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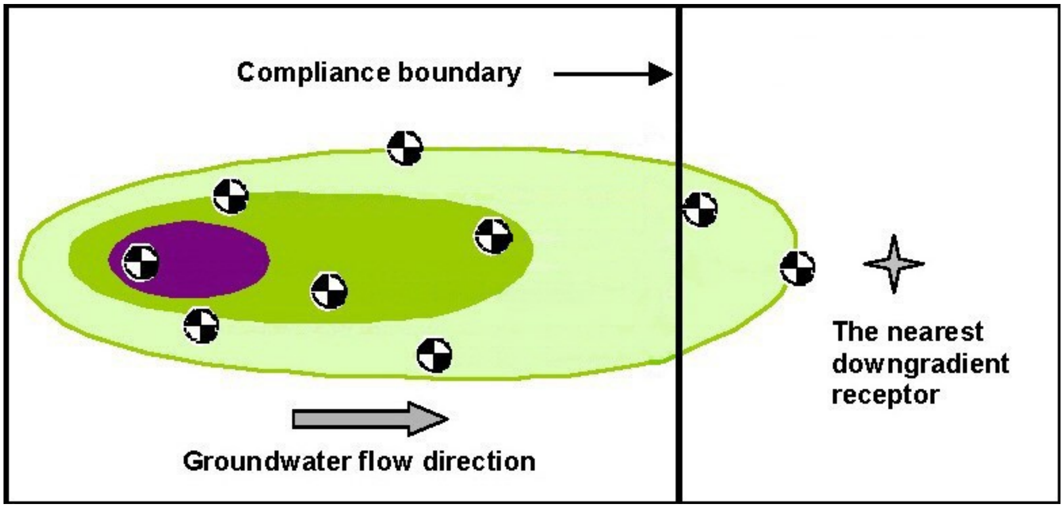
Demonstration of Two Long-Term Groundwater Monitoring Optimization Approaches

Report



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NOTICE

This report was prepared by Mitretek Systems (Mitretek) for the U.S. Environmental Protection Agency (U.S. EPA) under U.S. EPA Requisition #B4T024, QT-DC-04-000504, and summarizes the results of demonstration projects completed by The Parsons Corporation (Parsons) under Air Force Center for Environmental Excellence (AFCEE) contract (Contract No. F41624-00-D-8024, Task Order No. 0024), and by Groundwater Services, Inc. (GSI), also under an AFCEE contract (Contract No. F41624-98-C-8024). Reference to trade names, commercial products, process, or service does not constitute or imply endorsement, recommendation for use, or favoring by the United States Government or any agency thereof. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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PREFACE

This report summarizes the results of a demonstration in which optimization techniques were used to improve the design of long-term groundwater monitoring programs. Two different approaches to optimizing groundwater monitoring programs were used in the demonstration:

- The Monitoring and Remediation Optimization System (MAROS) software tool, developed by GSI for AFCEE (2000 and 2002), and
- A three-tiered approach applied by Parsons.

The report discusses the results of application of the two approaches 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, McClellan Air Force Base, California), and examines the overall results obtained using the two monitoring program optimization approaches. The primary goals of this demonstration were to highlight current strategies for applying optimization techniques to existing long-term monitoring programs, and to assist site managers in understanding the potential benefits associated with monitoring program optimization. The demonstration was conducted as part of an assessment of long-term monitoring optimization approaches, initiated by the U.S. Environmental Protection Agency's Office of Superfund Remediation and Technology Innovation (USEPA/OSRTI) and AFCEE.

ACKNOWLEDGEMENTS

This report summarizes the results of a demonstration of two different approaches to optimizing long-term groundwater monitoring programs. The demonstration projects summarized herein were completed by The Parsons Corporation (Parsons), Dr. Carolyn Nobel as principal investigator, and Groundwater Services, Inc. (GSI), Ms. Julia Aziz as principal investigator; the two teams are commended for the quality of their work, and the principal investigators are thanked for their helpful cooperation through the course of this project.

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EXECUTIVE SUMMARY

This report summarizes the results of a demonstration in which optimization techniques were used to improve the design of several long-term groundwater monitoring programs. Two different approaches to optimizing groundwater monitoring programs were applied in the demonstration:

- The Monitoring and Remediation Optimization System (MAROS) software tool, developed by Groundwater Services, Inc. (GSI) for AFCEE (2000 and 2002), and
- A three-tiered approach applied by The Parsons Corporation (Parsons).

The report discusses the results of application of the two approaches 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 long-term monitoring optimization (LTMO) approaches. The primary goals of this demonstration were to highlight current strategies for applying optimization techniques to existing long-term monitoring (LTM) programs, and to assist site managers in understanding the potential benefits associated with monitoring program optimization. The demonstration was conducted as part of an assessment of LTMO approaches, initiated by the U.S. Environmental Protection Agency's Office of Superfund Remediation and Technology Innovation (USEPA/OSRTI) and the Air Force Center for Environmental Excellence (AFCEE).

The MAROS tool is a public-domain software package that operates in conjunction with an electronic database environment (Microsoft Access® 2000) and performs certain mathematical and/or statistical functions appropriate to completing qualitative, temporal, and spatial-statistical evaluations of a groundwater monitoring program, using data that have been loaded into the database (AFCEE, 2000 and 2002). MAROS utilizes parametric temporal analyses (using linear regression) and non-parametric trend analyses (using the Mann-Kendall test for trends) to assess the statistical significance of temporal trends in concentrations of contaminants of concern (COCs). MAROS then uses the results of the temporal-trend analyses to develop recommendations regarding optimal sampling frequency at each sampling point in a monitoring program by applying a modified Cost-Effective Sampling algorithm, to assess the feasibility of reducing the frequency of sampling at individual sampling points. Although the MAROS tool primarily is used to evaluate temporal data, it also incorporates a spatial statistical algorithm, based on a ranking system that utilizes a weighted "area-of-influence" approach (implemented using Delaunay triangulation) to assess the relative value of data generated during monitoring, and to identify the optimal locations of monitoring points. Formal decision logic and methods of incorporating user-defined secondary lines of evidence (empirical or modeling results) also are provided, and can be used to further evaluate monitoring data and make recommendations for adjustments to sampling frequency, monitoring locations, and the density of the monitoring network.

In the three-tiered LTMO approach, the monitoring-program evaluation is conducted in stages to address each of the objectives and considerations of monitoring: a qualitative evaluation first is completed, followed in succession by temporal and spatial evaluations. At the conclusion of each stage (or "tier") in the evaluation, recommendations are generated regarding potential changes in the temporal frequency of monitoring, and/or whether to retain or remove each monitoring point considered in the evaluation. After all three stages have been completed, the results of all of the analyses are combined and interpreted, using a decision algorithm, to generate final recommendations for an effective and efficient LTM program.

Application of the two approaches to the optimization of LTM programs at each of the three case-study example sites generated recommendations for reductions in sampling frequency and changes in the numbers and locations of monitoring points that are sampled. Implementation of the optimization recommendations could lead to reductions ranging from only a few percent to more than 50 percent in the numbers of samples collected and analyzed annually at particular sites (Table ES.1). The median recommended reduction in the annual number of samples collected, generated during the optimization demonstration, was 39 percent. Although available information regarding monitoring-program costs at each of the three case-study example sites is not directly comparable, it is projected that depending upon the scale of the particular LTM program, and the nature of the optimization recommendations, adoption of optimized monitoring programs at each of the case-study sites could lead to annual cost savings ranging from a few hundred dollars (using the recommendations generated by MAROS for the monitoring program at Operable Unit D [OU D], former McClellan Air Force Base [AFB]) to approximately $36,500 (using the results generated by the three-tiered approach for the monitoring program at the Fort Lewis Logistics Center Area). The results of the evaluations also demonstrate that each of the optimized monitoring programs remains adequate to address the primary objectives of monitoring at the sites. Although the general characteristics of each of the three case-study example sites are similar (chlorinated solvent contaminants in groundwater, occurring at relatively shallow depth in unconsolidated sediments), the assumptions underlying the two approaches, and the procedures that are followed in conducting the evaluations are applicable to a much broader range of conditions (e.g., dissolved metals in groundwater, or contaminants in a fractured bedrock system).

Table ES.1: Summary of Results of LTMO Demonstrations

Feature of Monitoring Program	Example Site[a/]		
	Fort Lewis	**Long Prairie**	**McClellan AFB OU D**
Total number of samples (per year) in current program	180	51	34
Range[b/] of total number of samples (per year) in refined program	107 - 113	22 – 36	17 – 32
Percent reduction in number of samples collected per year	37 - 40	29 – 51	6 – 50
Projected range of cost savings[c/] (per year)	$33,500 - $36,500	$4,200 - $8,100	$300 - $2,550

[a/] Information regarding site characteristics and the site-specific monitoring programs of the three example sites is presented in Section 3 (Fort Lewis), Section 4 (Long Prairie) and Section 5 (McClellan AFB OU D), and in Appendices C and D.

[b/] Ranges of total numbers of samples collected annually in refined programs, percentage reductions in numbers of samples collected, and associated potential annual cost savings, reflect the results of the evaluations conducted using MAROS and the three-tiered approach.

[c/] Estimates of potential annual cost savings were based on information regarding monitoring program costs provided by facility personnel. Costs associated with monitoring include cost of sample collection, sample analyses, data compilation and reporting, and management of investigation-derived waste (e.g., purge water).

Prior to initiating an LTMO evaluation, it is of critical importance that the monitoring objectives of the program to be optimized be clearly articulated, with all stakeholders agreeing to the stated objectives, so that the program can be optimized in terms of recognized (and agreed-upon) objectives, using decision rules and procedures that are acceptable to all stakeholders. The decisions regarding whether to conduct an LTMO evaluation, which approach to use, and the degree of regulatory-agency involvement in the LTMO evaluation and implementation of optimization recommendations, must be made on a site-specific basis. Factors to be considered in deciding whether to proceed with an 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; and
- The potential benefits (e.g., cost savings) that could result from an optimized monitoring program.

Optimization of a monitoring program should be considered for most sites having LTM programs that are based on sampling of characterization monitoring points, or for sites where more than about 50 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, monitoring program optimization also should be undertaken periodically, rather than being regarded as a one-time event. Overall site conditions should be relatively stable, with no large changes in remediation approaches occurring or anticipated. Furthermore, successful application of either approach to the site-specific evaluation of a monitoring program is directly dependent upon the amount and quality of the available data – results from a minimum of four to six separate sampling events are necessary to support a temporal analysis, and results collected at a minimum of about six (for a MAROS evaluation) to 15 (for a three-tiered evaluation) separate monitoring points are necessary to support a spatial analysis. It also is necessary to develop an adequate conceptual site model (CSM) describing site-specific conditions prior to applying either approach. In particular, the extent of contaminants in the subsurface at the site must be adequately delineated before the monitoring program can be optimized.

Although the MAROS tool is capable of being applied by an individual with little formal statistical training, interpretation of the results generated by either approach requires a relatively sophisticated understanding of hydrogeology, statistics, and the processes governing the movement and fate of contaminants in the environment. Although many of the basic assumptions and techniques underlying both optimization approaches are similar, and both optimization approaches utilize qualitative, temporal, and spatial analyses, there are several differences between the two approaches, which can cause one optimization approach (e.g., the three-tiered approach) to generate results that are not completely consistent with the results obtained using the other approach (e.g., MAROS). Nevertheless, each approach is capable of generating sound and defensible recommendations for optimizing LTM programs.

The most significant advantage conferred by both optimization approaches is the fact that both approaches apply consistent, well-documented procedures, which incorporate formal decision logic, to the process of evaluating and optimizing groundwater monitoring programs. However, the process of data preparation, screening, processing, and evaluation can be extremely time-consuming for either approach. Both approaches could benefit from further development efforts to address current limitations; and continued development of both approaches is contemplated or in progress.

Typically, a program manager should anticipate incurring costs on the order of $6,000 to $10,000 to complete an LTMO evaluation at the level of detail of the case-study examples described in this demonstration. Consequently, an LTMO evaluation may be cost-prohibitive for smaller monitoring programs. However, an LTMO evaluation that can be used to reduce the total number of samples collected at a site by about 5 to 10 samples per annum should be cost-effective.

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LIST OF ACRONYMS AND ABBREVIATIONS

α	statistical confidence level
AFB	Air Force Base
AFCEE/ERT	Air Force Center for Environmental Excellence/Technology Transfer Division
AFRPA	Air Force Real Property Agency
AR	area ratio (calculated by MAROS)
ASCE	American Society of Civil Engineering
β	statistical power
bgs	below ground surface
BRAC	Base Realignment and Closure Act
CAH	chlorinated aliphatic hydrocarbon compound
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CES	cost-effective sampling
CFR	Code of Federal Regulations
COC	contaminant of concern
COV	coefficient of variation
CR	concentration ratio (calculated by MAROS)
CSM	conceptual site model
CT	concentration trend (calculated by MAROS)
DCA	dichloroethane
DCE	dichloroethene
DNAPL	dense, non-aqueous-phase liquid
DQO	data-quality objective
EGDY	East Gate Disposal Yard
ERPIMS	(US Air Force) Environmental Restoration Program Information Management System
ESRI	Environmental Systems Research Institute, Inc.
ETD	extraction, treatment, and discharge
EW	extraction well
FS	feasibility study
ft/day	feet per day
ft/yr	feet per year
GC	gas chromatograph
GeoEAS	Geostatistical Environmental Exposure Software
GIS	geographic information system
GWMP	Groundwater Monitoring Plan
gpm	gallon(s) per minute
GSI	Groundwater Services, Inc.
GTS	Geostatistical Temporal/Spatial optimization algorithm
GWOU	Groundwater Operable Unit
ID	identifier
IDW	investigation-derived waste
IROD	Interim Record of Decision
LOGRAM	revised Logistics Center monitoring program
LTM	long-term monitoring

LIST OF ACRONYMS AND ABBREVIATIONS (continued)

LTMO	long-term monitoring optimization
LTMP	long-term monitoring program
μg/L	microgram(s) per liter
MAROS	Monitoring and Remediation Optimization System
MCL	maximum contaminant level
Mitretek	Mitretek Systems
MMR	Massachusetts Military Reservation
MPCA	Minnesota Pollution Control Agency
MS	mass spectrometer
NPL	National Priorities List
NRC	National Research Council
O&M	operations and maintenance
ORP	oxidation-reduction potential
OU	operable unit
Parsons	The Parsons Corporation
PCE	tetrachloroethene
POL	petroleum, oils, and lubricants
QA	quality assurance
QC	quality control
RAO	remedial action objective
RCRA	Resource Conservation and Recovery Act
RI	remedial investigation
ROC	rate-of-change parameter (calculated by MAROS)
ROD	record of decision
S	Mann-Kendall test statistic
SF	slope factor (calculated by MAROS)
SVE	soil-vapor extraction
TCA	trichloroethane
TCE	trichloroethene
OSRTI	U.S. EPA’s Office of Superfund Remediation and Technology Innovation
US	United States
USACE	U.S. Army Corps of Engineers
U.S. EPA	U.S. Environmental Protection Agency
VOC	volatile organic compound

1.0 INTRODUCTION

This report describes the results of a demonstration in which optimization techniques were used to improve the design of long-term groundwater monitoring programs. The primary objectives of optimizing the particular monitoring programs addressed in this study were to assess the optimal frequency of monitoring implemented in each program, and to evaluate the spatial distribution of the components of each monitoring network. Two different long-term monitoring optimization (LTMO) approaches were used in the demonstration:

1. The Monitoring and Remediation Optimization System (MAROS) software tool, developed by Groundwater Services, Inc. (GSI) for the Air Force Center for Environmental Excellence (AFCEE) (2000 and 2002); and

2. A three-tiered approach applied by The Parsons Corporation (Parsons).

The primary goals of this demonstration were to highlight current strategies for applying optimization techniques to existing long-term monitoring (LTM) programs, and to assist site managers in understanding the potential benefits associated with monitoring program optimization. The report also presents the basic concepts underlying environmental monitoring and monitoring optimization, so that the discussion of particular procedures can be understood in terms of an overall monitoring approach. The work presented in this document was commissioned by the U.S. Environmental Protection Agency's (U.S. EPA's) Office of Superfund Remediation and Technology Innovation (OSRTI).

