TECHNOLOGY APPLICATION ANALYSIS REPORT

FINAL

Passive Diffusion Membrane Samplers

McClellan Air Force Base
Sacramento, California
Environmental Management Directorate

August 2, 2000

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1. Enclosed is the Final Technology Application Analysis Report (TAAR) for the evaluation of passive membrane diffusion sampling of volatile organic compounds in groundwater monitoring wells. This demonstration was conducted as part of the National Environmental Technology Test Site program under funding from the Air Force Base Conversion Agency.

2. This is a secondary document according to the Interagency Agreement. This document is number 358-5 on the McClellan Document Deliverable Status Report with a due date of 2 August 2000. Participation of the McClellan AFB Innovative Technology Program partners in the development of this report was appreciated.

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1. REPORT DATE *(DD-MM-YYYY)*
02-08-2000

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

Passive Diffusion Membrane Samplers

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

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10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Unclassified/Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This Technology Application Analysis Report has been prepared as part of the National Environmental Technology Test Site (NETTS) and Environmental Management programs at McClellan Air Force Base (AFB). The purpose of this report is to present the findings of a field demonstration of passive diffusion membrane samplers for monitoring volatile organic compounds (VOCs) in groundwater beneath McClellan AFB. An evaluation of technical and economic feasibility of the diffusion samplers compared to conventional groundwater purge-and-sample protocols is presented in the TAAR.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**		282	**19b. TELEPHONE NUMBER** *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

TECHNOLOGY APPLICATION ANALYSIS REPORT

NATIONAL ENVIRONMENTAL TECHNOLOGY
TEST SITES (NETTS)

FOR

PASSIVE DIFFUSION MEMBRANE SAMPLERS

FINAL

PREPARED BY:
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AUGUST 2000

NOTICE

This report has been prepared for McClellan Air Force Base (AFB) to aid in the implementation of a final remedial action plan under the Air Force Installation Restoration Program (IRP). As this work plan relates to actual releases of potentially hazardous substances, its release prior to an Air Force final decision on remedial action is in the public's interest. The on-going nature of the IRP, and the evolving knowledge of site conditions and chemical effects on the environment and on human health all must be considered when evaluating this work plan, since subsequent facts may become known that make this work plan premature or inaccurate.

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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AFBCA	Air Force Base Conversion Agency
AFCEE	Air Force Center for Environmental Excellence
AOC	Area of Concern
bgs	below ground surface
BRAC	Base Realignment and Closure
BW	Base Well
CA	California
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CoC	Chain of Custody
°C	Degrees Centigrade
DCA	Dichloroethane
DCE	Dichloroethene
DoD	Department of Defense
EPA	Environmental Protection Agency
ft	feet
GSAP	Groundwater Sampling and Analysis Program
GWMP	Groundwater Monitoring Program
GWOU	Groundwater Operable Unit
GWTP	Groundwater Treatment Plant
HCl	Hydrochloric Acid
IRP	Installation Restoration Program
L	Liter
MCL	Maximum Contaminant Level
MDL	Method Detection Limit
mg	milligrams
mL	Milliliters
MW	Monitoring Well
NA	Not Applicable
NETTS	National Environmental Technology Test Site Program
No.	Number
NPL	National Priority List
NW	Northridge Water Well
OSHA	Occupational Safety and Health Administration
OU	Operable Unit
PCE	Tetrachloroethene
PPE	Personal Protective Equipment
Q	Quarter (calendar)
QA	Quality Assurance
QAPP	Quality Assurance Project Plan (basewide)
QAPjP	Quality Assurance Project Plan (diffusion sampling)
QC	Quality Control
QL	Quantitiation Limit
RCRA	Resource Conservation and Recovery Act
RI/FS	Remedial Investigation/Feasibility Study
RPD	Relative Percent Difference
SARA	Superfund Amendments and Reauthorization Act

ACRONYMS AND ABBREVIATIONS (CONTINUED)

SDWA	Safe Drinking Water Act
SERDP	Strategic Environmental Research and Development Program
SMAQMD	Sacramento Metropolitan Air Quality Management District
SOP	Standard Operating Procedure
SVOC	Semivolatile Organic Compound
TAAR	Technology Application Analysis Report
TCA	Trichloroethane
TCE	Trichloroethene
USGS	United States Geologic Survey
VOA	Volatile Organic Analysis
VOCs	Volatile Organic Compounds
WIP	Work Implementation Plan
µg	Micrograms
u	mean

