003) details a range of methods and presents a substantial list of case studies and results. Table 2.5.1 highlights the methodology and data requirements for readily available standardized approaches and tools that have been applied to multiple sites. Table 2.5.2 lists implementation details for these approaches, including cost, required resources and availability. Additional references and contact information for these tools are available in the Appendix.

2.5.3 Current Research in LTMO

All of the LTMO approaches discussed in the preceding subsections are evolving, as they are continuously being refined as experience is gained during application to real-world sites and LTM programs. Several of the approaches are labor intensive; the most significant future enhancement to these approaches will be development of procedures to improve the automation of parts of the evaluation. Some approaches utilize only a single contaminant (an "indicator" contaminant that has relatively high toxicity and/or mobility) or a subset of the actual COCs in the evaluation; these approaches may be expanded to address multiple contaminants at several time periods. Approaches that rely on numerical optimization may benefit from development or refinement of the optimization algorithms that are used in the computer program. Finally, all of the LTMO approaches incorporate a framework for making decisions regarding the number and locations of monitoring points, and the frequency of sample collection, on the basis of qualitative, temporal, and/or spatial evaluations. These decision frameworks are being improved on the basis of experience, and could be improved further by applying insight from formal logic, systems engineering, and information theory. Developments in LTMO approaches will be tracked on the Federal Remediation Technologies Roundtable (FRTR) website and on the U.S. EPA's Clean Up Information CLU-IN Remediation Optimization website (see Appendix for references and additional information).

Table 2.5.1 LTMO Tools and Approaches Methodology and Data Requirements

LTMO Tool/Approach	*Overview*	*Frequency Optimization Methodology*	*Spatial Distribution Methodology*	*Data Requirements*	*Appropriate Site Size*
Cost Effective Sampling (CES)	CES is a methodology for reviewing and assessing the lowest-frequency sampling schedule for a given groundwater monitoring location.	Rule-based decision algorithm based on trend, variability, and magnitude statistics recommends optimal frequency at each well.	Not included	– At least 6 quarterly monitoring results per well – Clean down-gradient "guard wells"	Unlimited (well-by well analysis) within same operable unit
Geostatistical Temporal/Spatial Optimization Algorithm (GTS)	GTS is a spatial and temporal algorithm developed by AFCEE that utilizes geostatistical methods to optimize sampling frequency and to define the network of essential sampling locations. The GTS algorithm incorporates a decision pathway analysis that incorporates both spatial and temporal components and is used to identify spatial and temporal redundancies in existing monitoring networks.	1) Iterative thinning approach reconstructs baseline trends with fewer samples to determine optimal frequency on a well-by-well basis. 2) Temporal variogram is applied to determine composite autocorrelation and optimal site-wide frequency.	Weighting scheme utilizing locally weighted quadratic regression examines multiple "time slices" to identify redundant wells based on cost-accuracy trade-off curves.	– More than 8 events per well (temporal) – Greater than 30 wells (spatial)	30 to thousands of wells
Monitoring and Remediation Optimization System (MAROS)	The MAROS public domain software was developed in accordance with the AFCEE Long-Term Monitoring Optimization guide. MAROS is a decision support tool based on statistical methods applied to site-specific data that accounts for relevant current and historical site data as well as hydrogeologic factors. The software recommends optimal future sampling frequency, location and density, as well as providing information on the plume state over time.	Modified cost-effective sampling method (rule-based decision algorithm based on trend, variability, and magnitude statistics) recommends optimal frequency for each well.	Weighting scheme utilizing Delaunay triangulation identifies redundant wells. Can evaluate multiple chemicals at one time.	– More than 4 events per well (temporal) – Greater than 6 wells per zone (spatial)	40 to 80 wells recommended (per aquifer zone)
Parsons 3-Tiered LTMO	The 3-Tiered LTMO consists of a qualitative evaluation, an evaluation of temporal trends in contaminant concentrations, and a statistical spatial analysis. The results of the three evaluations are combined to assess the degree to which the monitoring network addresses the primary objectives of monitoring. A decision algorithm is applied to assess the optimal frequency of monitoring and the spatial distribution of the components of the monitoring network, and to develop recommendations for monitoring program optimization.	Qualitative evaluation, temporal statistical evaluation (Mann-Kendall), and spatial statistical evaluation are combined to identify wells for exclusion or retention and make final sampling frequency recommendations.	Qualitative evaluation, a weighting scheme using kriging, and temporal evaluation are combined to identify the relative spatial value of each well And make final network distribution recommendations.	– More than 4 events per well (temporal) – Greater than 10 wells per zone (spatial)	10 to 100s of wells (per aquifer zone)

LTMO Tool/Approach	*Overview*	*Frequency Optimization Methodology*	*Spatial Distribution Methodology*	*Data Requirements*	*Appropriate Site Size*
Adaptive Environmental Monitoring System (AEMS)	AEMS performs sample redundancy analyses and enables smart online data assessment and adaptive monitoring of environmental systems. The sample redundancy analyses use multi-objective optimization to remove spatial, temporal, or simultaneous spatial and temporal redundancies, including an option to explicitly account for uncertainty in the historical data. A suite of spatial and/or temporal models can be built from historical data and used within the redundancy analyses to find the optimal set of samples that meet user-specified performance objectives. The models can also be used to automatically assess new data in online systems, sending alerts when data indicate significant deviations from recent spatial and/or temporal trends. The adaptive optimization system can also recommend optimal locations and times for additional sampling to respond to any observed anomalies.	Genetic algorithms are used to search for optimal designs given a temporal interpolation model or multiple spatial interpolation models built from historical data.	Genetic algorithms are used to search for optimal designs given a spatial or spatiotemporal interpolation model built from historical data using geostatistical, statistical, or analytical approaches. AEMS is currently the only optimization software to perform simultaneous spatial and temporal optimization, as well as allowing optimal tradeoffs to be identified among user-specified performance objectives and allowing explicit consideration of uncertainty.	– More than 8 events per well (temporal) – More than 15 events per well (spatial) – More than 30 events per well (combined spatial and temporal optimization)	Unlimited