1.1 PROJECT DESIGN

This project was conducted to demonstrate and assess two different LTMO approaches that can be used to identify opportunities for streamlining groundwater monitoring programs. The project was designed as follows:

- Three sites having existing long-term groundwater monitoring programs were selected as case-study examples for this demonstration project. The sites were required to meet minimum screening criteria to ensure that the available monitoring data were sufficient for the LTMO evaluations (refer to Sections 3, 4, and 5, and Appendix C of this report for detailed site information).

- GSI and Parsons evaluated groundwater monitoring data from each of the three sites using their respective approaches, to assess whether the monitoring programs could be streamlined without significant loss of information. GSI and Parsons then prepared reports summarizing the results of their evaluations.

- The summary reports then were provided to Mitretek Systems (Mitretek) for review. Using those summary reports, Mitretek prepared this document, which summarizes the LTMO evaluations and examines the results.

1.2 CASE-STUDY EXAMPLES

The current LTM programs at the Fort Lewis Logistics Center, Washington (Fort Lewis), the Long Prairie Groundwater Contamination Superfund Site in Minnesota (Long Prairie), and Operable Unit (OU) D, McClellan Air Force Base (AFB), California (McClellan AFB OU D), were selected as case-study example programs, because the numbers and spatial coverage of wells, and length of the monitoring history at each site, were judged to be adequate to generate meaningful results. The primary characteristics of the monitoring programs at each of the three sites are presented in Table 1.1.

Table 1.1: Characteristics of Monitoring Programs at Three Example Sites Used in Long-Term Monitoring Program Optimization Demonstrations

Monitoring-Program Characteristic	Example Site[a/]		
	Fort Lewis	**Long Prairie**	**McClellan AFB OU D**
Number of distinct water-bearing units or monitoring zones addressed by the monitoring program	2 (Upper Vashon and Lower Vashon)	3 (water table [Zone A], base of upper glacial outwash [Zone B], lower glacial outwash [Zone C])	2 (Zones A and B)
Principal contaminants[b/]	*cis*-1,2-DCE, PCE, 1,1,1-TCA, TCE, VC	*cis*-1,2-DCE, PCE, TCE	1,2-DCA, *cis*-1,2-DCE, PCE, TCE
Total number of wells included in program	21 extraction wells 40 upper Vashon monitoring wells 11 lower Vashon monitoring wells	2 municipal supply wells 6 extraction wells 12 Zone A monitoring wells 15 Zone B monitoring wells 8 Zone C monitoring wells	6 extraction wells 32 Zone A monitoring wells 13 Zone B monitoring wells
Total number of samples collected (per year)	180	51	34
Total cost[c/] of monitoring (per year)	$90,000	$14,280	Information not provided

[a/] Information regarding site characteristics and the site-specific monitoring programs of the three example sites is presented in Section 3 (Fort Lewis), Section 4 (Long Prairie) and Section 5 (McClellan AFB OU D), and in Appendices C and D.

[b/] DCA = dichloroethane; DCE = dichloroethene; PCE = tetrachloroethene;
TCA = trichloroethane; TCE = trichloroethene; VC = vinyl chloride.

[c/] Information regarding annual monitoring program costs was provided by facility personnel. Costs associated with monitoring include cost of sample collection, sample analyses, data compilation and reporting, and management of investigation-derived waste (e.g., purge water).

1.3 PURPOSES OF GROUNDWATER MONITORING

The U.S. EPA (2004) defines monitoring to be

> *"… 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. Monitoring should not produce a 'snapshot in time' measurement, but rather should involve repeated sampling over time in order to define the trends in the parameters of interest relative to clearly-defined management objectives. Monitoring may collect abiotic and/or biotic data using well-defined methods and/or endpoints. These data, methods, and endpoints should be directly related to the management objectives for the site in question."*

Monitoring of groundwater systems has been practiced for decades. Monitoring activities have expanded significantly in recent years, to assess and address the problems associated with groundwater contamination and its environmental consequences, because the processes active within a groundwater system, and the interactions of a groundwater system with the rest of the environment, can be assessed only through monitoring (Zhou, 1996).

There are statutory requirements establishing the necessity for monitoring, and governing the types of monitoring that must be conducted under particular circumstances. Passage of the Resource Conservation and Recovery Act (RCRA) in 1976, and subsequent promulgation of the first regulations authorized under RCRA in 1980, resulted in significant expansion of the role of groundwater monitoring. RCRA and subsequent amendments include provisions for establishing groundwater monitoring programs at all of the hazardous-waste treatment, storage, and disposal facilities, at all of the solid-waste landfills, and at many underground storage tank facilities in the United States. In December 1980, the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) was passed, in part to address potential threats posed by "uncontrolled" hazardous waste sites. CERCLA statutory authority regarding monitoring gives U.S. EPA the authority to undertake monitoring to identify threats (42 USC §9604[b]), and defines removal and remedial actions as inclusive of any monitoring reasonably required to ensure that such actions protect the public health, welfare, and the environment (42 USC §9601[23] and 42 USC §9601[24], respectively). Therefore, response actions at such sites require that monitoring programs be developed and implemented to investigate the extent of environmental contamination and to monitor the progress of cleanup activities (Makeig, 1991).

Four inherently different types of groundwater monitoring programs can be distinguished (U.S. EPA, 2004):

- Characterization monitoring;
- Detection monitoring;
- Compliance monitoring; and
- Long-term monitoring.

Characterization monitoring is initiated in an area where contaminants are known or suspected to be present in environmental media (soil, air, surface water, groundwater) as a consequence of a release of hazardous substances. Site characterization involves delineating the nature, extent, and fate of potential contaminants in the environment, identifying human populations or other biota ("receptors") that could be adversely affected by exposure to those contaminants, and assessing the possibility that the contaminants could migrate to a location where a potential receptor could come into contact with the contaminant(s) ("exposure point"). Groundwater sampling is a critical element of site characterization, as it is necessary to establish whether site-related contaminants are migrating in groundwater to potential exposure points.

Detection monitoring and compliance monitoring generally are required for facilities that are regulated under RCRA. A groundwater-quality monitoring program designed for detection monitoring consists of a network of monitoring points (wells) in an uncontaminated water-bearing unit that is at risk of contamination from an overlying waste facility. If the results of periodic sampling conducted during detection monitoring indicate that a release may have occurred, the owner or operator of the facility must implement the next phase of groundwater monitoring – compliance monitoring. During compliance monitoring, groundwater samples are collected from locations designated as compliance points, and are analyzed for constituents that are known or suspected to have been released. After it has been established that a release of the type and magnitude suspected has occurred, a corrective-action program must be implemented (Makeig, 1991).

During a corrective action, the owner or operator of a facility must remove, control, and/or treat the wastes that have caused the release, so that groundwater quality can be brought into compliance with established groundwater protection criteria. (Additional characterization monitoring may be necessary during the selection of a corrective action, so that the actual extent and fate of contaminants in the subsurface can be assessed to the extent necessary to support remedy decisions.) Groundwater cleanup criteria usually are established by the individual states, or on a site-specific basis within a state. In all cases, the cleanup criteria must be as stringent as, or more stringent than, various standards established by the federal government, unless such requirements are waived. After a remedy has been selected and put in place, groundwater monitoring also is used in evaluating the degree to which the remedial measure achieves its objectives (e.g., abatement of groundwater contaminants, restoration of groundwater quality, etc.). This type of monitoring – known as LTM – typically is initiated only after a remedy has been selected and implemented, in conjunction with some type of corrective-action program. 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). 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 usually are applied only 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.

1.4 LONG-TERM GROUNDWATER MONITORING PROGRAM OPTIMIZATION

As of 1993, the National Research Council (NRC, 1993) estimated that groundwater had been contaminated at between 300,000 and 400,000 sites in the United States. As a consequence of the identification of certain technology limitations and recognition of the potentially significant costs for remediating all of these sites (approximately $500 billion to $1 trillion), the paradigm for groundwater remediation recently has shifted to some degree, from resource restoration to long-term risk management. This strategy change is expected to result in more contaminants being left in place for longer periods of time, thereby requiring long-term monitoring (NRC, 1999). At many sites, LTM can require decades of expensive sampling of monitoring networks, ranging in size from tens to hundreds of sampling locations, and resulting in costs of hundreds of thousands to millions of dollars per year for sampling and data management (Reed *et al.,* 2000). Development of cost-effective monitoring programs, or optimization of existing programs, can produce significant cost savings over the life of particular remediation projects. As a consequence of the resources required to maintain a monitoring program for a long period of time, most monitoring optimization efforts, including the monitoring optimization evaluations described in this report, have focused on LTM.

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. Monitoring program objectives are dependent upon the types of information that will be generated, and the intended uses of that information. The exact information needs of particular monitoring programs usually must be established by considering the program objectives during the planning stages or during periodic LTM program reviews. Clearly articulated program objectives will establish the end-uses of monitoring data, which in turn will clarify those data that must be collected. The connection between the data collected by monitoring and the uses to which those data are applied is an important element in the success of any water-quality monitoring program. Without carefully connecting the acquisition of data with the production and use of information contained within the data, there is a high probability that data collection will become an end in itself (Ward *et al*., 1990). 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.

Monitoring objectives fall into four general categories (U.S. EPA, 1994b and 2004; Gibbons, 1994):

- Identify changes in ambient conditions;
- Detect the movement and monitor the physico-chemical fate of environmental constituents of interest (COCs, dissolved oxygen, etc.) from one location to another;
- Demonstrate compliance with regulatory requirements; and
- Demonstrate the effectiveness of a particular response activity or action.

As is clear from the discussion in Section 1.3, the two primary objectives of long-term groundwater monitoring programs are a subset of these general objectives, and can be expressed as follow:

- 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*).

Ultimately, the relative success of any remediation system and its components (including the monitoring program) must be judged based on the degree to which they achieve their stated objectives. The most important components of a groundwater monitoring program are the network density (the number of monitoring wells and their relative locations) and the sampling frequency (the number of observations or samples per unit time) (Zhou, 1996). Designing an effective 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 relevant information (information required to effectively address the temporal and spatial objectives of monitoring) that can be obtained, while minimizing incremental costs. The efficiency of a monitoring program is considered to be optimal if it is effectively achieving its objectives at the lowest total cost, and/or with the fewest possible number of monitoring locations (Reed *et al*., 2000).

While several different LTMO methods have been developed and applied in recent years, this evaluation examines the results obtained by investigators applying two approaches in current use. The MAROS software tool, developed and applied by GSI, uses parametric and non-parametric trend analyses to assess temporal chemical concentration trends and recommend optimal sampling frequency, and also uses spatial statistical techniques to identify monitoring points that potentially are generating redundant information. The MAROS software then combines the results of the temporal trend analysis and spatial statistical analysis, and uses the combined results to generate recommendations regarding the frequency of monitoring and spatial distribution of the components of the monitoring network. Parsons has applied a three-tiered approach consisting of a qualitative evaluation, a statistical evaluation of temporal trends in contaminant concentrations, and a spatial-statistical analysis, to assess the degree to which the monitoring program addresses each of the two primary objectives of monitoring, and also to address other potentially-important considerations. The results of the three evaluations then are combined and used to assess the optimal frequency of monitoring and the spatial distribution of the various components of the monitoring network.

1.5 REPORT ORGANIZATION

The main body of this report is organized into seven sections, including this introduction:

- Concepts in groundwater monitoring and techniques for evaluating monitoring programs are discussed in Section 2; ways in which some of these techniques are implemented in the MAROS software tool and in the three-tiered approach also are described briefly.

- Background information relevant to the current groundwater monitoring programs at the Fort Lewis Logistics Center, the Long Prairie Groundwater Contamination Superfund Site, and OU D, McClellan AFB is reviewed in Sections 3, 4, and 5, respectively; and the summary results of the MAROS and three-tiered evaluations of each monitoring program are presented in those Sections.

- Section 6 examines the results of the MAROS and three-tiered evaluations of the three monitoring programs, and presents recommendations for implementing program improvements.

- References cited in this document are listed in Section 7.

Readers interested in a summary description of the demonstration project, and its results, will find this information in the main body of this report (EPA 542-R-04-001a). Readers interested in more detailed discussions can find supporting information contained in four appendices:

- ▪ Concepts and practices in groundwater monitoring, and in monitoring optimization, are discussed in detail in Appendix A.

- ▪ Features of the MAROS tool and the three-tiered LTMO approach are described in Appendix B.

- ▪ Synopses of the MAROS and three-tiered LTMO evaluations of the three monitoring programs are included in Appendix C.

- ▪ The detailed results of the MAROS and three-tiered LTMO evaluations of the three monitoring programs, as described in reports originally generated by GSI and Parsons, are presented in Appendix D.

The main body of the report, together with the appendices, comprise EPA 542-R-04-001b.

2.0 EVALUATION AND OPTIMIZATION OF LONG-TERM MONITORING PROGRAMS

2.1 CONCEPTS IN GROUNDWATER MONITORING

Designing an effective groundwater-quality monitoring program involves selecting a set of sampling sites, suite of analytes, and a sampling schedule based upon one or more monitoring-program objectives (Hudak *et al.*, 1993). An effective monitoring 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. The design of the monitoring program therefore should address existing receptor exposure pathways, as well as exposure pathways arising from potential future use of the groundwater.

The U.S. EPA (2004) 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 (a conceptual site model, or CSM).
3. Formulate monitoring decision rules.
4. Design the monitoring plan.
5. Conduct monitoring, and evaluate and characterize the results.
6. Establish the management decision.

In this paradigm, a 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. Thus, monitoring results are used to refine the CSM by tracking changes in site conditions through time. All monitoring-program activities are undertaken to support a management decision, established as an integral part of the monitoring program (e.g., assess whether a selected response action is/is not achieving its objectives).

Most past efforts in developing or evaluating monitoring programs have addressed only the design of the monitoring plan (Step 4 in the six-step process outlined above). The process of designing a groundwater monitoring plan involves four principal tasks (Franke, 1997):

1. Identify the volume and characteristics of the earth material targeted for sampling.
2. Select the target parameters and analytes, including field parameters/analytes and laboratory analytes.

3. Define the spatial and temporal sampling strategy, including the number of wells necessary to be sampled to meet program objectives, and the schedule for repetitive sampling of selected wells.

4. Select the wells to be sampled.

However, this procedure considers only the physical and chemical data that the monitoring plan is intended to generate, and does not completely take into account the objectives that the monitoring data are intended to address (Step 1, above), the decision(s) that the monitoring program is(are) intended to support (Step 6), or the means by which a decision will be selected (Step 3). All of the six steps outlined by the U.S. EPA (2004) should be considered during the development or evaluation of a monitoring program, if that program is to be effective and efficient, and also should be considered during optimization of existing programs.