1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

This Technology Application Analysis Report (TAAR) summarizes the findings of field demonstration using passive diffusion membrane samplers (herein referred to as diffusion samplers) as an innovative approach to monitoring volatile organic compound (VOC) contamination in groundwater. The diffusion sampler demonstration was conducted at McClellan Air Force Base (AFB), California (CA) between 12 May and 4 June, 1999. This demonstration was conducted under the guidance of the Strategic Environmental Research and Development Program (SERDP) National Environmental Technology Test Site (NETTS) program at McClellan AFB.

McClellan AFB (the base) is located approximately seven miles northeast of downtown Sacramento, CA. The main base includes 2,949 contiguous acres. Throughout its 60-plus year history, the base has been engaged in a wide variety of operations involving the use, storage, and disposal of hazardous materials. These materials include industrial solvents, caustic cleaners, electroplating chemicals, heavy metals, polychlorinated biphenyls, low-level radioactive wastes, and a variety of fuels, oils, and lubricants.

The diffusion sampler demonstration was conducted at 30 groundwater monitoring wells located in the south and western portion of the base. The main contaminants of concern included trichloroethene (TCE), tetrachloroethene (PCE), 1,1-dichloroethene (DCE), *cis*-1,2-DCE, 1,1-dichloroethane (DCA), and 1,2-DCA. The main objective of the demonstration was to assess the cost and performance of the diffusion samplers compared to conventional groundwater purge-and-sample techniques currently in use at McClellan AFB.

1.2 DEMONSTRATION DESCRIPTION

The diffusion sampling technique is an innovative approach to groundwater sampling for VOCs that does not require the well to be purged prior to sample collection. The diffusion samplers are tubular water-filled low-density, polyethylene membranes that allow passive collection of groundwater samples for VOC analysis. This method allows VOCs in groundwater to diffuse through semi-permeable membranes (*i.e.*, polyethylene bags) into the deionized water inside the membrane. The samplers are attached onto a nylon rope and lowered to the desired depth within a groundwater monitoring well. Each sampler is approximately 1-inch in diameter and 1.5-feet long which significantly reduces volume of wastewater generated during the sampling. In addition, multiple samplers can be installed at varying depths within a monitoring well, if desired. The devices are left in place until equilibrium VOC concentrations between the deionized water inside the sampler and the water in the well casing is achieved. An equilibration time of 14 days is typically sufficient to achieve results representative of VOC concentrations in the aquifer immediately adjacent to the well screen interval. Upon recovery, the diffusion samplers are cut open and the water transferred into volatile organic analysis (VOA) sample vials and transported to an analytical laboratory for chemical analysis.

Previous demonstrations of the methodology have shown a close correlation between VOC concentrations in water obtained using the samplers without prior purging and concentrations in water

samples obtained from the wells using traditional purging and sampling approaches (Vroblesky and Hyde, 1997). This approach has the potential to significantly reduce the costs of labor, materials, and wastewater disposal associated with conventional groundwater sampling.

The diffusion sampler demonstration was conducted concurrently with the Second Quarter 1999 (2Q99) Groundwater Monitoring Program (GWMP) sampling event at McClellan AFB. The McClellan AFB GWMP currently uses conventional purge-and-sample techniques. A total of 188 diffusion samplers were installed in 30 monitoring wells and allowed to equilibrate for at least 14 days prior to recovery. Conventional groundwater samplers were collected from the monitoring wells by the GWMP sampling crews on the same days the diffusion samplers were recovered and sent to the same analytical laboratory for chemical analysis. This methodology was developed to ensure the highest attainable degree of consistency and allow direct comparison between the diffusion sampler and GWMP data sets. The specific objectives of the demonstration were to:

- Demonstrate that the use of diffusion samplers for collecting groundwater monitoring well samples for VOC analysis is representative of the aquifer conditions encountered at McClellan AFB;

- Generate a statistically significant data set for comparison of VOC results from analyses on samples collected using diffusion samplers and those of standard purge-and-sample protocols currently used at McClellan AFB; and

- Generate data to be incorporated into an economic analysis of the costs associated with implementation of the diffusion sampling methodology basewide.