Table 2.5.2 LTMO Tools and Approaches Implementation Details

Tool/Approach	*# Sites Applied*	*Typical Cost to Apply to Site*	*Availability*	*Required Resources and Expertise*
Cost Effective Sampling (CES)	~10	$25-$50k	– Consulting method – Follow methodology presented in references	– High level of skill (initial setup) – Minimal skill (subsequent runs)
Geostatistical Temporal/Spatial Optimization Algorithm (GTS)	~10	~$25k for average site	– Currently consulting method – Scaled-down software available in Summer 2005	– Experienced statistician (current form) – Mid-level analyst (software)
Monitoring and Remediation Optimization System (MAROS)	Unknown*	$5-$15k for average site	– Free software available for download	– Mid-level analyst – IBM-compatible PC with MS Access 2000, Excel 2000
Parsons 3-Tiered LTMO	~20	$5-$15k for average site	– Consulting method – Follow methodology presented in references	– Experienced geologist (qualitative analyst) – Mid-level analyst familiar with statistics and GIS (quantitative) – GIS software (e.g., ArcView 3.2 or higher)
Adaptive Environmental Monitoring System (AEMS)	3	$5-$15k for average site	– Currently consulting method – Prototype software available for testing in Spring 2005.	– Mid-level analyst

* Because MAROS is freeware that can be used for multiple applications, it is unknown how many times it has been applied in LTMO applications.

2.6 PERFORM THE OPTIMIZATION

2.6.1 LTMO Preparation and Implementation

Optimization of an LTM program should be initiated only after:

- The site manager has evaluated the LTM program to determine whether the program is an appropriate candidate for an LTM optimization effort (Section 2.3),
- The level of detail proposed for the evaluation (qualitative, temporal, spatial, or a combination of the three) has been selected (Section 2.4),
- An appropriate tool (MAROS, three-tiered approach, GTS algorithm, or other) and/or guidance document has been identified (Section 2.5),
- The available data have been compiled and examined to ensure that the minimum data requirements have been met for the level of detail of the evaluation and the selected tool (Sections 2.2 and 2.4), and
- All stakeholders have agreed to the objectives developed for the monitoring program, the data to be used in the LTM optimization, and the approach to be followed (including the decision structure used to evaluate monitoring frequency, sampling locations, and other considerations).

After all of these requirements have been satisfied, the selected approach is applied to the LTM program. An annotated list of applicable policies and guidance documents, additional information on LTMO approaches, and links to web pages with more information and case study applications are included in the Appendix.

2.6.2 Optimization of Other Aspects of the LTM Program

Though the focus of this document is the optimization of the frequency of sampling and the monitoring network, other aspects of an LTM program also can be evaluated for potential improvements. These include the list of analytes, sampling method(s), analytical methods, and mechanisms used for data management and reporting. Typically, LTM programs are initiated only after site characterization has been completed (Reed *et al*., 2000), and site-related COCs have been identified. Because the COCs have been identified, it may be possible in some cases to conduct the required chemical analyses using a different analytical method than was used during site characterization activities. If the alternate method has a shorter list of analytes, or if the analyte list is restricted only to the identified site-related COCs, it may be possible to reduce the unit cost of chemical analysis of samples. For example, analyses for volatile organic compounds (VOCs) often are conducted during the site-characterization phase of investigations using Method SW8260B (a gas-chromatographic/mass-spectrometric [GC/MS] method). If the analytes to be determined in samples are known (e.g., after an LTM program has been initiated), Method SW8260B can be replaced by Method SW8021B (a GC method), with potentially significant cost savings realized on a unit-cost basis. One should be cautious that all potentially toxic daughter products of the COCs are included in the analytical suite.

Additionally, groundwater sampling methods have evolved over the past 20 years; relatively new sampling methods (http://www.clu-in.org/char1_tech.cfm#new_tech) including passive diffusion bag samplers (http://www.diffusionsampler.org/) and innovative *in-situ* and field-based analytical methods (http://www.frtr.gov/site/) may offer lower costs and, in many cases, more representative data than methods that historically have been widely applied. Analytical methods also have been improved through time, often resulting in associated improvements in analytical detection limits; therefore, updated or alternative methods should be considered. In particular, the rigorous fixed-laboratory methods used for site characterization may no longer be necessary for certain current uses of the data (e.g., treatment plant operational decisions) and lower cost methods may suffice. Analytical methods should be selected to detect and measure only those contaminants known to be present at the site, or other constituents/parameters necessary to assess remedy performance. The data quality objectives process developed by the U.S. EPA (1994) (http://www.epa.gov/quality/ qa_docs.html), and the USACE's technical project planning process both offer excellent frameworks within which to reassess these aspects of LTM.

Data generated by analytical laboratories should be transferred and managed electronically to avoid errors and reduce labor costs in both documentation and analysis of the results. Geographic information systems (GIS) can be highly effective tools for managing LTM program data and making those data readily available for interpretation and presentation. LTMO efforts also should assess these aspects of the program, particularly at large sites. Such data-management tools may also be evaluated considering their ability to export the data for use by any LTMO software.