Most monitoring programs have been designed and evaluated based on qualitative insight into the characteristics of the hydrologic system, and using professional judgment (Zhou, 1996). However, groundwater systems by nature are highly variable in space and through time, and it is difficult or impossible to account for much of the existing variability using qualitative techniques. More recently, other, more quantitative approaches have been developed, arising from the recognition that the results obtained from a monitoring program are used to make *inferences* about conditions in the subsurface on the basis of *samples*, and on the need to account for natural variability. The process of making inferences on the basis of samples, while simultaneously evaluating the associated variability, is the province of statistics; and to a large degree, the temporal and spatial variability of water-quality data currently are addressed through the application of statistical methods of evaluation, which enable large quantities of data to be managed and interpreted effectively, while the variability of the data also is quantified and managed (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 and anthropogenic changes (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 1.4), a monitoring-program evaluation must address the temporal and spatial characteristics of groundwater-quality data. Temporal and spatial data generally are evaluated using temporal and spatial-statistical techniques, respectively. In addition, there may be other considerations that best are addressed through qualitative evaluation.

In a qualitative evaluation, the relative performance of the monitoring program is assessed from calculations and judgments made without the use of quantitative mathematical methods (Hudak *et al*., 1993). Multiple factors may be considered qualitatively in developing recommendations for continuation or cessation of monitoring at each monitoring point. Qualitative approaches to the evaluation of a monitoring program range from relatively simple to complex, but often are highly subjective. Furthermore, the degree to which the program satisfies LTM objectives may not be readily evaluated by qualitative methods.

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. If attenuation or removal of contaminant mass is occurring in the subsurface as a consequence of natural processes or operation of an engineered remediation system, attenuation or mass removal will be apparent as a decrease in contaminant concentrations through time at a particular sampling location, as a decrease in contaminant concentrations with increasing distance from chemical source areas, and/or as a change in the suite of chemicals through time or with increasing migration distance. Conversely, if a persistent source is contributing to groundwater contaminant plumes 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.

The temporal objective of long-term monitoring (evaluate contaminant concentrations in groundwater through time; Section 1.4) can be addressed by defining trends in contaminant concentrations, by identifying periodic fluctuations in concentrations, and by estimating long-term average ("mean") values of concentrations (Zhou, 1996). The frequency of sampling necessary to achieve the temporal objective then can be based on trend detection, accuracy of estimation of periodic fluctuations, and accuracy of estimation of long-term mean concentrations. 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, Sen's (1968) non-parametric estimator of trend slope, and the Mann-Kendall test, are widely applied (Hirsch *et al.*, 1991).

Spatial techniques that can be applied to the design and evaluation of monitoring programs fall into two general categories – simulation approaches and ranking approaches (Hudak *et al.*, 1993). Simulation approaches utilize computer models to simulate the evolution of contaminant plumes. The results then are incorporated into an optimization model which derives an optimal monitoring network configuration (Reed *et al.*, 2000). Ranking approaches utilize weighting schemes that express the relative value to the monitoring program of candidate sampling sites distributed throughout a sampling domain (Hudak *et al.*, 1993). The relative value of a potential monitoring site can be ranked by assessing its spatial position relative to areas such as contaminant sources, receptor locations, or probable zones of contaminant migration. Ranking approaches commonly use geostatistical methods to assist in the design, evaluation, or optimization of a monitoring network (American Society of Civil Engineering [ASCE], 1990a and 1990b). General concepts in groundwater monitoring, and techniques used in the design/optimization of monitoring programs, are discussed further in Appendix A.

2.2 METHODS FOR DESIGNING, EVALUATING, AND OPTIMIZING MONITORING PROGRAMS

Although monitoring network design has been studied extensively in the past, most previous studies have addressed one of two problems (Reed *et al.*, 2000):

1. Application of numerical simulation and formal mathematical optimization techniques to screen monitoring plans for detection monitoring at landfills and hazardous-waste sites; or

2. Application of ranking methods, including geostatistics, to augment or design monitoring networks for site-characterization purposes.

A number of studies (Appendix A) have addressed detection monitoring by applying global approaches to the design of new monitoring networks. In contrast, few investigators have formally addressed the evaluation and optimization of LTM programs at sites having extensive monitoring networks that were installed during site characterization. The primary goal of optimization efforts at such sites is to reduce sampling costs by eliminating data redundancy to the extent possible. This type of optimization usually is not intended to identify locations for new monitoring wells, and it is assumed during optimization that the existing monitoring network sufficiently characterizes the concentrations and distribution of contaminants being monitored. It also is not intended for use in optimizing detection monitoring. Two approaches to evaluating monitoring networks – the MAROS tool and the three-tiered evaluation approach – were developed specifically for use in optimizing existing monitoring programs. (Although formal mathematical optimization techniques have been applied to the problem of optimizing monitoring programs [Appendix A], neither the MAROS tool nor the three-tiered approach incorporates mathematical optimization in the strict sense. Rather, in subsequent discussion, "optimization" refers to the application of rule-based procedures, incorporating statistical analysis and professional judgment, to identify possible improvements to a monitoring program that will continue to be effective at meeting the two objectives of monitoring while addressing qualitative constraints and minimizing the necessary incremental resources.) The principal features of these two approaches are discussed in the following sections, and are described in detail in Appendix B.

2.3 DESCRIPTION OF MAROS SOFTWARE TOOL

The MAROS software originally was developed primarily for use as a tool to assist non-technical personnel (e.g., facility environmental managers) in evaluating and optimizing long-term monitoring programs (AFCEE, 2000). As an added benefit, the MAROS tool provides a convenient platform for the organization, preliminary evaluation, and presentation of monitoring data in graphical or tabular formats. In the years since its development, the performance of the MAROS software tool has been assessed critically ("*beta* tested") by applying the tool to the evaluation and optimization of actual monitoring programs at a number of U.S. Air Force facilities (e.g., Parsons, 2000 and 2003a). In response to recommendations for modifications to the MAROS software, generated as a consequence of the *beta* testing, GSI developed MAROS Version 2, which was issued by AFCEE (2002) for additional testing in 2002. The public-domain software and accompanying documentation are available free of charge for download on the AFCEE website at http://www.afcee.brooks.af.mil/er/rpo.htm . All case-study example monitoring programs examined in the current demonstration project were evaluated and optimized using MAROS Version 2 (Sections 3.2, 4.2, and 5.2 of this report).

The MAROS tool consists of a software package that operates in conjunction with an electronic database environment (Microsoft Access® 2000) and performs certain mathematical and/or statistical functions appropriate to completing qualitative, temporal, and spatial-statistical evaluations of a monitoring program, using data that have been loaded into the database (AFCEE, 2002). MAROS utilizes parametric temporal analyses (using linear regression) and non-parametric trend analyses (using the Mann-Kendall test for trends) to assess the statistical significance of temporal trends in concentrations of contaminants of concern (COCs) (Appendix B). MAROS then uses the results of the temporal-trend analyses to develop recommendations regarding sampling frequency at each sampling point in a monitoring program by applying a modified Cost-Effective Sampling (CES) algorithm, based on the CES method developed at Lawrence Livermore National Laboratory (Ridley *et al.*, 1995). The modified CES method uses recent and historical COC measurements to determine optimal sampling frequency.

Although the MAROS tool primarily is used to evaluate temporal data, it also incorporates a spatial statistical algorithm, based on a ranking system that utilizes a weighted "area-of-influence" approach (implemented using Delaunay triangulation) to assess the relative value of data generated during monitoring, and to identify the optimal locations of monitoring points. Formal decision logic and methods of incorporating user-defined secondary lines of evidence (empirical or modeling results) also are provided, and can be used to further evaluate monitoring data and generate recommendations for adjustments to sampling frequency, monitoring locations, and the density of the monitoring network. Additional features (moment analyses) allow the user to evaluate conditions and the adequacy of the monitoring network across a contaminated site (rather than just at individual monitoring locations.)

MAROS is intended to assist users in establishing practical and cost-effective LTM goals for a specific site, by

- Identifying the COCs at the site;
- Determining whether temporal trends in groundwater COC concentration data are statistically significant;
- Using identified temporal trends to evaluate and optimize the frequency of sample collection;
- Assessing the extent to which contaminant migration is occurring, using temporal-trend and moment analyses;
- Evaluating the relative importance of each well in a monitoring network, for the purpose of identifying potentially-redundant monitoring points;
- Identifying those wells that are statistically most relevant to the current sampling program;
- Evaluating whether additional monitoring points are needed to achieve monitoring objectives;
- Providing indications of the overall performance of the site remediation approach; and
- Assessing whether the monitoring program is sufficient to achieve program objectives on local or site-wide scales.

As with any approach to LTM program optimization, successful application of the MAROS tool to the site-specific evaluation of a monitoring program is completely dependent upon the amount and quality of the available data (e.g., data requirements for a temporal trend analysis include a suggested minimum of six separate sampling events at an individual sampling point, and a spatial analysis requires sampling results from a minimum of six different sampling locations). It also is necessary to develop an adequate CSM (Section 2.1), describing site-specific conditions (e.g., direction and rate of groundwater movement, locations of contaminant sources and potential receptor exposure points) prior to applying the MAROS tool. In particular, the nature and extent of contaminants in the subsurface at the site must be adequately characterized and delineated before the monitoring program can be optimized.

MAROS is designed to accept data in any of three formats: text files in U.S. Air Force Environmental Restoration Program Information Management System (ERPIMS) format, Microsoft Access® files, or Microsoft EXCEL® files. Prior to conducting a monitoring-program evaluation, spatial and temporal data are loaded into a database, to include well identifiers (IDs), the sampling date(s) for each well, COCs, COC concentrations detected at each well sampled on each sampling date, laboratory detection limits for each COC, and any quality assurance/quality control (QA/QC) qualifiers associated with sample collection or analyses. The spatial analysis also requires that geographic coordinates (northings and eastings, referenced to some common datum) be supplied for each well.

Because MAROS can be used to evaluate the spatial and temporal characteristics of a maximum of five COCs in a single simulation, one or more COCs must be removed from data sets containing more than five COCs, or the data set must be split, so that only five COCs are included in a single simulation. MAROS is capable of evaluating a maximum of 200 monitoring points in each simulation. Prior to applying MAROS to the evaluation of a monitoring network comprising more than 200 monitoring points, those monitoring locations providing relatively little information (or information that is not compatible with the other points in the network) can be identified using qualitative methods and eliminated from the evaluation. As an alternative, a monitoring network comprising more than 200 monitoring points could be divided into subsets, each subset of the network could be evaluated using MAROS, and the results of the evaluations then could be combined to generate recommendations for the entire network.

After COCs have been identified, and the monitoring points in the network to be used in the evaluation have been selected, the MAROS evaluation and optimization of a monitoring program is completed in two stages:

- A preliminary evaluation of plume stability is completed for the monitoring network, and general recommendations for improving the monitoring program are produced; and

- More-detailed temporal and spatial evaluations then are completed for individual monitoring wells, and for the complete monitoring network.

In general, the MAROS tool is intended for use in evaluating single-layer groundwater systems having relatively simple hydrogeologic characteristics (GSI, 2003a). However, for a multi-layer groundwater system, the user could analyze those components of the monitoring network completed in individual layers, during separate evaluations.

The primary features of MAROS, and the ways in which it addresses the qualitative, temporal, and spatial aspects of environmental monitoring data, are summarized in Table 2.1. Additional details regarding the MAROS software tool, its functionality, capabilities, and methods of application, are presented in Appendix B. Details regarding specific examples of its application are presented in Appendix D.

Table 2.1: Primary Features of MAROS

Infrastructure
The MAROS tool is a public-domain software package that operates in conjunction with an electronic database environment (Microsoft™ Access® 2000) and performs certain mathematical and/or statistical functions appropriate to completing qualitative, temporal, and spatial-statistical evaluations of a monitoring program, using data that have been loaded into the database.
The MAROS software, and accompanying documentation, are available for download free of charge from the AFCEE website.
Although relatively sophisticated applications of the MAROS tool are possible, many of the steps in the evaluation are straightforward, and can be completed by a user unfamiliar with statistical concepts and practice. In such instances, the recommendations generated by application of the software should be reviewed by a more experienced individual.

Table 2.1: Primary Features of MAROS

Qualitative Evaluation
Qualitative information is used to make preliminary recommendations for the entire monitoring program rather than for individual wells. Qualitative considerations also may be applied to develop recommendations regarding sampling frequency at various stages throughout the evaluation, depending upon whether the available data are sufficient to be used reliably by the MAROS statistical tools.
Temporal Evaluation
MAROS includes a linear-regression analysis and a Mann-Kendall test to determine whether COC concentrations at a particular well display a statistically-significant temporal trend. MAROS also calculates the coefficient of variation (COV) for each statistical test, for use in evaluating whether COC concentrations displaying no trend at a particular well have a large degree of "scatter" or can be considered "Stable."
MAROS requires the results of a minimum of six sampling events to complete a temporal analysis at an individual well.
MAROS uses the results of the temporal-trend analyses to develop recommendations regarding optimal sampling frequency at each sampling location, by applying a modified CES algorithm.
MAROS uses the results of moment analyses to assess the overall stability of a plume, and can perform a data-sufficiency analysis, to assess whether RAOs have been/are being achieved at individual wells and at designated compliance points.
MAROS assigns the value of the reporting limit (or some fraction thereof) to samples having a constituent concentration below the reporting limit.
Spatial Evaluation
MAROS uses an inverse-distance weighting algorithm to estimate the concentrations of COCs at individual monitoring locations.
MAROS uses a "slope factor", calculated based on the standardized difference between the measured and estimated concentrations at a particular location, together with the average concentration ratio and area ratio, to determine the relative value of information obtained at individual monitoring points.
MAROS requires sampling results from a minimum of six different sampling locations to complete a spatial analysis.
The spatial-evaluation algorithm implemented in MAROS can be used to assess the spatial distribution of multiple COCs simultaneously.
Overall
MAROS uses the results of the temporal evaluation to generate recommendations regarding monitoring frequency, and uses the results of the spatial evaluation to identify potentially redundant monitoring points. Qualitative information is considered only during the preliminary evaluation of the monitoring program. A MAROS evaluation can be conducted using a maximum of five constituents.
A monitoring program evaluation completed using MAROS may cost in the range of $6,000 to $10,000, depending upon the size of the monitoring program.

2.4 DESCRIPTION OF THREE-TIERED APPROACH

As described by Parsons (2003b, 2003c, and 2003d), a three-tiered LTMO evaluation is conducted in stages to address each of the objectives and considerations of monitoring: a qualitative evaluation first is completed, followed in succession by temporal and spatial evaluations. At the conclusion of each stage (or "tier") in the evaluation, recommendations are generated regarding potential changes in the temporal frequency of monitoring, and/or whether to retain or remove each monitoring point considered in the evaluation. After all three stages of evaluation have been completed, the results of all of the analyses are combined and interpreted, using a decision algorithm, to generate final recommendations for an effective and efficient LTM program.

In the qualitative evaluation, the primary elements of the monitoring program (numbers and locations of wells, frequency of sample collection, analytes specified in the program) are examined, in the context of site-specific conditions, to ensure that the program is capable of generating appropriate and sufficient information regarding plume migration and changes in chemical concentrations through time. Criteria used in the qualitative evaluation are discussed in detail in Appendix B, and examples of application of these criteria are presented in the detailed case-history examples (Appendices D-1, D-2, and D-3). In the temporal evaluation, the historical monitoring data for every sampling point in the monitoring program are examined for temporal trends in COC concentrations, using the Mann-Kendall test (Appendices A and B).