A detailed description of the experimental design are documented in the *Final Passive Diffusion Membrane Samplers Work Implementation Plan* (McClellan AFB, 1999).

1.3 RESULTS

The wells chosen for this study had well screen lengths that ranged from 10 to 20 feet in length; 13 wells had screens longer than 10 feet. Multiple samplers (*e.g.,* three to 13 depending on well screen length) were installed end-to-end along the length of the well screen to develop vertical concentration profiles for each well. These profiles were used in conjunction with available lithologic data and GWMP concentration data to evaluate the performance of the diffusion samplers assess whether geologic conditions affected the concentrations at different depths. A test of means (*i.e.,* t-test) was performed to determine if individual VOC concentrations reported in the diffusion samplers were statistically equivalent to the GWMP results for each well. In addition, a test of differences (*i.e.,* paired t-test) was performed to determine if the concentrations of specific VOCs in the diffusion samplers are statistically equivalent to the GWMP results on a basewide basis. A second set of these statistical tests were performed in the same manner to determine whether the diffusion samplers placed at the midpoint of the saturated well screen interval (*i.e.*, the middle diffusion sampler) were statistically equivalent to the GWMP results.

The results of data evaluation are presented below:

- Nine of the 30 study wells exhibited a statistically significant difference in VOC concentrations with depth (*i.e.*, vertical concentration gradients). Seven of these nine wells were screened in the shallow (A-monitoring zone). Of the 12 long-screened wells (*i.e.,*

saturated screen lengths greater than 10 feet) included in this study, five exhibited a statistically significant vertical concentration gradient;

- The test of means results indicated that 81% of the diffusion sampler concentrations were statistically equivalent to or greater than those reported in the GWMP results, while 19% were statistically lower;

- All of the individual VOCs (*i.e.,* TCE, PCE, 1,1-DCA, 1,2-DCA, 1,1-DCE, *cis*-1,2-DCE, *trans*-1,2-DCE, carbon tetrachloride, chloroform, and Freon® 113) passed the test of differences;

- When comparing the middle diffusion sampler concentrations directly to the GWMP results, nearly 70% of the data pairs had a relative percent difference (RPD) of less than 15%. A closer inspection of the data revealed that 84% of the data had an RPD value less than 30% and/or a concentration difference less than 1.0 ug/L; and

- The two-sided paired t-tests on the midpoints indicated that 1,1-DCA and *cis*-1,2-DCE concentrations in the middle diffusion samplers were statistically higher than the GWMP results, while PCE concentrations were statistically lower.

1.4 CONCLUSIONS

Results from this and previous studies (Vroblesky and Hyde, 1997; Vroblesky *et al.*, 1999) have shown a close correlation between VOC concentrations in the diffusion samplers and concentrations in water samples obtained from wells using conventional purge-and-sample approaches. The main conclusions that can be drawn from this study are:

- The diffusion sampler protocol is a passive approach to monitoring VOC concentrations in groundwater. The technology may only be appropriate for monitoring wells with hydraulic gradients sufficient to allow the water within the well casing to exchange with formation water without purging. Thus, the diffusion samplers may not be appropriate for sites where groundwater is stagnant (*i.e.,* no horizontal or vertical flow through the well screen interval);

- Statistical analysis of the demonstration data suggests that the diffusion sampler technique produces sample results that are comparable to the conventional samples collected during the McClellan AFB 2Q99 GWMP sampling event;

- In a number of wells, the combination of lithologic data, well construction details, and VOC contamination profiles developed from the diffusion sampler results suggest that the conventional sampling is indeed susceptible to the representativeness issues mentioned above. In many of the wells, the diffusion samplers provided data that appears to be more representative of the true nature of contamination in the geologic formation immediately adjacent to the monitoring well screen; and

- The diffusion sampler devices are not appropriate when sampling groundwater for non-VOC contaminants such as toxic metals and some semi-volatile organic compounds (SVOCs) that do not readily diffuse through the membranes. The McClellan GWMP does not routinely sample for these analytes.