2.7 ASSESS AND IMPLEMENT RESULTS

2.7.1 Examine Results of LTMO Evaluation

The final product of a LTMO evaluation of an existing monitoring program comprises a series of program refinements, potentially including

- A refined CSM,
- Refinements or clarification of program objectives,
- Changes in the number and locations of monitoring points,
- Increases or reductions in the frequency of sampling at each monitoring point in the program,
- Changes in sampling and/or analytical methods, and
- Changes in methods of data handling, management, and reporting.

At the conclusion of the LTMO evaluation, it is beneficial for the refined LTM program to be examined critically by the project team. This would help ensure that the refined program is capable of generating sufficient information, at appropriate locations and frequencies so that the objectives of the program continue to be addressed adequately. In essence, this "reality check" involves completing a qualitative evaluation of the refined

LTM program, and comparing the results that the refined program is projected to generate with the requirements of the refined CSM and the program objectives. Often, performing an LTMO and assessing and implementing the result can be an iterative process, in which the initial results identify issues that are addressed in a revised analysis. If both qualitative and quantitative analyses were performed, the results should be compared and differences in the recommendations resolved by the project team. The project team should discuss the disposition of monitoring wells that may be eliminated from the program. The unneeded wells may prove useful in the future as conditions evolve and should be secured but not decommissioned. In other cases, particularly where the plume has shrunk significantly, the wells are very unlikely to contribute in the future and should be decommissioned in accordance with all state and local requirements. This requires planning, funding, and coordination.

2.7.2 Implementation Steps

The recommendations generated during a LTMO evaluation should be implemented in a defensible manner consistent with good project planning, including developing appropriate documentation for the proposed changes (with approval from stakeholders, as necessary). Actions that typically would be completed during implementation of LTMO recommendations are presented in the following checklist:

- Continue coordination with stakeholders (as discussed above),
- Obtain necessary changes to permits or other decision documents, if required (see below),
- Modify, as necessary, elements of the current sampling and analysis plan (SAP), including the field sampling plan and quality assurance plan (e.g., modify monitoring plan, quality assurance project plan [QAPP], decision documents, O&M contracts, etc.),
- Procure necessary equipment, laboratory services, etc.; install additional wells (if required); or modify existing contracts for sampling and analytical services (as necessary),
- Train field personnel in the revised procedures, and
- Assess field experiences or sampling results for potential unexpected consequences that might be related to implementation of the LTMO recommendations, and modify the process as needed. This may require additional coordination with the appropriate regulatory agency or other stakeholders.

2.7.3 Cost to Implement Recommendations

Revision of existing monitoring program documents can cost thousands of dollars, though the costs of document revision generally are lower than initial document preparation. Changes to a monitoring program, including the process of obtaining necessary approvals, also may require significant amounts of time and must be accommodated in the project schedule. Modification of decision documents can be time-consuming, and typically requires coordination with entities outside of the immediate project team. Costs for new sampling equipment or data management software (e.g., GIS) can be significant, and installation or replacement of monitoring wells can represent large additional costs. Accordingly, implementation of optimization recommendations must be undertaken in a manner that balances the benefits of optimization with implementation costs. If an excessive time (say more than several years) is required for any cost savings to offset these up-front costs, the changes may not be appropriate, and may need to be deferred for some time. In situations where expansion of the monitoring program is necessary to meet program objectives, additional costs may be unavoidable.

Experience demonstrates (e.g., U.S. EPA, 2004b) that implementation of the results of a LTMO evaluation of an existing program of moderate size (30 to 100 samples collected and analyzed per annum) can result in reductions ranging from 10 to about 50 percent in the number of samples collected annually. In addition to monitoring reductions, LTMO evaluations can potentially identify data deficiencies that lead to recommendations for additional wells and/or sampling. Typically, a program manager should anticipate incurring costs ranging from perhaps $2,500 (for a qualitative evaluation of a monitoring program that includes on the order of 20 to 30 monitoring points) to approximately $25,000 to complete a detailed LTMO evaluation of a larger program, using a combination of qualitative, temporal, and spatial approaches. Consequently, a detailed LTMO evaluation may be cost-prohibitive for smaller monitoring programs, although successful LTMO evaluations have been performed at sites with around 20 monitoring events per year. Assuming a payback period of three years, potential cost savings ranging from approximately $800 to $8,300 per year must be realized if optimization of a monitoring program is to be cost-effective. Because the costs associated with collection and analysis of a groundwater sample typically range from about $200 per sample to about $800 per sample (Air Force Center for Environmental Excellence [AFCEE], 2004), a LTMO evaluation that is able to reduce the total number of samples collected at a site by about 5 to 15 samples per annum should be cost-effective. Note that costs incorporating all other associated activities (e.g., mobilization, data validation and management, reporting) may result in an average per-sample cost of over $1000.

2.7.4 Benefits of Flexibility in Planning and Decision Documents

The use of flexible decision documents and plans are strongly encouraged and this facilitates the implementation of LTMO recommendations. Modification of the LTM program can be facilitated in terms of cost and time if decision documents (e.g., the ROD) or permits are constructed to be adaptable to periodic changes, and incorporate flexibility in LTM requirements. This can be addressed by acknowledging the need for periodic review of the response action and associated LTM program in the decision documents, or by including performance-based monitoring requirements in a decision document, together with an evaluation process for assessing the degree to which such requirements are achieved. The decision documents or a site exit strategy document should also identify a process by which a decision can be made as to when LTM is no longer needed. It is very important to have a rationale for cessation of LTM identified and endorsed early in the remediation process. A general SAP, that presents standard site information and specifies standard procedures, but which is periodically updated with specific addenda or that allows actual sampling locations and frequency to be proposed and periodically modified via a separate document, is beneficial.