After the Mann-Kendall test for trends has been completed for all COCs at all monitoring points, the spatial distribution of temporal trends in COC concentrations is used to evaluate the relative value of information obtained from periodic monitoring at each monitoring well by considering the location of the well within (or outside of) the horizontal extent of the contaminant plume, the location of the well with respect to potential receptor exposure points, and the presence or absence of temporal trends in contaminant concentrations in samples collected from the well. In the third stage of the three-tiered evaluation, spatial statistical techniques are used to assess the relative value of information (in the spatial sense) generated by sampling at each monitoring point in the network. COC concentration data collected during a single sampling event are used to identify those areas having the greatest uncertainty associated with the estimated extent and concentrations of COCs in groundwater. At the conclusion of the spatial-statistical evaluations, each well is ranked, from those providing the least information to those providing the most information, based on the amount of information the well contributed toward describing the spatial distribution of the COC being examined. Wells providing the least amount of information represent possible candidates for removal from the monitoring program, while wells providing the greatest amount of information represent sampling points that probably should be retained in any refined version of the monitoring program.

At each stage in the three-tiered evaluation, monitoring points that provide relatively greater amounts of information regarding the occurrence and distribution of COCs in groundwater are identified, and are distinguished from those monitoring points that provided relatively lesser amounts of information. After all three stages have been completed, the results of the three stages are combined to generate a refined monitoring program that potentially can provide information sufficient to address the primary objectives of monitoring at the site, at reduced cost.

The qualitative evaluation can be completed by a competent hydrogeologist. The temporal evaluation can be completed using commercially-available statistical software packages having the capability of using non-parametric methods (e.g., the Mann-Kendall test) to examine time-series data for trends. The spatial-statistical evaluation can be completed by a user familiar with geostatistical concepts, and having access to a standard geostatistical software package (e.g., the Geostatistical Environmental

Exposure Software [GeoEAS; Englund and Sparks, 1992], GSLIB [Deutsch and Journel, 1998] or similar package). In practice, data manipulation, temporal and spatial analyses, and graphical presentation of results are simplified, and the quality of the results is enhanced, if a commercially available geographic information system (GIS) software package (e.g., ArcView® GIS) (Environmental Systems Research Institute, Inc. [ESRI], 2001) with spatial-statistical capabilities (e.g., Geostatistical Analyst™, an extension to the ArcView® GIS software package) is utilized in the LTMO evaluation.

As with the MAROS tool, the site-specific evaluation of a monitoring program using the three-tiered approach is directly dependent upon the amount and quality of the available data. The primary features of the three-tiered approach, and the ways in which it addresses the qualitative, temporal, and spatial aspects of environmental monitoring data, are summarized in Table 2.2. Additional details regarding the three-tiered approach, its functionality, capabilities, and methods of application, are presented in Appendix B. Details regarding specific examples of its application are presented in Appendix D.

Table 2.2: Primary Features of Three-Tiered LTMO Approach

Infrastructure
A three-tiered LTMO evaluation is conducted in stages to address each of the objectives and considerations of monitoring: a qualitative evaluation first is completed, followed in succession by temporal and spatial evaluations. At the conclusion of each stage (or "tier") in the evaluation, recommendations are generated to retain or remove each monitoring point considered in the evaluation. After all three stages have been completed, the results of all of the analyses are combined and interpreted, using a decision algorithm, to generate final recommendations for an effective and efficient LTM program.
No software is required for the qualitative evaluation. The temporal evaluation can be completed using commercially-available statistical software packages having the capability of using non-parametric methods to examine time-series data for trends. The spatial-statistical evaluation can be completed using a standard geostatistical software package. Data manipulation, temporal and spatial analyses, and graphical presentation of results are simplified, and the quality of the results is enhanced, if a commercially-available GIS software package with spatial-statistical capabilities is used.
Completion of the qualitative evaluation requires a competent hydrogeologist and an adequate CSM. The temporal and spatial-statistical evaluations require a user familiar with non-parametric statistical and geostatistical concepts, having access to appropriate software.
Qualitative Evaluation
Qualitative information is evaluated to determine optimal sampling frequency and removal/inclusion of each well in the monitoring program based on all historical monitoring results.
Temporal Evaluation
The three-tiered temporal statistical analysis includes classifications for wells at which a particular COC has never been detected at a concentration greater than the reporting limit ("Not Detected") and for wells at which a particular COC consistently has been detected at concentrations less than the practical quantitation limit ("< PQL").
The three-tiered approach requires the results of a minimum of four sampling events (if seasonal effects are not present) to complete a temporal analysis at an individual well.

Table 2.2: Primary Features of Three-Tiered LTMO Approach

Temporal Evaluation (continued)
The three-tiered approach uses the results of the temporal evaluation to develop recommendations regarding sampling frequency, and to identify wells to be retained in or removed from the program. The approach uses a formal decision framework to develop these recommendations.
The three-tiered approach uses the results of the temporal evaluation to assess trends only at individual monitoring points.
The three-tiered approach assumes that monitoring points having historical results with “No Trend” are of limited value, while MAROS treats a monitoring point having “No Trend” in COC concentrations similar to a monitoring point having an “Increasing Trend” in concentrations.
Spatial Evaluation
The three-tiered approach applies geostatistics to estimate the spatial distribution of COCs. Application of this procedure depends upon the development of an appropriate semi-variogram.
The three-tiered approach uses changes in the median kriging error generated during different realizations to rank the relative value of information obtained at individual monitoring points. The relative ranking (from “Provides Most Information” to “Provides Least Information”) is used to develop recommendations regarding which wells should be retained in or removed from the monitoring program.
The three-tiered approach requires sampling results from a minimum of 15 different sampling locations to complete a spatial analysis.
Currently, only a single “indicator COC” (typically, the COC that has been detected at the greatest number of separate monitoring locations) is used in the three-tiered spatial evaluation.
Overall
The three-tiered approach combines the results of the qualitative, temporal, and spatial evaluations to generate overall recommendations regarding optimal sampling frequency and number of monitoring points in a monitoring program. Although the spatial evaluation stage is restricted to a single constituent, the qualitative and temporal stages of the evaluation can be applied to an unlimited number of constituents.
A monitoring program evaluation completed using the three-tiered approach may cost in the range of \$6,000 to \$10,000, depending upon the size of the monitoring program.

2.5 CASE-STUDY EXAMPLES

The MAROS tool and the three-tiered approach each were applied to the evaluation and optimization of existing groundwater monitoring programs at three different sites – the Logistics Center at Fort Lewis, Washington, the Long Prairie Groundwater Contamination Superfund Site in Minnesota, and OU D at the former McClellan AFB, California. Pertinent features of the groundwater monitoring programs for each site, and the results of the MAROS evaluation and the three-tiered evaluation of the monitoring program at each site, are summarized in the following sections.

3.0 SUMMARY OF DEMONSTRATIONS AT LOGISTICS CENTER AREA, FORT LEWIS, WASHINGTON

An overview of features pertinent to the groundwater monitoring program at the Logistics Center area, Fort Lewis, Washington is provided in this section, together with a summary of the results of the LTMO demonstrations. The features of the site, and of the monitoring-program evaluations that were completed using the MAROS tool and the three-tiered approach, are summarized in Appendix C, and are described in detail in Appendix D-1.

3.1 FEATURES OF FORT LEWIS LOGISTICS CENTER

The Fort Lewis Military Reservation is located near the southern end of Puget Sound in Pierce County, Washington, approximately 11 miles south of Tacoma and 17 miles northeast of Olympia. The Logistics Center occupies approximately 650 acres of the Fort Lewis Military Reservation. Process wastes were disposed of at several on- and off-installation locations, including the East Gate Disposal Yard (EGDY), located southeast of the Logistics Center. Between 1946 and 1960, waste solvents (primarily trichloroethene [TCE]) and petroleum, oils, and lubricants (POL) generated during cleaning, degreasing, and maintenance operations were disposed of in trenches at the EGDY, resulting in the introduction of contaminants to soils and groundwater at and downgradient from this former landfill. The dissolved chlorinated solvent plume that originates at the EDGY extends downgradient across the entire width of the Logistics Center, and beyond the northwestern facility boundary to the southeastern shore of American Lake (Figure 3.1). The program that was developed to monitor the concentrations and extent of contaminants in groundwater in the vicinity of, and downgradient from the EDGY, and to assess the performance of remedial systems installed to address contaminants in groundwater, was the subject of the MAROS and three-tiered evaluations (Appendices C and D).

TCE has been identified as the primary COC in groundwater beneath the Logistics Center, based on its widespread detection in wells across the site. Other COCs in groundwater include *cis*-1,2-dichloroethene (DCE), tetrachloroethene (PCE), 1,1,1-trichloroethane (TCA), and vinyl chloride (VC). TCE, DCE, and TCA have been detected consistently in many wells, while PCE and VC have been detected only sporadically, in a few wells. The former waste-disposal trenches at the EGDY are the apparent source of these chlorinated aliphatic hydrocarbon compounds (CAHs) in groundwater beneath and downgradient from the Logistics Center.

Beginning in December 1995, groundwater monitoring was conducted at the Logistics Center on a quarterly basis. Under the monitoring program, 38 monitoring wells and 21 groundwater extraction wells were sampled, resulting in 236 primary samples per year (59 wells each sampled four times per year) (Appendices C and D). The primary objectives of the monitoring program, as expressed in the monitoring plan, are to confirm that the groundwater extraction systems are preventing the continued migration of contaminants in groundwater to downgradient locations, to evaluate potential reductions in contaminant concentrations through time, to assess temporal changes in the lateral and vertical extent of contaminants in groundwater, and to assess the rate of removal of contaminant mass from the subsurface.

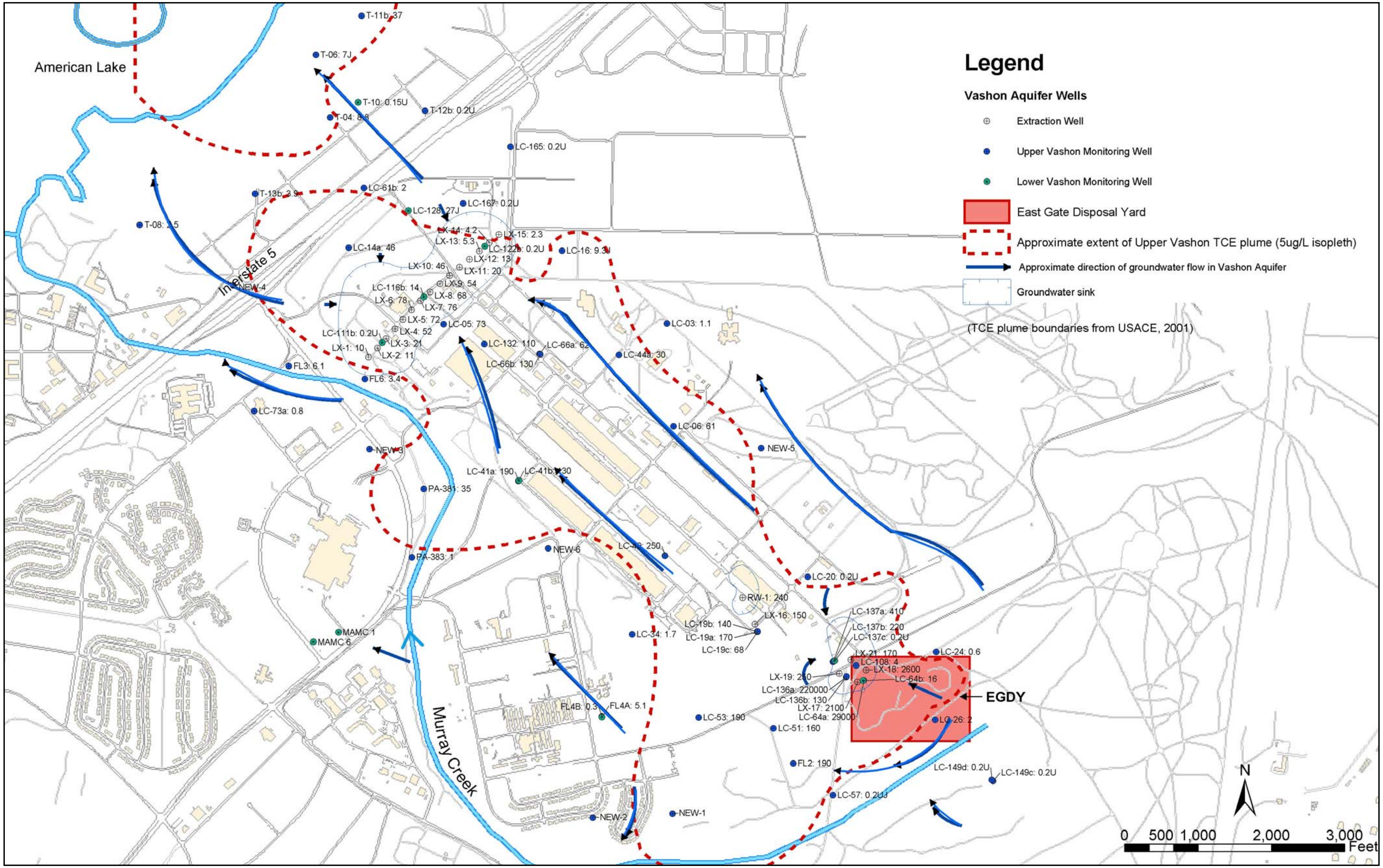


Figure 3.1: Features of Fort Lewis Logistics Center Area (after Parsons, 2003b)

Two distinct monitoring zones are recognized in the groundwater system beneath the Logistics Center area. Most groundwater monitoring wells are completed in the upper monitoring zone (the "Upper Vashon" zone); relatively few monitoring wells are completed in the lower monitoring zone (the "Lower Vashon" zone). An LTMO evaluation of the groundwater extraction system and associated monitoring network at the Logistics Center was completed by the Fort Lewis project team in May 2001 (Appendices C and D); the refined monitoring program generated as a result of this evaluation is known as the LOGRAM program. Based on the results of the LOGRAM LTMO evaluation, 24 monitoring wells were added to the Logistics Center monitoring program, and 11 previously sampled monitoring wells were removed from the program (a net increase of 13 monitoring wells); sampling frequencies generally were reduced. The revised Logistics Center monitoring program (LOGRAM), which was initiated in December 2001, includes 72 wells -- 51 monitoring wells (29 wells sampled quarterly, 3 wells sampled semi-annually, and 19 wells sampled annually), and 21 extraction wells (6 wells sampled quarterly and 15 wells sampled annually). The reduction in sampling frequency at a number of wells produced a net reduction in the total number of primary samples collected and analyzed per year, from 236 samples to 180 samples. All samples from the monitoring and extraction wells are analyzed for volatile organic compounds (VOCs) using U.S. EPA Method SW8260B.

3.2 RESULTS OF LTMO EVALUATION COMPLETED USING MAROS TOOL

Because extensive historical data were not available for the new wells installed during implementation of the current LOGRAM monitoring program, the MAROS tool was used to evaluate data from the 59 wells that remained in the monitoring program in September 2001 (21 extraction wells and 38 groundwater monitoring wells; Appendix C) included in the original monitoring program, and was not used to evaluate the LOGRAM program. The detailed results of the MAROS evaluation of the groundwater monitoring program at the Fort Lewis Logistics Center area are presented in Appendices C (Section C1.5) and D-1, and are summarized in this subsection.

Prior to the evaluation, five wells that potentially would provide "redundant" information were identified on the basis of qualitative considerations (Appendices C and D-1); these were not included in the moment analysis or in the spatial evaluation. Historic monitoring results from all monitoring and extraction wells were included in the temporal evaluation. However, results from groundwater extraction wells were not used in the spatial evaluation; and the results from two monitoring wells completed in the lower part of the Lower Vashon subunit also were excluded from the spatial evaluation, because these two wells were considered to be within a different monitoring zone than the other monitoring wells (Appendix D-1).