Optimal placement of the diffusion samplers along the length of the well screen appears to be an issue that remains unresolved. Ideally, a groundwater monitoring program would only require one diffusion sampler placed in the well to represent the contamination along the length of the entire screen. The results of this study suggest that blindly placing one sampler at the midpoint of the saturated well screen may not be sufficient. In the seven wells that exhibited significant variations in VOC concentrations along the well screen, the higher concentrations were typically associated with coarse-grained materials (*i.e.*, sands and gravels). Thus, one diffusion sampler placed near the midpoint of the saturated well screen interval and adjacent to a coarse-grained formation, will likely yield results representative of the highest degree of contamination in the well. For long-screened wells, more in-depth and site-specific studies, such as using multiple samplers during an initial sampling event or borehole flowmetering (Vroblesky *et al.*, 1999) to investigate the hydraulics of the monitoring well, may be necessary to determine optimal placement of the a single diffusion sampler along the length of the saturated well screen interval.

Finally, the diffusion sampling technique has the potential to dramatically reduce the costs associated with long-term monitoring of VOCs in groundwater. The follow cost-related conclusions can be drawn from this study:

- This technology does not require the purchase of expensive equipment that must be continually maintained or replaced;
- The volume of wastewater generated and requiring disposal is also significantly reduced by eliminating well purging;
- Furthermore, the technique is extremely simple and does not require any special training, and reduces the potential for human error to compromise the integrity of collected samples;
- The passive diffusion membrane sampling technique requires very little labor to implement, allowing fewer field personnel to sample the a larger number of groundwater monitoring wells in a significantly shorter period of time compared to conventional groundwater sampling and micropurging techniques; and
- Programs that routinely monitor groundwater for both VOC and non-VOC contaminants may not realize a significant cost savings using the diffusion samplers since non-VOC samples would be collected with conventional or micropurge sampling protocols. But these programs could potentially benefit from more accurate representation of the VOC contamination with the diffusion samplers.

1.5 RECOMMENDATIONS

Based on the results of the demonstration and associated cost analysis, the following recommendations are presented concerning the application of diffusion samplers for monitoring VOCs in groundwater aquifers:

- Initial pilot testing should be conducted to determine if the diffusion sampler approach is appropriate for hydrogeologic and contaminant transport conditions at the site. It is recommended that a side-by-side evaluation of the previous conventional sampling method and diffusion sampling be conducted for one sampling round following the recommendations presented below.

- An initial evaluation of the hydrogeology of the aquifer to be monitored should be conducted prior to diffusion sampler implementation. Diffusion samplers should only be used at sites where there groundwater gradients are sufficient to allow water to pass through the monitoring well screens without purging (*i.e.*, water within the well screen is not stagnant). Longer-screened wells may also be affected by vertical flow within the well casing.

- An initial evaluation of the lithology adjacent to the well screen should be conducted to identify zones of coarse- (*i.e.*, sands and gravels) and fine- (*i.e.*, silts and clays) grained materials. Results of this study suggests that the highest concentrations within a well are generally associated with the coarser-grained materials. This is likely a site-specific condition and may not be applicable to all sites, especially those with wells screened in fractured media. For McClellan AFB, one diffusion sampler placed adjacent to a coarse-grained geologic formation nearest to the midpoint of the saturated well screen interval should provide data representative of the highest contamination within the well.

- The diffusion samplers should be left in the wells for a minimum of 14 days prior to sample collection. It may be reasonable to increase this time in colder climates where diffusion rates may be slower. Further site-specific analysis may be warranted to evaluate the minimum equilibrium time should this be desirable for a site.

2.0 INTRODUCTION AND BACKGROUND

This TAAR summarizes the demonstration findings of diffusion sampler protocol developed by the United States Geologic Survey (USGS), Water Resources Division. Demonstration planning, data analysis, and reporting were performed by the McClellan NETTS Program. This report evaluates the cost and performance of the diffusion sampling technique as an innovative approach for monitoring VOC concentrations in groundwater. The technology demonstration was conducted at the McClellan NETTS location under funding from the Air Force Base Conversion Agency (AFBCA) and SERDP.

2.1 SERDP AND NETTS

Congress established SERDP to improve cooperation among the U.S. Environmental Protection Agency (EPA), the Department of Defense (DoD) armed services, and the Department of Energy to more effectively use resources in the development of innovative monitoring and remediation technologies for use at contaminated military sites. SERDP has funded the NETTS program to facilitate the demonstration, evaluation, and commercialization of cost-effective and innovative environmental technologies. The NETTS program currently includes four test locations across the country: McClellan AFB, CA; Port Hueneme, CA; Dover AFB, Delaware; and the former Wurtsmith AFB, Michigan.