2.7.5 Periodic Re-Evaluation of LTM Programs and Validation of LTMO Recommendations

Although significant benefits can be realized by completing a one-time LTMO evaluation, additional benefits may result from periodic evaluation and optimization of an LTM program. At sites where active remediation is in progress, or where natural attenuation processes are effectively removing contaminant mass, the concentrations and spatial distribution of contaminants are likely to change over time, resulting in decreases in the extent of contaminants in groundwater. At other sites where releases from source areas are uncontrolled, the concentrations or extent of contaminants may increase. In such situations, periodic re-evaluation of the LTM program can be beneficial in assessing whether the program remains capable of meeting monitoring objectives. There also may be external influences that can cause changes in the distribution or extent of contaminants, such as climatic changes (e.g., drought) or changes in groundwater extraction rates at nearby locations. It is a good idea for the effectiveness of the LTM program to be periodically re-evaluated in light of the changes resulting from such external influences. Periodic re-evaluation can support public and regulatory confidence in the response action and its associated LTM program, and also may reduce costs incrementally over time as site conditions are addressed. The time interval between periodic LTMO evaluations will vary depending upon site conditions; typically, programs should be evaluated at least every two to five years. Periodic LTMO could be integrated with or timed to support the CERCLA Five-Year Review process or RCRA permit reapplication process. In the course of the periodic iterative review, new optimization approaches may become available such that a totally different tool may be used. In order to capitalize on new approaches, the original optimization technique or tool may be modified, transformed or replaced by a future approach. Note that the data collected under the LTM program should be assessed as it is collected for making timely site decisions, including urgent changes to the LTM program.

Once LTMO has been accomplished and an optimized network and sampling frequency has been implemented, some effort may be needed to validate the optimized approach is performing the expected way. Validation involves limited future and perhaps random sampling of wells originally slated for removal from the network to verify that they are predictable in behavior prior to abandonment of the wells, removal of equipment, etc. The notion of testing the ability of essential wells to predict concentrations in neighboring areas where redundant wells exist, is important to addressing the proof of optimization concept.

2.7.6 Considerations in Reviewing LTMO Analyses

The review of LTMO reports involves consideration of many issues. Although this document cannot address all possible project conditions that would affect the review of LTMO results, some consistent guiding principles exist. Primarily, the review weighs the recommended changes to the LTM program in light of what is known about the monitoring objectives, hydrogeology, and decision logic of the optimization method and tools. The evaluation must have been done realistically considering the monitoring objectives identified by all stakeholders. The recommended monitoring program (sample frequency and monitoring point network) must be appropriate considering the three-dimensional nature of the plume, its likely flow paths, and contaminant transport velocities. Furthermore, the recommended monitoring program should support sampling requirements addressing key potential exposure points, such as those points that monitor for the protection of production wells. The approach and methods used for the evaluation need to be clearly described and should have been based on sound technical logic appropriate to the project. The approach must be balanced and allow for additional monitor points and/or more frequent sampling if data gaps exist in the current program. Some additional issues to be considered during review of LTMO results include:

- The quality and comparability of data used in the analysis,
- Confirmation of adequate reasons for optimizing the LTM program,
- The qualifications of the person(s) performing the evaluation considering the complexity of the hydrogeology,
- Adequacy of the data for quantitative temporal and spatial evaluation (4-6 sampling rounds, >6-15 separate monitoring points, depending on method)
- The availability of the results (output) from any software package in an appendix,
- Modifications (with rationale) to the sampling methods, chemical analysis, data management and reporting aspects of the LTM program, in addition to the sample locations and frequency,
- The potential need for some wells targeted for exclusion from the LTM program to meet other objectives not considered in the LTMO evaluation
- The efficient logistics of performing the recommended site monitoring (e.g., would some sampling rounds consist of only a few wells?),
- The disposition of wells that are to be removed from the LTMO program (i.e., decommissioning or stand-by status), and
- Consistency between the recommended changes to the program and the output of the evaluation process (any differences between the results and the actual recommendations should be explained).

The review of LTMO reports inevitably requires some qualitative assessment of the suitability of the proposed monitoring program as a “reality check” on the recommendations. Some interaction between the reviewer(s) and the analyst(s) will be typically be required and will likely be beneficial.

A good LTMO report would address the following topics:

- A description of the current site conditions and monitoring program, including a discussion of the media sampled, the hydrogeology as it affects the LTMO, a map of all monitoring points and tables of the sampling frequencies and analytes.

- A description of the Conceptual Site Model and the objectives of the monitoring program as understood by the LTM optimization team.
- The results of the evaluation of the usability of the existing monitoring data, including the identification of comparability issues, outliers, and data management problems.
- A discussion of the optimization approach, including description of decision logic and any quantitative methods used.
- The results of the optimization including an optimized sampling plan with essential wells ranked in order of importance, optimal sampling frequencies, list of redundant or needed wells, changes to the analytical program, etc.
- A discussion of any issues that affect the potential implementation of the recommendations, including, for example, the consideration of planned changes to the remedy or land use, required changes to plans, permits, or decision documents, the need for abandonment of any redundant wells, etc.
- Appendices with specifics on the analysis or output from software tools.

3.0 REFERENCES

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APPENDIX
LTMO RESOURCES

LTMO POLICY AND GUIDANCE RESOURCES

***Department of the Navy Policy for Optimizing Remedial and Removal Actions Under the Environment Restoration Programs*.** April 2004.
http://enviro.nfesc.navy.mil/erb/erb_a/regs_and_policy/don-policy-ra-optimiz.pdf

This policy establishes procedures (including the Guide to Optimal Groundwater Monitoring) for optimizing the screening, evaluation, selection, design, and implementation for long-term operation and management of response actions conducted under the Navy's Environmental Restoration program.