Application of the Mann-Kendall and linear-regression temporal trend evaluation methods (Appendices B and C) indicated that the extent and concentrations of TCE in groundwater at the Logistics Center source area (the EGDY) probably are decreasing (GSI, 2003a). TCE concentrations in groundwater at most of the extraction wells located northwest of the EGDY source area also are probably decreasing. The results of the moment analysis indicated that the location of the center of mass of the plume has remained essentially unchanged, and that the extent of TCE in groundwater has decreased over time, providing further evidence that the plume is stable under current conditions. The evaluation of overall plume stability indicated that the extent of TCE in groundwater is stable or decreasing, resulting in the recommendation that a monitoring strategy appropriate for a "*Moderate*" design category be adopted (Appendices C and D).

The results of detailed spatial analyses using the Delaunay method (Appendices C and D) indicated that 8 monitoring wells could be removed from the original monitoring program (which included 38 monitoring wells) without significant loss of information. However, the accompanying well-sufficiency analysis indicated that there is a high degree of uncertainty in predicted TCE concentrations in six areas within the network where the available historical sampling information may be inadequate; new monitoring wells were recommended for installation in these six areas (GSI, 2003a). These six locations recommended for installation of new wells correspond to six wells that had been installed and were being monitored in conjunction with the LOGRAM program (Appendix C). All groundwater extraction wells were recommended for retention in the refined monitoring program. The results of the sampling-frequency optimization analysis completed using MAROS (Appendices C and D) indicated that most wells in the monitoring network could be sampled less frequently than in the current (LOGRAM) monitoring program. The results of the data-sufficiency evaluation, completed using power-analysis methods, indicated that RAO concentrations of TCE in groundwater have nearly been achieved at the compliance boundary.

The optimized monitoring program generated using the MAROS tool includes 57 wells, with 19 sampled quarterly, 2 sampled semiannually, 30 sampled annually, and 6 sampled biennially (Appendices C and D). Adoption of the optimized program would result in collection and analysis of 113 samples per year, as compared with collection and analysis of 180 samples per year in the current LOGRAM monitoring program (Table 3.1) and 236 samples per year in the original sampling program. Implementing these recommendations could lead to a 37-percent reduction in the number of samples collected and analyzed annually, as compared with the current LOGRAM program, or a 52-percent reduction in the number of samples collected and analyzed, as compared with the original program (Table 3.1). Assuming a cost per sample of $500 for collection and chemical analyses (based on information provided by the U.S. Army Corps of Engineers [USACE, 2001]), adoption of the monitoring program as optimized using the MAROS tool is projected to result in savings of approximately $33,500 per year as compared with the LOGRAM program (Table 3.1). (The estimated cost per sample is based on information provided by facility personnel in conjunction with efforts to estimate potential cost savings resulting from optimization of the monitoring program, and includes costs associated with sample collection and analysis, data compilation and reporting, and handling of materials generated as investigation-derived waste [IDW] during sample collection [e.g., purge water].) The optimized program remains adequate to delineate the extent of TCE in groundwater, and to monitor changes in the plume over time (GSI, 2003a).

3.3 RESULTS OF LTMO EVALUATION COMPLETED USING THREE-TIERED APPROACH

The three-tiered approach was used to evaluate the original monitoring program at the Logistics Center area (which included 59 wells), and also was used to evaluate the current LOGRAM program (which includes 72 wells). Because extensive historical data were not available for the new wells included in the LOGRAM program, temporal analyses were not used in evaluating the new LOGRAM wells – only qualitative and spatial evaluations of that program were completed for these wells, and as a consequence, the results of evaluation of the two programs are not directly comparable. The detailed results of the three-tiered evaluation of the groundwater monitoring programs at the Fort Lewis Logistics Center area are presented in Appendices C (Section C1.6) and D (Appendix D-1), and are summarized in this subsection.

Table 3.1: Results of Optimization Demonstrations at Logistics Center Area Fort Lewis, Washington

Monitoring-Program Feature	Monitoring Program[a/]			
	Original (prior to December 2001)	Current (LOGRAM, after December 2001)	Original Refined using MAROS	Refined using 3-Tiered Approach
Wells sampled quarterly	59	35	19	16
Wells sampled semi-annually	--	3	2	7
Wells sampled annually	--	34	30	16
Wells sampled biennially	--	--	6	14
Wells sampled every 3 years	--	---	--	15
Total wells included in LTM program	59	72	57	69
Total number of samples (per year)	236	180	113	107
Annual cost[b/] of LTM program	$118,000	$90,000	$56,500	$53,500

[a/] Details regarding site characteristics and the site-specific monitoring programs at the Logistics Center area, Fort Lewis, Washington, are presented in Appendices C and D-1.

[b/] Information regarding annual monitoring program costs was provided by facility personnel. Costs associated with monitoring include cost of sample collection, sample analyses, data compilation and reporting, and management of investigation-derived waste (e.g., purge water).

The primary COCs (TCE, PCE, *cis*-1,2-DCE, and VC) were considered in the qualitative and temporal stages of the three-tiered evaluation; however, because TCE has been the most frequently detected COC in groundwater at the Fort Lewis Logistics Center area, the spatial-statistical stage of the three-tiered evaluation of the monitoring program used only the results of analyses for TCE in groundwater samples. Furthermore, because the Upper Vashon and Lower Vashon subunits are considered to be separate monitoring zones (Section 3.1), and the results of only a single water-bearing unit or monitoring zone can be considered in the spatial-statistical evaluation, the spatial-statistical evaluation was conducted using the sampling results from those monitoring wells completed in the Upper Vashon subunit only. Sampling results from groundwater extraction wells were not used in the spatial-statistical evaluation; however, sampling results from all wells (groundwater extraction wells, and groundwater monitoring wells completed in the Upper Vashon and Lower Vashon subunits) were used in the qualitative and temporal evaluations.

The results of the three-tiered evaluation indicated that 6 of the 72 existing wells could be removed from the LOGRAM groundwater LTM program with little loss of information (Parsons, 2003b), but also indicated that 2 existing wells that are not currently sampled should be included in the program, and that one new well should be installed and monitored. A refined monitoring program (Appendices C and D), consisting of 69 wells, with 16 wells sampled quarterly, 7 wells sampled semi-annually, 17 wells sampled annually, 14 wells sampled biennially, and 15 of the extraction wells sampled every 3 years (Table 3.1), would be adequate to address the two primary objectives of monitoring. If this refined monitoring program were adopted, 107 samples per year would be collected and analyzed, as compared with the collection and analysis of 180 samples per year in the current LOGRAM monitoring program and 236 samples per year in the original sampling program. This would represent a 40-percent reduction in the number of samples collected and analyzed annually, as compared with the LOGRAM program, or a 55-percent reduction in the number of samples collected and analyzed, as compared with the original program. Assuming a cost per sample of $500 for collection and chemical analyses, adoption of the monitoring program as optimized using the three-tiered approach is projected to result in savings of approximately $36,500 per year as compared with the LOGRAM program, or $64,500 per year as compared with the original monitoring program (Table 3.1). Additional cost savings potentially could be realized if groundwater samples collected from select wells (e.g., upgradient wells, and wells along the lateral plume margins) were analyzed for a short list of halogenated VOCs using U.S. EPA Method SW8021B instead of U.S. EPA Method SW8260B (Parsons, 2003b).

4.0 SUMMARY OF DEMONSTRATIONS AT LONG PRAIRIE GROUNDWATER CONTAMINATION SUPERFUND SITE, MINNESOTA

An overview of features pertinent to the groundwater monitoring program at the Long Prairie Groundwater Contamination Superfund Site, Minnesota (Long Prairie site) is provided in this section, together with a summary of the results of the LTMO demonstrations. The features of the site, and of the monitoring-program evaluations that were completed using the MAROS tool and the three-tiered approach, are summarized in Appendix C, and are described in detail in Appendix D-2.

4.1 FEATURES OF LONG PRAIRIE SITE

The town of Long Prairie, Minnesota is a small farming community located on the east bank of the Long Prairie River in central Minnesota. The Long Prairie site comprises a 0.16-acre source area of contaminated soil that has generated a plume of dissolved CAHs in the drinking-water aquifer underlying the north-central part of town. The source of contaminants in groundwater was a dry-cleaning establishment, which operated from 1949 through 1984 in the town's commercial district. Spent dry-cleaning solvents, primarily PCE, were discharged into the subsurface via a french drain. The subsequent migration of contaminants through the vadose zone to groundwater produced a dissolved CAH plume that has migrated to the north a distance of at least 3,600 feet from the source area, extending beneath a residential neighborhood and to within 500 feet of the Long Prairie River.

The plume of contaminated groundwater currently is being addressed by extraction of CAH-contaminated groundwater via nine extraction wells, treatment of the extracted water, and discharge of treated water to the Long Prairie River. The performance of the groundwater extraction system is monitored by means of periodic sampling of monitoring wells and water-supply wells, and routine operations and maintenance (O&M) monitoring of the extraction and treatment systems. The program that was established to monitor the concentrations and extent of contaminants in groundwater in the vicinity of, and downgradient from the PCE source area, and to assess the performance of the OU1 groundwater extraction, treatment, and discharge (ETD) system, was the subject of the MAROS and three-tiered evaluations (Appendices C and D).

PCE and its daughter products TCE and *cis*-1,2-DCE are the primary COCs at the Long Prairie site, and have been detected through a volume of groundwater about 1,000 feet wide, which extended (in October 2002) from the source area, approximately 3,200 feet downgradient to the northwest (Figure 4.1). VC also has been detected in groundwater samples, although at few locations and at lower concentrations than other CAHs.

Groundwater conditions are monitored periodically at the Long Prairie site, to evaluate whether the groundwater ETD system is effectively preventing the continued migration of CAH contaminants in groundwater to downgradient locations, and to confirm that contaminants are not migrating to the water-supply wells of the municipality of Long Prairie. Several of the monitoring locations include wells installed in clusters, with each well in a cluster completed at a different depth. Groundwater monitoring wells, extraction wells, and municipal water-supply wells are included in the monitoring program. A total of 44 wells in the Long Prairie area were sampled during the most recent

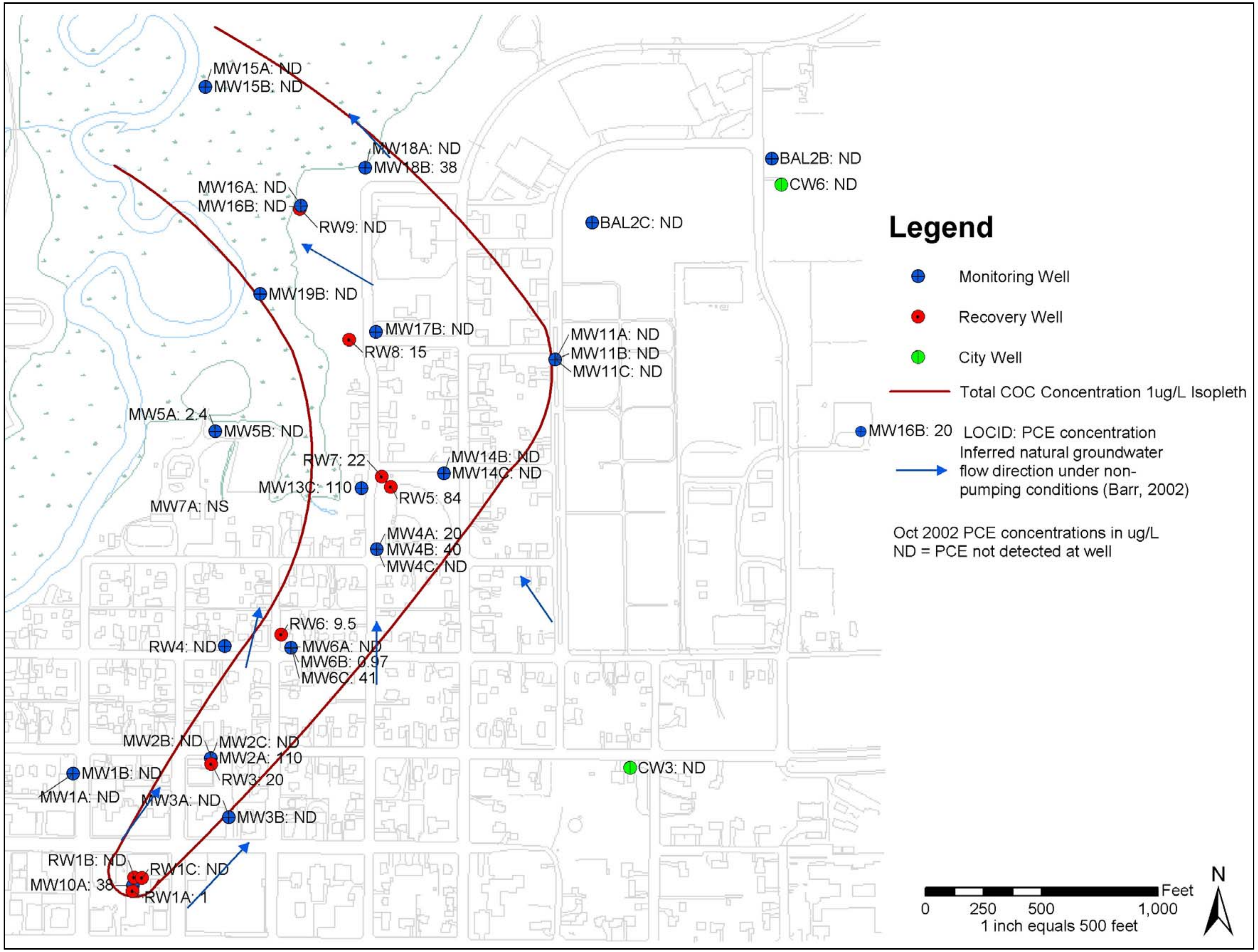


Figure 4.1: Features of Long Prairie Groundwater Contamination Superfund Site (after Parsons, 2003c)

monitoring event (October 2002) for which sampling results are available. Approximately one-half of the wells sampled during October 2002 are sampled routinely in conjunction with the groundwater monitoring program. The "current" (2002) 27-well monitoring program at the Long Prairie site includes the 18 monitoring wells, 6 active groundwater extraction wells, and one inactive extraction well sampled during scheduled monitoring events in 2000 and 2001, together with two nearby municipal-supply wells (Appendices C and D). All samples from the monitoring and extraction wells are analyzed for VOCs using U.S. EPA Method SW8021B.

4.2 RESULTS OF LTMO EVALUATION COMPLETED USING MAROS TOOL

The detailed results of the MAROS evaluation of the groundwater monitoring program at the Long Prairie site are presented in Appendix C (Section C2.6) and D (Appendix D-2), and are summarized in this subsection.

Application of the Mann-Kendall and linear-regression temporal trend evaluation methods (Appendices B and C) indicated that the extent and concentrations of PCE in groundwater at the Long Prairie source area probably are decreasing (GSI, 2003b). PCE concentrations in groundwater at 24 of 27 wells downgradient of the source area also are probably decreasing under current conditions. The results of the moment analysis indicated that the mass of PCE in groundwater is relatively stable, and that although the location of the center of mass of the plume has moved downgradient over time, the extent of PCE in groundwater has decreased through time. Overall, the results of trend analyses and moment analyses indicated that the extent of PCE in groundwater is stable or decreasing, resulting in a recommendation that a monitoring strategy appropriate for a "*Moderate*" design category be adopted (Appendices C and D).