McClellan AFB was designated as a NETTS location by SERDP in 1993. The primary focus of the McClellan AFB NETTS location is the evaluation of innovative technologies for the treatment and monitoring of chlorinated solvents and heavy metals in soil, soil gas, and groundwater. SERDP provides funding for infrastructure support to the Technology Integration Group for the McClellan NETTS location. The NETTS program identifies test locations with established infrastructures for rigorous pilot-scale to full-scale testing of emerging or innovative technologies that can potentially reduce costs and risks associated with current monitoring and cleanup processes. The technologies must be applicable to the Installation Restoration Program (IRP) efforts for the Air Force and other DoD facilities.

2.2 TECHNOLOGY OBJECTIVES

At McClellan AFB, chlorinated organic compounds contaminating the groundwater are a major focus for environmental remediation. McClellan AFB has identified a need to find cost effective alternative technologies for monitoring VOC-contamination in the groundwater. The demonstration was designed to evaluate the use of the diffusion sampler technology to collection samples that are representative of VOC concentrations in the groundwater immediately adjacent to the monitoring well screen. The suitability of the diffusion samplers to meet this technology need was assessed in this demonstration.

This field investigation was designed to evaluate the technical and economic feasibility for the basewide application of passive diffusion membrane samplers for the collection of groundwater samples for VOC analysis from groundwater monitoring wells. The suitability of the diffusion samplers to meet McClellan AFB long-term monitoring criteria will be evaluated using the results of this field investigation. Specific objectives of this project are:

Objective 1: Demonstrate that the use of diffusion samplers for collecting groundwater monitoring well samples for VOC analysis is representative of the aquifer conditions encountered at McClellan AFB.

Objective 2: Generate a statistically significant data set for comparison of VOC results from analyses on samples collected using diffusion samplers and those of standard purge-and-sample protocols currently used at McClellan AFB.

Objective 3: Generate data to be incorporated into an economic analysis of the costs associated with implementation of the diffusion sampling methodology basewide.

A detailed description of the experimental design is documented in the *Final Passive Diffusion Membrane Samplers Work Implementation Plan* (McClellan AFB, 1999).

2.3 TECHNOLOGY OVERVIEW

The diffusion sampling technique is an innovative approach to groundwater sampling for VOCs that does not require the well to be purged prior to sample collection. The diffusion samplers are tubular low-density, water-filled polyethylene membranes that allow passive collection of groundwater samples for VOC analysis. This method allows VOCs in groundwater to diffuse through semi-permeable membranes (*i.e.*, polyethylene bags) into the deionized water inside the membrane. The samplers are attached onto a nylon rope and lowered to the desired depth within a groundwater monitoring well. Each sampler is approximately 1-inch in diameter and 1.5-feet long which significantly reduces volume of wastewater generated during the sampling. In addition, multiple samplers can be installed at varying depths within a monitoring well, if desired. The devices are left in place until equilibrium between the deionized water inside the sampler and the water in the well casing is achieved. An equilibration time of 14 days is typically sufficient to achieve results representative of VOC concentrations in the aquifer immediately adjacent to the well screen interval (Vroblesky and Campbell, 1999). Upon recovery, the diffusion samplers are cut open and the water transferred into VOA sample vials and transported to an analytical laboratory for chemical analysis.

2.4 DEMONSTRATION SCOPE

This field investigation is a follow-on to work performed by the USGS at the Davis Global Communications Site, an annex of McClellan AFB, in December 1998 and January 1999. This initial work by the USGS was part of an AFBCA-funded project with the Air Force Center for Environmental Excellence (AFCEE). The USGS had an integral role in the of the development of the project Work Implementation Plan (WIP), providing technical support, published journal articles, and unpublished or yet-to-be published materials used in the development of the experimental design.