Performance Monitoring of MNA Remedies for VOCs in Ground Water. April 2004.
http://www.epa.gov/ada/download/reports/600R04027/600R04027.pdf

This document is designed to be used during preparation and review and long-term monitoring plans for sites where MNA has been or may be selected as part of the remedy. Performance monitoring system design depends on site conditions and site-specific remedial objectives; this document provides information on technical issues to consider during the design process. Discussions include details of issues concerning monitoring parameters, locations, and monitoring frequencies. This document does not provide details of particular methodologies for sampling, analysis, modeling, or other characterization tools.

Final Remedial Process Optimization Handbook prepared for the Air Force Center for Environmental Excellence and the Defense Logistics Agency. June 2001.
http://www.afcee.brooks.af.mil/products/rpo/rpooutreach/rl72/A_Final_RPO_Handbook.pdf

This handbook describes the general regulatory and technical framework for evaluating existing remediation systems, including a section on monitoring optimization based on the AFCEE Long-Term Monitoring Optimization Guide.

Guide to Optimal Groundwater Monitoring (Interim Final). January 2000.
http://enviro.nfesc.navy.mil/erb/erb_a/support/wrk_grp/raoltm/case_studies/Int_Final_Guide.pdf

This document, prepared for the Naval Facilities Engineering Service Center by Radian International, is the Navy LTM/RAO Working Group guidance for the optimization of groundwater monitoring programs. It is based on "lessons learned" from optimization efforts undertaken by the Navy and Marine Corps, as well as optimization evaluations performed by the Working Group. The guidance is presented in a question and answer format and includes example decision criteria, decision flow charts and diagrams, statements of work, statistical tools and more.

***Long-Term Monitoring Optimization Guide, Final Version 1.1*.** October, 1999.
http://www.afcee.brooks.af.mil/products/techtrans/PBM/downloads/ltmfiles.exe

This document was prepared to assist Department of Defense (DoD) installation managers in the optimization of their long-term monitoring (LTM) programs by identifying and applying the appropriate strategies and optimization tools. These strategies and tools should assure compliance with data quality objectives (DQOs) and quality assurance (QA) requirements to improve overall effectiveness while minimizing cost. This file expands to a series of Microsoft Word 6.0 documents, Microsoft PowerPoint slides and bitmap files.

Technical Guidance for the Long-Term Monitoring of Natural Attenuation Remedies at Department of Energy Sites**.** October 1999.
http://web.em.doe.gov/techguide/

The purpose of this guide is to provide project managers with technical direction on: the role of monitoring for effective implementation of a natural attenuation remedy; the key considerations for designing a natural attenuation monitoring network; and statistical approaches for interpreting monitoring data and refining conceptual site models.

Method for Monitoring Pump-and-Treat Performance**.** EPA/600/R-94/123, NTIS Order Number PB95-125456, 102p. June 1994.
http://cfpub.epa.gov/si/osp_sciencedisplay.cfm?dirEntryID=45536&ref_site=SI&kwords=Monitoring%20Pump%20and%20Treat%20Performance

This publication by EPA's Office of Research and Development provides guidance for monitoring the effectiveness and efficiency of pump-and-treat remediation systems, with emphasis on the "pump" part of the technology rather than chemical enhancements. The report includes sections on monitoring hydraulic containment, monitoring groundwater restoration, evaluation restoration success/closure, a case study, and references. It includes performance criteria, monitoring objective, and protocols for evaluating effectiveness of containment and restoration systems.

LTMO APPROACHES & METHODS

Loaiciga, H.A., R.J. Charbeneau, L.G. Everett, G.E. Fogg, B.F. Hobbs, and S. Rouhani. 1992. "Review of ground-water quality monitoring network design." *Journal of Hydraulic Engineering* 118(1):11-37.

Loaiciga *et al.* examined several methods of designing and optimizing monitoring networks, including qualitative techniques based primarily on hydrogeologic interpretations, and statistical methods, including simulation methods, variance-reduction methods, and probabilistic methods. They found that most of the existing methods used in designing groundwater monitoring networks make several important simplifications:

- Monitoring design decisions are made only once, at the beginning of program development, with no opportunity to modify the program as additional information is compiled and evaluated;
- Surrrogate objectives are used for cost and risk-based criteria; and
- The hydrogeologic environment is oversimplified, and the applicability in more complex and realistic settings remains unproven.

If not recognized, these shortcomings can lead to the development and implementation of a flawed monitoring program.

***Demonstration of Two Long-Term Groundwater Monitoring Optimization Methods – Report with Appendices*.** EPA-542-R-04-001B. July 2004.
http://clu-in.org/download/char/542-r-04-001b.pdf

This recent report by EPA's Office of Solid Waste and Emergency Response summarizes the results of a demonstration in which optimization techniques were used to improve the design of several long-term groundwater monitoring programs. The report discusses the results of application of the MAROS software tool and the Three-Tiered approach applied by The Parsons Corporation to the evaluation and optimization of groundwater monitoring programs at three sites (the Fort Lewis Logistics Center, Washington, the Long Prairie Groundwater Contamination Superfund Site in Minnesota, and Operable Unit D, former McClellan Air Force Base, California), and examines the overall results obtained using the two MNO approaches. The primary goals of this demonstration were to highlight current strategies for applying optimization techniques to existing LTM programs, and to assist site managers in understanding the potential benefits associated with monitoring program optimization.

***Demonstration of Two Long-Term Groundwater Monitoring Optimization Methods*.** June 2004.
http://clu-in.org/siteopt/proceedings_04/track_b/tue/04_yager_kathleen.pdf

These slides were presented at the Conference on Accelerating Site Closeout, Improving Performance, and Reducing Costs Through Optimization in Dallas, TX, and summarize the demonstration project described in the previous citation.