Seventeen of the 44 wells in the existing monitoring network were included in the detailed spatial analysis (Appendices C and D); the results indicated that none of the 17 wells evaluated was redundant. Other wells in the monitoring network were examined qualitatively; and the results of qualitative considerations (GSI, 2003b) indicated that nine monitoring wells could be removed from the monitoring network without significant loss of information. Using similar qualitative analyses, three extraction wells in the source area were identified as candidates for removal from service, because concentrations of COCs in effluent from these wells historically have been below reporting limits (GSI, 2003b). However, six wells that currently are not routinely sampled were recommended for inclusion in the monitoring program. These changes in the monitoring network were projected to have a negligible effect on the degree of characterization of the extent of PCE in groundwater. The accompanying well-sufficiency analysis indicated that there is only a moderate degree of uncertainty in predicted PCE concentrations throughout the network, so that no new monitoring wells were recommended for installation (GSI, 2003b). The results of the sampling-frequency optimization analysis completed using MAROS (Appendices C and D) indicated that most wells in the monitoring network could be sampled less frequently than in the current monitoring program. The results of the data-sufficiency evaluation, completed using power-analysis methods (Appendices B and C) suggest that the monitoring program is adequate to evaluate the extent of PCE in groundwater relative to compliance points through time (GSI, 2003b).

The optimized monitoring program generated using the MAROS tool includes 32 wells, with 10 monitoring wells and 5 extraction wells sampled annually, and 13 monitoring wells, two extraction wells, and two municipal wells sampled biennially (Appendices C and D). Adoption of the optimized program would result in collection and analysis of 22 samples per year, as compared with collection and analysis of 51 samples per year in the current monitoring program (Table 4.1). Implementing these recommendations could lead to a 51-percent reduction in the number of samples collected and analyzed annually, as compared with the current program. Assuming a cost per sample in the range of \$100 to \$280 for collection and chemical analyses, adoption of the monitoring program as optimized using the MAROS tool is projected to result in savings ranging from approximately \$2,900 to \$8,120 per year. (The estimated range of costs per sample is based on information provided by facility personnel in conjunction with efforts to estimate potential cost savings resulting from optimization of the monitoring program, and includes costs associated with sample collection and analysis, data compilation and reporting, and handling of IDW [e.g., purge water].) The optimized program remains adequate to delineate the extent of COCs in groundwater, and to monitor changes in the plume over time (GSI, 2003b).

Table 4.1: Results of Optimization Demonstrations at Long Prairie Groundwater Contamination Superfund Site, Minnesota

Monitoring-Program Feature	Monitoring Program[a/] Actual (October 2002)	Refined using MAROS	Refined using 3-Tiered Approach
Wells sampled quarterly	8	--	2
Wells sampled semi-annually	--	--	6
Wells sampled annually	19	16	14
Wells sampled biennially	--	16	4
Total wells included in LTM program	27	32	26
Total number of samples (per year)	51	22	36
Annual cost[b/] of LTM program	\$14,280	\$6,160	\$10,080

[a/] Details regarding site characteristics and the site-specific monitoring programs at the Long Prairie Groundwater Contamination Superfund Site are presented in Appendices C and D-2.

[b/] Information regarding annual monitoring program costs was provided by facility personnel. The cost of monitoring is assumed to be \$280 dollars per sample; costs associated with monitoring include cost of sample collection, sample analyses, data compilation and reporting, and management of investigation-derived waste (e.g., purge water).

4.3 RESULTS OF LTMO EVALUATION COMPLETED USING THREE-TIERED APPROACH

The detailed results of the three-tiered evaluation of the groundwater monitoring program at the Long Prairie site are presented in Appendices C (Section C2.6) and D (Appendix D-2), and are summarized in this subsection.

The results of the three-tiered evaluation indicated that 18 of the 44 existing wells could be removed from the groundwater monitoring network with little loss of information (Parsons, 2003c). The results further suggested that the current monitoring program (18 monitoring wells, 6 active extraction wells, one inactive extraction well, and 2 municipal water-supply wells included in the 2002 sampling program) could be further refined by removing 4 of the 27 wells now in the LTM program, and adding three wells not currently included in the program. If this refined monitoring program, consisting of 26 wells (2 wells to be sampled quarterly, 6 wells to be sampled semi-annually, 14 wells to be sampled annually, and 4 wells to be sampled biennially) were adopted, an average of 36 samples per year would be collected and analyzed, as compared with the collection and analysis of 51 samples per year in the current (2001/2002) monitoring program (Table 4.1) – a reduction of about 29 percent. Assuming a cost per sample ranging from \$100 to \$280 for collection and chemical analyses, adoption of the monitoring program as optimized using the three-tiered approach is projected to result in savings ranging from about $1,500 per year to about $4,200 per year (Table 4.1), as compared with the current program (Parsons, 2003c).

5.0 SUMMARY OF DEMONSTRATIONS AT McCLELLAN AFB OU D, CALIFORNIA

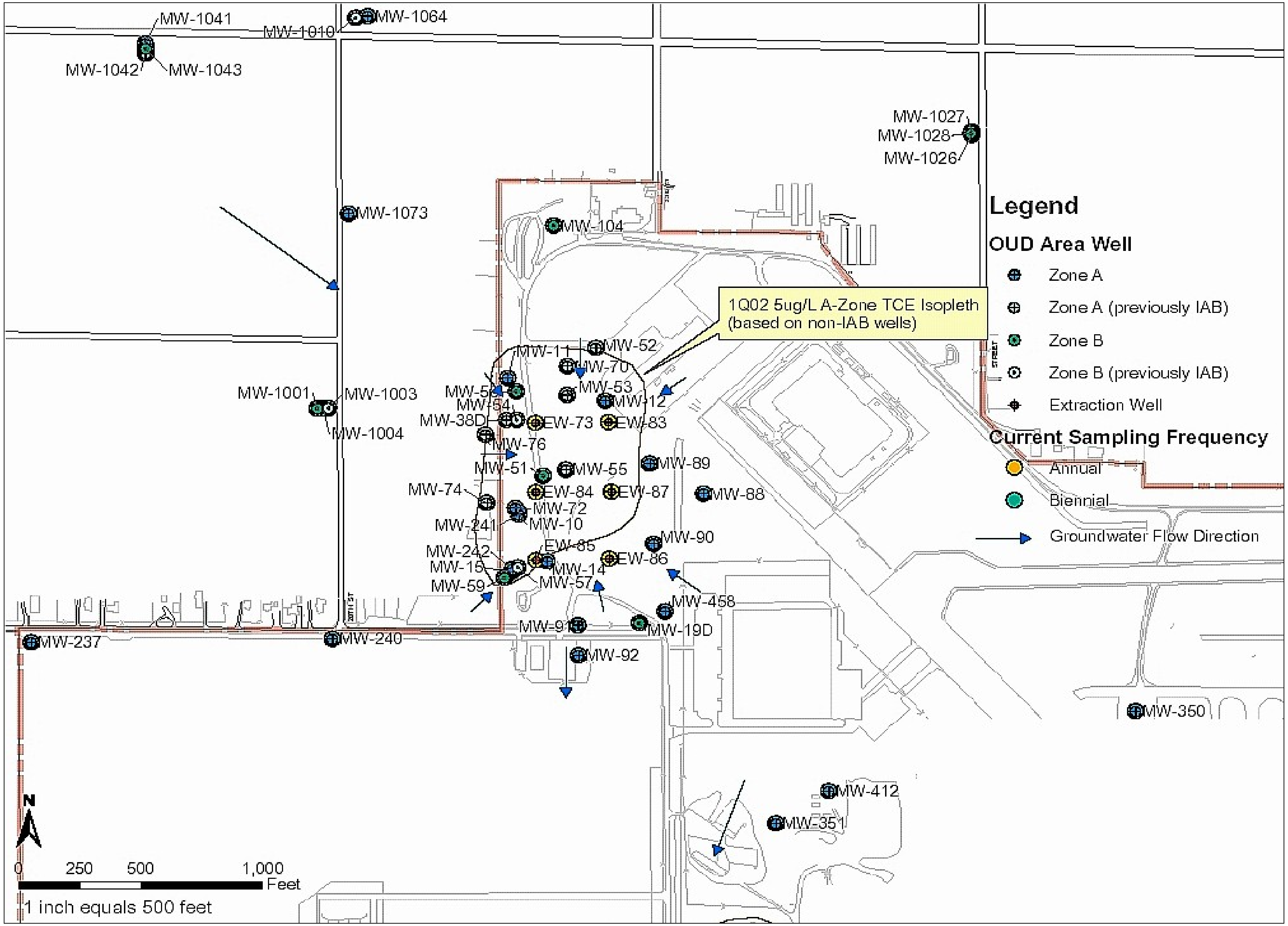
An overview of features pertinent to the groundwater monitoring program at OU D, McClellan AFB, California, is provided in this section, together with a summary of the results of the LTMO demonstrations. The features of the site, and of the monitoring-program evaluations that were completed using the MAROS tool and the three-tiered approach, are summarized in Appendix C, and are described in detail in Appendix D-3.

5.1 FEATURES OF MCCLELLAN AFB OU D

The former McClellan AFB is located approximately 7 miles northeast of downtown Sacramento, California, and covers approximately 3,000 acres. OU D consists of contaminated groundwater beneath and downgradient from contaminant source areas in the northwestern part of McClellan AFB, and occupies approximately 192 acres. Through most of its operational history, McClellan AFB was engaged in a wide variety of military/industrial operations involving the use, storage, and disposal of hazardous materials, including industrial solvents, caustic cleaners, electroplating chemicals, metals, polychlorinated biphenyls, low-level radioactive wastes, and a variety of fuel oils and lubricants.

The COCs in groundwater targeted by the current LTM program at OU D are exclusively CAHs, including PCE, TCE, *cis*-1,2-DCE, and 1,2-dichloroethane (DCA), with 1,1-DCA, 1,1-DCE, 1,1,1-TCA, and VC also detected, but at lower concentrations and/or lower frequencies. Dissolved CAHs originating at sources near former disposal areas at OU D have migrated with regional groundwater flow to the south and southwest, and historically extended off-base, to the west of OU D. Currently, VOCs (primarily TCE) are present in groundwater primarily in the central and southwestern parts of OU D (Figure 5.1). The remediation systems currently operating to address CAH contaminants in groundwater at OU D include a groundwater ETD system, and the associated monitoring network.

In accordance with the requirements of the basewide groundwater monitoring plan, wells in the OU D area are sampled during the first quarter of each year. In the OU D area, groundwater sampling is conducted to monitor areas where dissolved VOC concentrations exceed their respective maximum contaminant levels (MCLs) in monitoring zones A and B. Groundwater monitoring data also are used to evaluate contaminant mass-removal rates. Because the extent of COCs in groundwater at OU D is relatively well defined, and COCs appear to be contained by the groundwater extraction system, the wells associated with the OU D plume are sampled relatively infrequently (annually or biennially). Currently, 22 of the 32 wells that monitor the upper part (Zone A) of the groundwater system at OU D are sampled biennially, and 10 are sampled annually. Twelve of the 13 wells that monitor a deeper part (Zone B) of the groundwater system are sampled biennially, and the remaining well is sampled annually. The six extraction wells (EWs) are sampled annually. Historically, however, the sampling schedule for wells at OU D was irregular, so that some monitoring wells at OU D have been sampled as few as five times through the historic monitoring from the monitoring and extraction wells are analyzed for VOCs by U.S. EPA Method SW8260B.



1Q02 5ug/L A-Zone TCE Isopleth (based on non-IAB wells)

Figure 5.1: Features of McClellan AFB OU D (after Parsons, 2003d)

5.2 RESULTS OF LTMO EVALUATION COMPLETED USING MAROS TOOL

The detailed results of the MAROS evaluation of the groundwater monitoring program at McClellan AFB OU D are presented in Appendices C (Section C3.5) and D-3, and are summarized in this subsection.

Application of the Mann-Kendall and linear-regression temporal trend evaluation methods (Appendices B and C) indicated that the extent and concentrations of TCE in groundwater at the OU D source area probably are decreasing (GSI, 2003c). However, the absence of identifiable trends in TCE concentrations at many locations downgradient of the plume may be a consequence of less-frequent sampling in these areas than occurs near the OU D source area (GSI, 2003c). The results of the moment analysis indicated that the mass of TCE in groundwater is relatively stable, with occasional fluctuations suggesting increases or decreases in TCE mass. The location of the center of mass of the plume also appears to be relatively stable, with periodic temporal fluctuations in concentrations tending to cause the center of TCE mass to appear to move in the upgradient or downgradient directions. The lateral extent of TCE in groundwater has been variable, suggesting that TCE concentrations in wells used to evaluate conditions over large, off-axis areas of the plume have varied considerably through time, or that the wells have not been sampled consistently enough for a clear trend in TCE concentrations to emerge. Temporal fluctuations in the apparent mass of TCE in groundwater (calculated using the zeroth moment), the center of mass of TCE (calculated using the first moment), and the lateral extent of TCE (calculated using the second moment) likely are due to long-term variability in locations sampled, resulting from an inconsistent monitoring program through time (GSI, 2003c). The evaluation of overall plume stability indicated that the extent of TCE in groundwater at OU D is stable or slightly decreasing, resulting in a recommendation that a monitoring strategy appropriate for a "*Moderate*" design category be adopted (Appendices C and D).

The results of the detailed spatial analysis, supplemented with a qualitative evaluation (Appendices C and D), identified five monitoring wells as candidates for removal from the monitoring network. Removal of the recommended five wells would result in an 11 percent reduction in the number of wells in the monitoring network, with negligible effect on the degree of characterization of the extent of TCE in groundwater. The possibility of removing additional monitoring wells on the periphery of OU D also was examined qualitatively, and it was concluded (GSI, 2003c) that the decision to stop sampling the periphery wells should be made in accordance with non-statistical considerations, including regulatory requirements, community concerns, and/or public health issues. Non-statistical considerations may indicate that continued sampling of the periphery wells is warranted. The accompanying well-sufficiency analysis indicated that there is only a low to moderate degree of uncertainty in predicted TCE concentrations throughout the network, so that no new monitoring wells were recommended for installation (GSI, 2003c). In nearly all instances, the results of the sampling-frequency optimization analyses at McClellan AFB OU D were adversely affected by the lack of consistent temporal monitoring data (Appendices C and D). Accordingly, all recommendations generated by MAROS were examined qualitatively, after the temporal statistical evaluations had been completed, to generate recommendations regarding sampling frequency (GSI, 2003c). The results of the data-sufficiency evaluation, completed using power-analysis methods, indicate that the monitoring program is more than sufficient to evaluate the extent of TCE in groundwater relative to the compliance boundary through time, assuming continued operation of the extraction system (GSI, 2003c).

The optimized monitoring program generated using the MAROS tool includes 29 A-zone wells, 11 B-zone wells, and 6 groundwater extraction wells, with 11 monitoring wells and 6 extraction wells sampled annually, and 29 monitoring wells sampled biennially (Appendices C and D). Adoption of the optimized program would result in collection and analysis of 32 samples per year, as compared with collection and analysis of 34 samples per year in the current monitoring program (Table 5.1). Implementing these recommendations could lead to an approximately 6-percent reduction in the number of samples collected and analyzed annually, as compared with the current program. Adoption of the monitoring program as optimized using the MAROS tool is projected (GSI, 2003c) to result in savings of approximately $300 per year (Table 5.1). (Estimated annual cost savings were provided by facility personnel; however, specific information regarding the estimated annual cost of the LTM program at McClellan AFB OU D, and the total cost per sample is not available; and the means used to derive the estimated cost savings are uncertain.) The optimized program remains adequate to delineate the extent of COCs in groundwater, and to monitor changes in the condition of the plume over time (GSI, 2003c).