Minsker, B. (Editor). 2003. ***Long-Term Groundwater Monitoring-The State of the Art*.**
http://www.pubs.asce.org/HTML/water3.htm

This ASCE publication contains summary of state-of-the-art groundwater monitoring network designs and was prepared specifically for the needs of analysts and practitioners. The book includes detailed descriptions of the leading methodologies for groundwater monitoring network designs and guidance for the implementation in a variety of field conditions, as well as chapters that address: The Objectives of Long-Term Groundwater Monitoring; Data Requirements in Groundwater Monitoring Network Design; Case Studies; and Future Research and Technology Transfer Needs in Groundwater Hydrology and Hydrogeology.
Extended Book Description
http://cee.uiuc.edu/emsa/conference/AFCEE_LTM_Extended_Abstract.pdf

ADAPTIVE ENVIRONMENTAL MONITORING SYSTEM (AEMS)

Minsker, B., Groves, P., and Beckmann, B. May 2005. ***Optimizing Long-Term Monitoring at BP Sites Using Multi-Objective Optimization*.**

This paper was presented at the ASCE World Water and Environmental Resources Congress, Anchorage, AK.

http://cee.uiuc.edu/research/emsa/publications

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COST-EFFECTIVE SAMPLING

Ridley, M. N., and D. MacQueen. 2004. **"Sampling Plan Optimization: A Data Review and Sampling Frequency Evaluation Process."** *Ground Water Monitoring and Remediation*, 24(1), 74-80.

Ridley, M. and MacQueen, D. 2001. ***Cost-Effective Sampling of Groundwater Monitoring wells: A Data Review & Well Frequency Evaluation.***
http://www-erd.llnl.gov/library/JC-118909.pdf

Ridley *et al.* developed a method (the "Cost-Effective Sampling [CES] Method") for estimating the lowest-frequency (and, as a result, lowest- cost) sampling schedule for a particular sampling location which will still provide information at the level needed for making regulatory and remedial decisions. The determination of optimal sampling frequency is based on the magnitude and variability of concentrations, and on concentration trends at the sampling location. The underlying principle is that the sampling schedule at a particular location should be determined primarily by the rate of change in contaminant concentrations that have been detected at that location in the recent past -- the faster the rate of change, the more frequently sampling should be conducted.

Ridley, M.N., Johnson, V.M, and Tuckfield, R.C. April 1995. ***Cost Effective Sampling of Ground Water Monitoring Wells*.**
http://www.llnl.gov/tid/lof/documents/pdf/226247.pdf

Paper presented at HAZMACON, San Jose, CA.

Johnson V.M., Tuckfield, R.C., Ridley, M., and Anderson, R. 1996. "**Reducing the Sampling Frequency of Groundwater Monitoring Wells,"** *Environmental Science & Technology***,** Vol 30, No. 1.

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GEOSTATISTICAL TEMPORAL-SPATIAL MONITORING OPTIMIZATION ALGORITHM (GTS)

GTS overview, flowchart and decision path, and detailed description and discussion of GTS.
http://www.afcee.brooks.af.mil/products/rpo/

Cameron, K. & Hunter, P. June 2004. ***Optimizing LTM Networks with GTS: Three New Case Studies*.**

This paper was presented at Conference on Accelerating Site Closeout, Improving Performance, and Reducing Costs Through Optimization, Dallas, TX,
http://clu-in.org/siteopt/proceedings_04/track_b/tue/06_cameron_kirk.pdf

Cameron, K.M. & Hunter, P. 2003. **"Optimization of LTM networks at AF Plant 6 using GTS."** *In Situ and On-Site Bioremediation, 2003: Proceedings of the Seventh International In Situ and On-Site Bioremediation Symposium (Orlando, FL; June 2003)*. ISBN 1-57477-139-6, Columbus, OH: Battelle Press.

Cameron, K. & Hunter, P. 2002. **"Using spatial models and kriging techniques to optimize long-term ground-water monitoring networks: a case study."** *Environmetrics*, 13, 629-656.

The GTS Optimization Algorithm was applied to the evaluation and optimization of two existing monitoring programs at the Massachusetts Military Reservation (MMR), Cape Cod, Massachusetts. The results of the temporal analysis applied to the monitoring programs at MMR indicated that sampling frequency could be reduced at most locations by 40 to 70 percent. The results of the spatial analysis indicated that 109 of the 536 wells included in the two monitoring programs at MMR were spatially redundant, and could be removed from the programs. More recently, Cameron and Hunter (2004) applied the GTS algorithm to monitoring programs at three other sites, and confirmed that use of this optimization approach could generate savings ranging from 30 percent to 63 percent of monitoring costs.

Cameron, K. 2004. **"Better optimization of long-term monitoring networks."** *Bioremediation Journal*, 8 (3-4): 89-107.

This article presents examples of GTS highlighting improved methods to measure both cost and accuracy of baseline estimates, chose optimal subsets of the existing data, and flexibility and adaptability of the optimization scheme.

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MONITORING & REMEDIATION OPTIMIZATION SYSTEM (MAROS)

MAROS software homepage.
Maintained by Groundwater Services, Inc., this site includes a description of features and copies of the MAROS Software Version 2.0, and User's guide**.**
http://www.gsi-net.com/software/Maros.htm

Aziz, J.J., M. Ling, H.S. Rifai, C.J. Newell, and J.R. Gonzales**.** 2003. **"MAROS: A decision support system for optimizing monitoring plans."** *Ground Water* 41, no. 3: 355-367**.**

Wu, J. and D. Guvanasen. **Software Spotlight/MAROS: A Decision Support Tool for Improving the Cost-Effectiveness of Ground Water Monitoring Plans**
http://www.ngwa.org/publication/softspot/sf03-5.htm
This article, which appears on the National Ground Water Association (NGWA) web site, reviews the MAROS software (Beta Version 2.0), discusses what the reviewers found, what they liked, and what they did not like.

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PARSONS 3-TIERED LTMO APPROACH

Nobel, C. and J.A. Anthony. 2004. **"Three-Tiered Approach to Long Term Monitoring Program Optimization."** *Bioremediation Journal*, Vol. 8, Issue 3-4:147-165.

This paper discusses the three-tiered approach methodology, including data compilation and site screening, qualitative evaluation decision logic, temporal trend evaluation, and spatial statistical analysis, illustrated using the results of a case study site. Additionally, results of multiple applications of the three-tiered LTMO approach are summarized, and future work is discussed.

Nobel, C. June 2004. ***Three-Tiered Approach to Long Term Monitoring Optimization Workshop*.**

These slides were presented at Conference on Accelerating Site Closeout, Improving Performance, and Reducing Costs Through Optimization, Dallas, TX, June 2004

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OTHER APPROACHES

Dresel, E.P., and C. Murray. 1998. **"Groundwater monitoring network design using stochastic simulation."** *Geological Society of America Abstracts with Programs* 30(7):181**.**

Dresel and Murray used a ranking approach to assist in the design of a groundwater monitoring network at the US Department of Energy's Hanford site in Washington. A geostatistical model of existing plumes was used to generate a large number of realizations of contaminant distribution in groundwater at the facility. Analysis of the realizations provided a quantitative measure of the uncertainties in contaminant concentrations, and a measure of the probability that a cutoff value (e.g., a target remedial concentration) would be exceeded at any point. A metric based on uncertainty measures and declustering weights was developed to rank the relative value of each monitoring well in the network design. The metric was used, together with hydrogeologic and regulatory considerations, in identifying candidate locations for inclusion in or removal from the network.

Francone, F.D. and L. Deschaine. 2004. **"Extending the boundaries of design optimization by integrating fast optimization techniques with machine-code-based, linear genetic programming."** *Information Science* 161(3-4): 99-120**.**

Optimized models of complex physical systems are difficult to create and time consuming to optimize. The physical and business processes are often not well understood and are therefore difficult to model. The models are often too complex to be well optimized with available computational resources. Too often approximate, less than optimal models result. This work presents an approach to this problem that blends three well-tested components. First: Linear Genetic Programming (LGP) is applied to those portions of the system that are not well understood. Second: those portions of the system are simulated.. Finally: the resulting meta-model is optimized using Evolution Strategies (ES). ES is a fast, general-purpose optimizer that requires little pre-existing domain knowledge. Results and examples are presented where this approach can greatly improve the development and optimization of complex physical systems.

Ling, M., .S. Rifai, C.J. Newell, J.J. Aziz, and J.R. Gonzales. 2003. **"Groundwater monitoring plans at small-scale sites – an innovative spatial and temporal methodology."** *Journal of Environmental Monitoring* 5(1):126-134.

Ling *et al.* developed an innovative methodology for improving existing groundwater monitoring plans at small-scale sites. The methodology consists of three stand-alone procedures: a procedure for reducing spatial redundancy, a well-siting procedure for adding new sampling locations, and a procedure for determining optimal sampling frequency. The spatial redundancy reduction procedure was used to eliminate redundant wells through an optimization process that minimizes the errors in plume delineation and the estimation of average plume concentration. The well-siting procedure was used to locate possible new sampling points for an inadequately delineated plume *via* regression analysis of plume centerline concentrations and estimation of plume dispersivity values. The sampling frequency determination procedure was used to generate recommendations regarding the future frequency of sampling for each sampling location based on the direction, magnitude, and uncertainty of the concentration trend derived from representative historical concentration data. Although the methodology was designed for small-scale sites, it is adaptable for large-scale site applications. The methodology was applied to a small petroleum hydrocarbon-contaminated site with a network of 12 monitoring wells to demonstrate its effectiveness and validity.

Reed, P.M., B.S. Minsker, and A.J. Valocchi. 2000. **"Cost-effective long-term groundwater monitoring design using a genetic algorithm and global mass interpolation."** *Water Resources Research* 36(12):3731-3741.

A simulation approach for optimizing existing monitoring programs was developed and applied using a numerical model of groundwater flow and contaminant transport, several statistically-based plume-interpolation techniques, and a formal mathematical optimization model based on a genetic algorithm. The optimization approach was used to identify cost-effective sampling plans that were based on the assumption that the total mass of dissolved contaminant in groundwater could be accurately quantified. Application of the approach to the monitoring program at Hill AFB indicated that monitoring costs could be reduced by as much as 60 percent without significant changes in the resulting estimates of dissolved contaminant mass. Reed et al, extended this work using several different mathematical optimization algorithms to address multi-objective monitoring optimization problems (see reference below).

Reed, P.M. and B.S. Minsker. 2004. **"Striking the balance: Long term groundwater monitoring design for multiple, conflicting objectives."** *Journal of Water Resources and Planning Management* 130(2):140-149**.**

Reed, P.M., B.S. Minsker, and D.E. Goldberg. 2001. **"A multiobjective approach to cost effective long-term groundwater monitoring using an elitist nondominated sorted genetic algorithm with historical data."** *Journal of Hydroinformatics* 3:71-89.