Table 5.1: Results of Optimization Demonstrations at McClellan AFB OU D, California

	Monitoring Program[a/]		
Monitoring-Program Feature	**Actual (October 2002)**	**Refined using MAROS**	**Refined using 3-Tiered Approach**
Wells sampled annually	17	17	13
Wells sampled biennially	34	29	8
Total wells in LTM program	51	46	21
Total number of samples (per year)	34	32	17
Annual cost[b/] of LTM program	--	--[c/]	--[c/]

[a/] Details regarding site characteristics and the site-specific monitoring programs at McClellan AFB OU D are presented in Appendices C and D-3.

[b/] No information regarding annual monitoring program costs was provided by facility personnel.

[c/] Total costs associated with refined monitoring programs cannot be estimated; no information available.

5.3 SUMMARY OF LTMO EVALUATION COMPLETED USING THREE-TIERED APPROACH

The detailed results of the three-tiered evaluation of the groundwater monitoring program at McClellan AFB OU D are presented in Appendices C (Section C3.6) and D (Appendix D-3), and are summarized in this subsection.

The results of the three-tiered evaluation (Parsons, 2003d) indicated that 30 of the 51 existing wells could be removed from the groundwater monitoring program with comparatively little loss of information (Parsons, 2003d). Most of the wells recommended for removal from the monitoring program are wells peripheral to the OU D plume, which also were identified as possible candidates for removal during the MAROS evaluation. If this refined monitoring program (Appendices C and D), consisting of 21 wells (13 wells to be sampled annually, and 8 wells to be sampled biennially) were adopted, an average of 17 samples per year would be collected and analyzed, as compared with the collection and analysis of 34 samples per year in the current monitoring program – a reduction of 50 percent in the number of samples collected and analyzed annually, as compared with the current program. Although information regarding the annual costs associated with the LTM program at McClellan AFB OU D including the estimated total cost per sample is not available, based on analytical costs alone, and assuming a cost per sample of $150 for chemical analyses (analyses for VOCs only), adoption of the monitoring program as optimized using the three-tiered approach is projected to result in savings of about $2,550 per year as compared with the current program

(Parsons, 2003d). Additional cost savings could be realized if groundwater samples collected from select wells (e.g., upgradient wells, and wells along the lateral plume margins) were analyzed for a short list of halogenated VOCs using U.S. EPA Method SW8021B instead of U.S. EPA Method SW8260B (Parsons, 2003d).

6.0 CONCLUSIONS AND RECOMMENDATIONS

A software tool (MAROS) developed for AFCEE, and a three-tiered approach applied by Parsons, were used to evaluate and optimize groundwater monitoring programs at the Fort Lewis Logistics Center, Washington, the Long Prairie Groundwater Contamination Superfund Site in Minnesota, and OU D, McClellan AFB, California. Although many of the basic assumptions and techniques underlying both optimization approaches are similar, and both approaches utilize qualitative, temporal, and spatial analyses, there are several differences in the details of implementation in the two approaches, which can cause one optimization approach (e.g., the three-tiered approach) to generate results that are not completely consistent with the results obtained using the other approach (e.g., MAROS). As a consequence of structural differences in approaches to the evaluation and optimization of monitoring programs, the results generated by <u>any</u> 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.

6.1 SUMMARY OF RESULTS OF MAROS EVALUATIONS AND THREE-TIERED APPROACH

The results of the MAROS optimization and three-tiered evaluation of the monitoring program at the Fort Lewis Logistics Center are summarized in Table 6.1. “Final” recommendations for the entire program could be developed by considering together the results of the three-tiered evaluation and of the MAROS evaluation for each well. Example composite recommendations are provided in Column 5 of Table 6.1.

Table 6.1: Summary of Optimization of Groundwater Monitoring Program at Fort Lewis Logistics Center Area[a/]

Well ID	Current[b/] Sampling Frequency	Recommendations Generated Using MAROS Tool	Recommendations Generated Using Three-Tiered Approach	Example Composite[c/] Recommendations
Monitoring Wells Completed in Upper Vashon Subunit				
FL2 (new[d/])	Annual	Not Considered[e/]	Annual	Annual
FL3 (new)	Quarterly	Quarterly	Remove[f/]	Quarterly
FL4B (new)	Quarterly	Not Considered	Biennial	Biennial
FL6 (new)	Quarterly	Not Considered	Biennial	Biennial
LC-03	Quarterly	Annual	Biennial	Annual
LC-05	Annual	Quarterly	Remove	Annual
LC-06	Semi-Annual	Quarterly	Annual	Semi-Annual
LC-14a	Annual	Annual	Annual	Annual
LC-16 (new)	Quarterly	Quarterly	Remove	Quarterly
LC-19a	Quarterly	Annual	Annual	Annual
LC-19b	--[g/]	Remove	Remove	Remove
LC-19c	--	Remove	Remove	Remove
LC-20 (new)	Quarterly	Quarterly	Biennial	Quarterly
LC-24 (new)	Quarterly	Not Considered	Biennial	Biennial

Table 6.1: Summary of Optimization of Groundwater Monitoring Program at Fort Lewis Logistics Center Area

Well ID	Current Sampling Frequency	Recommendations Generated Using MAROS Tool	Recommendations Generated Using Three-Tiered Approach	Example Composite Recommendations
Monitoring Wells Completed in Upper Vashon Subunit (continued)				
LC-26	Annual	Annual	Remove	Annual
LC-34 (new)	Quarterly	Not Considered	Biennial	Biennial
LC-41a	Annual	Quarterly	Annual	Annual
LC-44a	--	Remove	Remove	Remove
LC-49	Annual	Semi-Annual	Annual	Annual
LC-51	--	Remove	Remove	Remove
LC-53	Annual	Quarterly	Annual	Annual
LC-57 (new)	Quarterly	Not Considered	Biennial	Biennial
LC-61b (new)	Quarterly	Not Considered	Semi-Annual	Semi-Annual
LC-64a	Quarterly	Quarterly	Quarterly	Quarterly
LC-66a	--	Remove	Remove	Remove
LC-66b	Annual	Annual	Annual	Annual
LC-73a	--	Biennial	Remove	Remove
LC-108	--	Annual	Remove	Remove
LC-132	--	Quarterly	Annual	Annual
LC-136a	Quarterly	Quarterly	Quarterly	Quarterly
LC-136b	Annual	Remove	Annual	Annual
LC-137a	--	Remove	Remove	Remove
LC-137b	Quarterly	Quarterly	Remove	Quarterly
LC-149c	Annual	Biennial	Biennial	Biennial
LC-149d	--	Remove	Biennial	Biennial
LC-165	--	Biennial	Remove	Biennial
LC-167 (new)	Quarterly	Quarterly	Semi-Annual	Quarterly
LC-180	**Proposed for installation using 3-tiered approach**[h/]		Annual	Annual
NEW-1 (new)	Quarterly	Not Considered	Quarterly	Quarterly
NEW-2 (new)	Quarterly	Not Considered	Quarterly	Quarterly
NEW-3 (new)	Quarterly	Quarterly	Quarterly	Quarterly
NEW-4 (new)	Quarterly	Not Considered	Quarterly	Quarterly
NEW-5 (new)	Quarterly	Quarterly	Quarterly	Quarterly
NEW-6 (new)	Quarterly	Not Considered	Quarterly	Quarterly
PA-381	Annual	Annual	Biennial	Annual
PA-383	Annual	Biennial	Biennial	Biennial
T-04	Annual	Annual	Annual	Annual
T-06 (new)	Quarterly	Not Considered	Quarterly	Quarterly
T-08	Semi-Annual	Annual	Semi-Annual	Semi-Annual
T-11b (new)	Quarterly	Not Considered	Quarterly	Quarterly
T-12b	Quarterly	Annual	Biennial	Biennial
T-13b	Semi-Annual	Annual	Semi-Annual	Semi-Annual

Table 6.1: Summary of Optimization of Groundwater Monitoring Program at Fort Lewis Logistics Center Area

Well ID	Current Sampling Frequency	Recommendations Generated Using MAROS Tool	Recommendations Generated Using Three-Tiered Approach	Example Composite Recommendations
Monitoring Wells Completed in Lower Vashon Subunit				
FL4a (new)	Quarterly	Not Considered	Biennial	Biennial
LC-41b (new)	Quarterly	Not Considered	Annual	Annual
LC-64b	Annual	Annual	Annual	Annual
LC-111b	Annual	Biennial	Biennial	Biennial
LC-116b	Annual	Semi-Annual	Annual	Annual
LC-122b	Annual	Biennial	Remove	Biennial
LC-128	Annual	Annual	Annual	Annual
LC-137c	Annual	Annual	Annual	Annual
MAMC 1	Quarterly	Not Considered	Quarterly	Quarterly
MAMC 6 (new)	Quarterly	Not Considered	Quarterly	Quarterly
T-10 (new)	Quarterly	Not Considered	Semi-Annual	Semi-Annual
Groundwater Extraction Wells				
LX-1	Annual	Annual	Every 3 years	Annual
LX-2	Annual	Annual	Every 3 years	Annual
LX-3	Annual	Annual	Every 3 years	Annual
LX-4	Annual	Annual	Every 3 years	Annual
LX-5	Annual	Annual	Every 3 years	Annual
LX-6	Annual	Annual	Every 3 years	Annual
LX-7	Annual	Annual	Every 3 years	Annual
LX-8	Annual	Annual	Every 3 years	Annual
LX-9	Annual	Annual	Every 3 years	Annual
LX-10	Annual	Annual	Every 3 years	Annual
LX-11	Annual	Annual	Every 3 years	Annual
LX-12	Annual	Annual	Every 3 years	Annual
LX-13	Annual	Annual	Every 3 years	Annual
LX-14	Annual	Annual	Every 3 years	Annual
LX-15	Annual	Annual	Every 3 years	Annual
LX-16	Quarterly	Quarterly	Semi-Annual	Quarterly
LX-17	Quarterly	Quarterly	Quarterly	Quarterly
LX-18	Quarterly	Quarterly	Quarterly	Quarterly
LX-19	Quarterly	Quarterly	Quarterly	Quarterly
LX-21	Quarterly	Annual	Quarterly	Quarterly
RW-1	Quarterly	Quarterly	Semi-Annual	Quarterly

[a/] Information from GSI (2003a) and Parsons (2003b).

[b/] “Current” monitoring program was initiated in December 2001 (Section 3.1).

[c/] “Composite” recommendations generated considering the current monitoring program, and recommendations generated by MAROS tool and three-tiered approach.

[d/] “new” = the well was not included in the monitoring program prior to December 2001.

[e/] “Not Considered” = the well was not included in the MAROS evaluation.

[f/] “Remove” indicates that the well is recommended for removal from the monitoring program.

[g/] A dash (--) indicates that the well is not included in the current or refined monitoring program.

[h/] “Proposed for installation” indicates that a location for an additional monitoring well was identified on the basis of the evaluation.

A well was not selected for removal from the program in the example "composite" recommendations, unless that well was recommended for removal in both the MAROS and three-tiered evaluations, or unless that well was recommended for removal in one of the evaluations, and was not included in the monitoring program that was initiated in December 2001. The frequency of sampling provided in the "composite" recommendations was the frequency of sampling specified in the recommendations generated in the MAROS and three-tiered evaluations, if those recommendations were in agreement. If the frequencies recommended in the MAROS and three-tiered evaluations did not agree, but one of the recommended frequencies was the same as the current sampling frequency, the current sampling frequency was retained in the example "composite" recommendations. If the frequency of sampling at a particular well, specified in the recommendations generated in the three-tiered evaluation, did not agree with the frequency of sampling at that well in the current monitoring program, and the MAROS evaluation did not consider that well, the frequency of sampling recommended in the three-tiered evaluation was specified in the "composite" recommendations. If none of the current, and recommended, sampling frequencies were in agreement, the intermediate sampling frequency was specified in the "composite" recommendations. This example represents a "conservative" approach to LTMO for the program at the Fort Lewis Logistics Center area, because it considers recommendations generated using two different approaches, in addition to giving weight to currently-accepted monitoring practice at the site, by also considering the current monitoring program. Adoption of the example "composite" monitoring program would result in removal of eight wells from the current monitoring program at the Fort Lewis Logistics Center area, together with adjustment of the frequency of sampling to less-frequent events at most locations. Of course, more aggressive approaches to a "composite" optimization scheme also could be applied.

The results of the MAROS optimization and the three-tiered evaluation, including recommendations for removal of wells and adjustments to sampling frequency, were fully consistent for approximately 40 percent of the wells in the Fort Lewis Logistics Center monitoring program. (Wells that MAROS did not consider are not included in this comparison.)

The results of the three-tiered evaluation and MAROS optimization of the monitoring program at the Long Prairie Groundwater Contamination Superfund Site are summarized in Table 6.2. Example composite recommendations also are provided in Column 5 of Table 6.2.

Table 6.2: Summary of Optimization of Groundwater Monitoring Program at Long Prairie Groundwater Contamination Superfund Site[a]

Well ID	Current[b] Sampling Frequency	Recommendations Generated Using MAROS Tool	Recommendations Generated Using Three-Tiered Approach	Example Composite[c] Recommendations
Monitoring Wells				
BAL2B	--[d]	Biennial	Remove[e]	Remove
BAL2C	--	Biennial	Remove	Remove
MW1A	--	Remove	Remove	Remove
MW1B	--	Biennial	Remove	Remove
MW2A	Annual	Remove	Remove	Remove
MW2B	Annual	Annual	Annual	Annual
MW2C	Annual	Annual	Remove	Annual
MW3A	--	Remove	Remove	Remove
MW3B	--	Biennial	Remove	Remove

Table 6.2: Summary of Optimization of Groundwater Monitoring Program at Long Prairie Groundwater Contamination Superfund Site

Well ID	Current Sampling Frequency	Recommendations Generated Using MAROS Tool	Recommendations Generated Using Three-Tiered Approach	Example Composite Recommendations
Monitoring Wells (continued)				
MW4A	--	Remove	Remove	Remove
MW4B	Annual	Annual	Annual	Annual
MW4C	Annual	Annual	Annual	Annual
MW5A	--	Remove	Remove	Remove
MW5B	--	Biennial	Annual	Biennial
MW6A	Annual	Remove	Remove	Remove
MW6B	Annual	Annual	Annual	Annual
MW6C	Annual	Annual	Annual	Annual
MW10A	Annual	Annual	Annual	Annual
MW11A	--	Remove	Remove	Remove
MW11B	Annual	Biennial	Biennial	Biennial
MW11C	Annual	Biennial	Biennial	Biennial
MW13C	--	Biennial	Biennial	Biennial
MW14B	Annual	Annual	Annual	Annual
MW14C	Annual	Biennial	Biennial	Biennial
MW15A	Annual	Biennial	Biennial	Biennial
MW15B	Annual	Biennial	Biennial	Biennial
MW16A	--	Remove	Remove	Remove
MW16B	Annual	Annual	Annual	Annual
MW17B	Annual	Annual	Annual	Annual
MW18A	--	Remove	Remove	Remove
MW18B	--	Biennial	Biennial	Biennial
MW19B	Annual	Biennial	Biennial	Biennial
Groundwater Extraction Wells				
RW1A	--	Remove	Remove	Remove
RW1B	--	Remove	Remove	Remove
RW1C	--	Remove	Remove	Remove
RW3	Quarterly	Annual	Annual	Annual
RW4	Annual	Biennial	Biennial	Biennial
RW5	Quarterly	Annual	Annual	Annual
RW6	Quarterly	Annual	Annual	Annual
RW7	Quarterly	Annual	Annual	Annual
RW8	Quarterly	Annual	Annual	Annual
RW9	Quarterly	Biennial	Biennial	Biennial
RW7	Quarterly	Annual	Annual	Annual
RW8	Quarterly	Annual	Annual	Annual
RW9	Quarterly	Biennial	Biennial	Biennial

Table 6.2: Summary of Optimization of Groundwater Monitoring Program at Long Prairie Groundwater Contamination Superfund Site

Well ID	Current[b/] Sampling Frequency	Recommendations Generated Using MAROS Tool	Recommendations Generated Using Three-Tiered Approach	Example Composite Recommendations
Municipal Water-Supply Wells				
CW3	Quarterly	Biennial	Biennial	Biennial
CW6	Quarterly	Biennial	Biennial	Biennial

[a/] Information from GSI (2003b) and Parsons (2003c).