Reed, P.M., B.S. Minsker, and D.E. Goldberg. 2003. **"Simplifying multiobjective optimization II: An automated design methodology for the nondominated sorted genetic algorithm."** *Water Resources Research* 39(7):1196**.**

Rizzo, D., D. Dougherty, and M. Yu. 2000. ***An Adaptive Long-Term Monitoring and Operations System (aLTMOs™) for Optimization in Environmental Management*.**

This paper was delivered at the *ASCE Joint Water 2000 Conference*. Rizzo, Dougherty and Yu describe aLTMOs, and integrated monitoring and operations optimization system that utilizes kriging methods, artificial neural networks and Extended Kalman filtering to assess and optimization long term monitoring network performance and cost. The paper describes the system, provides a brief methodology review of long-term monitoinrg optimization, presents a brief benefit-cost analysis, and discussess an application at an Army facility in Massachusetts.

http://www.subterra.com/downloads/ASCE2000JWC.pdf

Tuckfield, R.C., E.P. Shine, R.A. Hiergesell, M.E. Denham, S. Reboul, and C. Beardsley. 2001. ***Using Geoscience and Geostatistics to Optimize Groundwater Monitoring Networks at the Savannah River Site*.** U.S. Department of Energy Publication No. WSRC-MS-2001-00145.

The operational efficiency of groundwater monitoring networks at the U.S. Department of Energy's Savannah River Site was reviewed in order to optimize the number of groundwater wells needed for monitoring the plumes of the principal constituent of concern, trichloroethylene (TCE). A multidisciplinary approach, combining geochemistry, geohydrology, geostatistics, and regulatory knowledge were used to evaluate whether or not a well should remain on the current sampling schedule. At the conclusion of the evaluation, approximately 20 percent of the currently-sampled wells were recommended for removal from the monitoring program; and the list of analytes to be sampled and analyzed was reduced considerably.

WEB PAGES

Conference on Accelerating Site Closeout, Improving Performance, and Reducing Costs Through Optimization, Dallas, TX, June 2004.
http://clu-in.org/siteopt/ataglance.htm

This web page includes an agenda for the conference as well as links slides from several LTMO-themed presentations.

Federal Remediation Technologies Roundtable Optimization Case Study Search
http://costperformance.org/optimization/search.cfm

A searchable database of case studies of specific optimization efforts at FRTR member sites, including several LTMO case studies.

Federal Remediation Technologies Roundtable Monitoring Optimization Webpage
http://www.frtr.gov/optimization/monitoring.htm

Links to approaches for increasing efficiency, reducing cost, identifying uncertainty, and increasing reliability of long-term monitoring including data quality objectives, long-term monitoring, well placement and sampling frequency, optimized field sampling procedures, contaminants of concern and indicator parameters, and data management and data evaluation

NAVFAC Environmental Restoration and BRAC Website

http://enviro.nfesc.navy.mil/scripts/WebObjects.exe/erbweb.woa#slide_show_end

This web site is a resource for Navy Remedial Project Managers (RPMs) and other environmental professionals involved in environmental cleanup. It includes groundwater monitoring optimization resources such as a description of monitoring changes that might prompt LTMO, links to related policies, and case studies.

Navy and Marine Corps Working Group Optimizing Remedial Action Operations and Long Term Monitoring Website

http://enviro.nfesc.navy.mil/scripts/WebObjects.exe/erbweb.woa/6/wa/DisplayPage?pageShortName=RAO%2FLTMgt+Workgroup&PageID=165&wosid=PNaOWVZBAkHzJL86g56tOM

As part of the Navy's overall Installation Restoration (IR) program, the Navy and Marine Corps Working Group was formed in April 1998. The goal is to develop guidance for optimizing Remedial Action Operation (RAO) and Long Term Monitoring (LTM) phases of site cleanup projects. This site reports on their progress and has links to Navy LTM/Groundwater Monitoring Optimization Guidance and case studies.

US Air Force Center for Environmental Excellence (AFCEE) Environmental Restoration Products Page

http://www.afcee.brooks.af.mil/products/rpo/default.asp

This page provides access to the Long-Term Monitoring Optimization Guide, as well as links to the other AFCEE Environmental Restoration products including MAROS, GTS, and the RPO Handbook.

US Army Corps of Engineers Remedial System Evaluation Checklist Page

http://www.environmental.usace.army.mil/library/guide/rsechk/Envmon.pdf

USASCE Environmental Monitoring Checklist

http://www.environmental.usace.army.mil/library/guide/rsechk/Envmon.pdf

The US Army Corps of Engineers developed the Remediation System Evaluation process to assist in the holistic optimization of remedial actions. The primary tools for the process are a set of checklists, including one that addresses environmental monitoring. This checklist guides the user through a qualitative evaluation of the current monitoring program and suggests ways to optimize the program.

US Environmental Protection Agency "Clu-In" Remediation Optimization Page

http://www.cluin.org/optimization

This website is a resource for EPA optimization efforts. It provides information on optimization-related EPA demonstration projects as well as optimization-related fact sheets developed by EPA.

US Environmental Protection Agency Ground Water and Ecosystems Restoration Research Optimal Well Locator (OWL) Version 1.2

http://www.epa.gov/ada/csmos/models/owl.html

The OWL program is a simple tool to evaluate existing monitoring well networks and assist in the selection of new monitoring well locations. The program uses ground-water elevation measurements to evaluate variations in ground-water flow magnitude and direction over time and calculate corresponding plume migration paths. A simple analysis combining the potential locations of the plume and the coverage of monitoring wells at a site allows the user to evaluate whether existing monitoring wells are optimally located, and to optimize the placement of new monitoring wells to better characterize plume location and future movement. The program accomplishes these tasks using simple algorithms and typically available field data.

Office of Superfund Remediation
and Technology Innovation
(5102G)

EPA 542-R-05-003
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www.clu-in.org/optimization