[b/] "Current" monitoring program was in effect in 2002.

[c/] "Composite" recommendations generated considering the current monitoring program, and recommendations generated by MAROS tool and three-tiered approach.

[d/] A dash (--) indicates that the well is not included in the current monitoring program.

[e/] "Remove" indicates that the well is recommended for removal from the monitoring program.

The results of the MAROS optimization and the three-tiered evaluation, including recommendations for removal of wells and adjustments to sampling frequency, were fully consistent for nearly 90 percent of the wells in the monitoring program at the Long Prairie site. Adoption of the example "composite" monitoring program would result in removal of 16 wells from the current monitoring network at the Long Prairie site, together with adjustment of the frequency of sampling to less-frequent events at several locations.

The results of the three-tiered evaluation and MAROS optimization of the monitoring program at McClellan AFB OU D are summarized in Table 6.3. Example composite recommendations also are provided in Column 5 of Table 6.3.

Table 6.3: Summary of Optimization of Groundwater Monitoring Program at McClellan AFB OU D[a/]

Well ID	Current[b/] Sampling Frequency	Recommendations Generated Using MAROS Tool	Recommendations Generated Using Three-Tiered Approach	Example Composite[c/] Recommendations
Zone A Monitoring Wells				
MW-10	Annual	Annual	Annual	Annual
MW-11	Annual	Annual	Annual	Annual
MW-12	Annual	Annual	Annual	Annual
MW-14	Biennial	Remove[d/]	Biennial	Biennial
MW-15	Annual	Annual	Annual	Annual
MW-38D	Annual	Annual	Annual	Annual
MW-52	Biennial	Biennial	Remove	Biennial
MW-53	Biennial	Biennial	Remove	Biennial
MW-55	Biennial	Biennial	Biennial	Biennial
MW-70	Biennial	Biennial	Remove	Biennial

Table 6.3: Summary of Optimization of Groundwater Monitoring Program at McClellan AFB OU D

Well ID	Current Sampling Frequency	Recommendations Generated Using MAROS Tool	Recommendations Generated Using Three-Tiered Approach	Example Composite Recommendations
Zone A Monitoring Wells (continued)				
MW-72	Annual	Annual	Remove	Annual
MW-74	Biennial	Annual	Remove	Annual
MW-76	Annual	Annual	Annual	Annual
MW-88	Biennial	Biennial	Remove	Biennial
MW-89	Biennial	Biennial	Biennial	Biennial
MW-90	Biennial	Biennial	Biennial	Biennial
MW-91	Biennial	Biennial	Remove	Biennial
MW-92	Biennial	Biennial	Remove	Biennial
MW-237	Biennial	Biennial	Remove	Biennial
MW-240	Biennial	Biennial	Remove	Biennial
MW-241	Annual	Remove	Remove	Remove
MW-242	Annual	Annual	Remove	Annual
MW-350	Biennial	Biennial	Remove	Biennial
MW-351	Annual	Annual	Remove	Annual
MW-412	Biennial	Biennial	Remove	Biennial
MW-458	Biennial	Biennial	Remove	Biennial
MW-1004	Biennial	Biennial	Remove	Biennial
MW-1026	Biennial	Biennial	Remove	Biennial
MW-1041	Biennial	Remove	Remove	Remove
MW-1042	Biennial	Biennial	Remove	Biennial
MW-1064	Biennial	Biennial	Remove	Biennial
MW-1073	Biennial	Biennial	Remove	Biennial
Zone B Monitoring Wells				
MW-19D	Biennial	Biennial	Biennial	Biennial
MW-51	Biennial	Biennial	Biennial	Biennial
MW-54	Annual	Annual	Annual	Annual
MW-57	Biennial	Biennial	Remove	Biennial
MW-58	Biennial	Biennial	Biennial	Biennial
MW-59	Biennial	Biennial	Biennial	Biennial
MW-104	Biennial	Biennial	Remove	Biennial
MW-1001	Biennial	Biennial	Remove	Biennial
MW-1003	Biennial	Remove	Remove	Remove
MW-1010	Biennial	Biennial	Remove	Biennial
MW-1027	Biennial	Biennial	Biennial	Biennial
MW-1028	Biennial	Remove	Remove	Remove
MW-1043	Biennial	Biennial	Biennial	Biennial

Table 6.3: Summary of Optimization of Groundwater Monitoring Program at McClellan AFB OU D

Well ID	Current Sampling Frequency	Recommendations Generated Using MAROS Tool	Recommendations Generated Using Three-Tiered Approach	Example Composite Recommendations
Groundwater Extraction Wells				
EW-73	Annual	Annual	Annual	Annual
EW-83	Annual	Annual	Annual	Annual
EW-84	Annual	Annual	Annual	Annual
EW-85	Annual	Annual	Annual	Annual
EW-86	Annual	Annual	Annual	Annual
EW-87	Annual	Annual	Annual	Annual

[a] Information from GSI (2003c) and Parsons (2003d).

[b] "Current" monitoring program was in effect in 2002.

c/ "Composite" recommendations generated considering the current monitoring program, and recommendations generated by MAROS tool and three-tiered approach.

[d] "Remove" indicates that the well is recommended for removal from the monitoring program.

The results of the MAROS optimization and the three-tiered evaluation, including recommendations for removal of wells and adjustments to sampling frequency, were fully consistent for approximately 50 percent of the wells in the monitoring program at McClellan AFB OU D. Application of the three-tiered approach to the monitoring program generated considerably more recommendations for well-removal from the program than did the MAROS evaluation, primarily on the basis of the qualitative evaluation, which recommended the removal of wells at the periphery of OU D, that historically have had no detections (or few detections at low concentrations) of COCs in groundwater. Even though the example "composite" program represents a conservative approach to program optimization, adoption of the example "composite" monitoring program would result in removal of four wells from the current monitoring program at OU D, together with adjustment of the frequency of sampling to less-frequent events at several locations.

Application of the two approaches to the optimization of long-term monitoring programs at each of the three case-study example sites generated recommendations for reductions in sampling frequency and changes in the numbers and locations of monitoring points that are sampled. Implementation of the optimization recommendations could lead to reductions ranging from only a few percent (using MAROS at McClellan AFB OU D) to more than 50 percent (using MAROS at the Long Prairie site and the three-tiered approach at McClellan AFB OU D) in the numbers of samples collected and analyzed annually at particular sites. The median recommended reduction in the annual number of samples collected, generated during the optimization demonstration, was 39 percent. Depending upon the scale of the particular long-term monitoring program, and the nature of the optimization recommendations, adoption of an optimized monitoring program could lead to annual cost savings ranging from a few hundred dollars (using MAROS at McClellan AFB OU D) to approximately $36,500 (using the three-tiered approach at the Fort Lewis Logistics Center Area). The results of the evaluations also demonstrate that each of the optimized monitoring programs remains adequate to address the primary objectives of monitoring.

6.2 OTHER ISSUES

The procedures used in the LTMO evaluations were discussed with various stakeholders (the environmental coordinators, responsible parties, and regulatory-agency personnel) through the entire course of the project. After the evaluations had been completed, the results were presented to stakeholder groups at each facility. Presenting the results to regulators at the three facilities raised questions that had to do more with the data quality objectives (DQOs) than with the approaches themselves. It became clear that every monitoring location that was recommended for removal, or for a change in sampling frequency, had a non-quantifiable, subjective value that depended on the person making the optimization decision. Much discussion revolved around the necessity of monitoring to a degree sufficient to incontrovertibly document plume capture. Other questions were raised regarding whether changes to monitoring programs would require modifications to existing Records of Decision (RODs).

Based on those discussions, it is clear that before any optimization recommendation is accepted, there must be a careful and thorough presentation of the long-term groundwater monitoring DQOs from the viewpoint of all the stakeholders, followed by stakeholder agreement on DQOs, possibly for every groundwater monitoring location. After the objectives have been defined, and consensus has been reached, the results of the optimization analyses can be examined, and a decision made to accept or reject recommendations. Note that there may be intangible costs associated with the development and presentation of recommendations to reduce the spatial density or temporal frequency of monitoring, including resistance of stakeholders and changes in public perception.

Depending upon the degree of difficulty in arriving at stakeholder concurrence with LTMO recommendations, the tangible and intangible costs associated with conducting and implementing an LTMO evaluation may outweigh the dollar cost savings that might be realized from an optimized program. This possibility must be addressed on a site-specific basis.

6.3 CONCLUSIONS

The most significant advantage conferred by the optimization approaches is the fact that both approaches apply consistent, well-documented procedures, which incorporate formal decision logic, to the process of evaluating and optimizing monitoring programs. However, there are certain limitations to each approach to monitoring program optimization. The primary limitation of MAROS is associated with the way in which the tool deals with COC concentrations that are below the reporting limit – MAROS assigns the value of the reporting limit (or some fraction thereof) to samples having a constituent concentration below the reporting limit (Appendix B). This can lead to identification of spurious temporal trends in concentrations, or to incorrectly concluding that reported concentrations are unstable through time. Identification of spurious trends, in turn, will affect the recommendations regarding the optimal frequency of sampling. The primary limitation of the three-tiered approach is that the spatial-statistical stage of the evaluation generally is completed using sampling results for only one constituent (Appendix B). The fact that the spatial evaluation currently is conducted in two spatial dimensions (rather than three) represents a limitation of both approaches.

For either 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. Both approaches could benefit from further development efforts to address these limitations; continued development of both approaches is contemplated or in progress.

Experience obtained during the demonstrations indicates that although the MAROS tool is capable of being applied by an individual with little formal statistical training, interpretation of the results generated by either approach requires a relatively sophisticated understanding of hydrogeology, statistics, and the processes governing the movement and fate of contaminants in the environment. The two approaches differ primarily in the procedures used to select a sampling frequency. MAROS utilizes a relatively rigorous, statistical approach based on identification of temporal trends in COC concentrations, while the three-tiered approach depends primarily upon qualitative considerations, applied using detailed knowledge of the local hydrogeologic system, with support from the results of the temporal and spatial-statistical evaluations. However, if the assumptions underlying the MAROS statistical approach are violated (e.g., the number of separate monitoring events is not sufficient to identify a trend), application of MAROS to develop recommendations regarding monitoring frequency also will depend on qualitative considerations (e.g., GSI, 2003c). Both approaches use a ranking approach to identify potentially-unnecessary monitoring locations, although the spatial-statistical procedures used to implement the ranking approach are somewhat different.

In general, the recommendations generated by MAROS regarding spatial redundancy and sampling frequency were more conservative than the recommendations generated during the three-tiered evaluation (e.g., MAROS may recommend semi-annual sampling at a particular monitoring location, while the three-tiered evaluation may recommend annual sampling at the same location). In addition, the three-tiered approach tends to generate recommendations for removing a larger proportion of wells from a monitoring program than does MAROS, because the three-tiered approach considers the results of qualitative, temporal, and spatial analyses together to determine whether a particular well should be retained or removed from the monitoring program, while MAROS will recommend a well for removal from the program only if it is classified as redundant for all COCs based on the results of the spatial evaluation alone. It is possible that the more rigorous qualitative evaluation in the three-tiered approach justifies less-conservative recommendations than are generated using the MAROS approach. For example, the three-tiered evaluation generated a recommendation for biennial sampling at well LC-149c in the optimized Fort Lewis Logistics Center monitoring program, because the qualitative review in the three-tiered evaluation identified well LC-149c as having no historical detections of COCs throughout a monitoring history comprising 24 sampling events. By contrast, the temporal-statistical evaluation algorithm in MAROS originally generated a recommendation for annual sampling at that well. (The recommendation for annual sampling later was revised by applying qualitative considerations during subsequent stages of the MAROS evaluation.)

The general characteristics of each of the three case-study example sites addressed in this demonstration project are similar, comprising chlorinated solvent contaminants in groundwater, occurring at relatively shallow depth in unconsolidated sediments. However, the assumptions underlying the two approaches, and the procedures that are followed in conducting the evaluations, are applicable to a much broader range of conditions (e.g., dissolved metals in groundwater, or contaminants in a fractured bedrock system). In summary, either the MAROS tool or the three-tiered approach can be used to generate sound and defensible recommendations for optimizing a long-term monitoring program, under a wide range of site conditions.

Prior to initiating an LTMO evaluation, it is of critical importance that the monitoring objectives of the program to be optimized and the DQOs for individual monitoring points be clearly articulated, with all stakeholders agreeing to the stated objectives, decision rules, and procedures, so that the program can be optimized in terms of recognized objectives, using decision rules and procedures that are acceptable to all stakeholders. The decisions regarding whether to conduct an LTMO evaluation, which approach to use, and the degree of regulatory-agency involvement in the LTMO evaluation and subsequent implementation of optimization recommendations, must be made on a site-specific basis. Factors to be considered in deciding whether to proceed with an 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; and
- The potential benefits (e.g., cost savings) that could result from an optimized monitoring program.

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 50 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, monitoring program optimization also should be undertaken periodically, rather than being regarded as a one-time event. Overall site conditions should be relatively stable, with no large changes in remediation approaches occurring or anticipated. For sites at which response decisions are being validated or refined (e.g., during periodic remedy-performance reviews), optimization of the LTM program should be postponed until adjustments to the response have been implemented and evaluated. Successful application of either LTMO approach to the site-specific evaluation of a monitoring program is directly dependent upon the amount and quality of the available data – results from a minimum of four to six separate sampling events are necessary to support a temporal analysis, and results collected at a minimum of about six (for a MAROS evaluation) to 15 (for a three-tiered evaluation) separate monitoring points are necessary to support a spatial analysis. It also is necessary to develop an adequate CSM, describing site-specific conditions (e.g., direction and rate of groundwater movement, locations of contaminant sources and potential receptor exposure points) prior to applying either approach; the extent of contaminants in the subsurface at the site also must be adequately delineated before the monitoring program can be optimized.

Typically, a program manager should anticipate incurring costs on the order of \$6,000 to \$10,000 to complete an LTMO evaluation using one of the two approaches presented in this demonstration, at the level of detail of the case-study examples used in the demonstration (Sections 3, 4, and 5; and Appendices C and D). Consequently, an LTMO evaluation may be cost-prohibitive for smaller monitoring programs. Assuming a payback period of three years, potential cost savings of approximately \$2,000 to \$3,300 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 (including prorated mobilization costs, and costs for field sampling, management of water produced during sampling, laboratory analyses, QA/QC, and reporting) using conventional sampling technologies (bailer or purge pump) can range from about \$200 per sample to more than \$500 per sample (U.S. Air Force, 2004), an LTMO evaluation that can be used to reduce the total number of samples collected at a site by about 5 to 10 samples per annum should be cost-effective.

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