The scope of work involved in this demonstration included an initial characterization of the site, experimental design, equipment mobilization and demobilization, demonstration sampling, and disposal of generated wastes. The demonstration was conducted concurrently with 2Q99 GWMP sampling event to compare the diffusion sampler techniques to standard purge-and-sample protocols currently employed at McClellan AFB. The actual tasks completed within this scope of work to achieve the objectives in Section 2.2 were as follows:

- Existing site data were reviewed and an initial assessment of the range of VOC contamination in the groundwater beneath the base was conducted to identify a set of groundwater monitoring wells that represented an accurate cross-section of the varying groundwater conditions across the base;
- Preparation of the project WIP (McClellan AFB, 1999);
- Installation of 188 diffusion samplers in 30 groundwater monitoring wells;
- Recovery and sample collection from the diffusion samplers approximately 14 days after installation;
- Collection of conventional purge-and-sample groundwater samples by the McClellan GWMP sampling teams on the same days as the diffusion sampler recovery and sample collection;
- Analysis of diffusion sampler and GWMP samples from the same analytical laboratory; and
- Preparation of this TAAR documenting the findings of the demonstration.

2.5 DOCUMENT ORGANIZATION

This TAAR was developed in accordance with report development guidance from the SERDP NETTS Program. This report organized in the following sections:

Section 1 **Executive Summary:**
Summarizes the demonstration results, conclusions, and recommendations;

Section 2 **Introduction and Background:**
Presents an overview of the technology and demonstration objectives and scope;

Section 3 **Site Description:**
Summarizes site characterization data including operational history and a review of environmental investigations conducted to date;

Section 4 **Demonstration Description:**
Presents a detailed description of the technology, installation, operation, and sampling strategy used to characterize the performance of the demonstration;

Section 5 **Technology Performance Evaluation:**
Details the numeric success of the demonstration in terms of monitoring effectiveness and system performance;

Section 6 **Other Technology Issues:**
Presents regulatory, health and safety, and community acceptance issues;

Section 7 **Cost Analysis:**
Compares cost of full-scale implementation of passive diffusion membrane samplers to other groundwater monitoring technologies, including those currently employed at McClellan AFB;

Section 8 **Recommendations:**
Presents recommended improvements for future application of the technology;

Section 9 **Conclusions:**
Presents the applicability of the technology to other contaminated sites, costs, and limitations; and

Section 10 **References:**
A compilation of literature sources used throughout this report.

This report also includes nine appendices. Appendix A presents the master log of analytical results from the diffusion sampler data set. Appendix B contains the master log of 2Q99 GWMP analytical results for the 30 wells included in this study. A summary of the quality assurance (QA) and quality control (QC) review of the project data is included as Appendix C. An analysis of acceptable analytical variability is presented in Appendix D. Appendix E contains the monitoring well lithologic data and well contaminant profiles generated from the diffusion sampler data set. Spreadsheets and tables used in the statistical analyses are provided in Appendix F. Appendix G presents the basis for the cost comparison. The Standard Operating Procedures (SOPs) for groundwater monitoring using diffusion samplers are contained in Appendix H. Appendix I contains responses to comments received on the draft TAAR. No comments were received on the draft final TAAR.

3.0 SITE DESCRIPTION

This section presents background information about McClellan AFB applicable to the diffusion sampler technology demonstration. The information presented includes the current understanding of site location, history, geology, hydrogeology, and contaminant distribution at the time of this report.

3.1 LOCATION AND SETTING

McClellan AFB is located approximately seven miles northeast of downtown Sacramento, CA. The main base includes 2,949 contiguous acres (see Figure 3.1). The base was established in 1936 as the Sacramento Air Depot. As part of its current and historic mission, the base has provided logistics support for aircraft, weapons systems, communications equipment, and commodity items as well as maintenance, supply, and contracting services. In July 1995, the congressional Base Realignment and Closure (BRAC) Commission announced that McClellan AFB would close as an active military installation in 2001. Throughout its history, the base has been engaged in a wide variety of operations involving the use, storage, and disposal of hazardous materials. These materials include industrial solvents (*e.g.*, VOCs), caustic cleaners, electroplating chemicals, heavy metals, polychlorinated biphenyls, low-level radioactive wastes and a variety of fuels, oils and lubricants. Many of these materials have been released into the environment resulting in organic and inorganic contamination of surface and subsurface soils, soil gas, and groundwater.

Hazardous wastes were disposed of at numerous burial pits, sludge pits, and miscellaneous disposal trenches and pits across the base. TCE was first detected in groundwater beneath the base and nearby off-base properties in 1979 and continues to be one of the most significant environmental concerns at McClellan AFB. Environmental studies conducted under the Air Force IRP concluded that past disposal practices resulted in the reported groundwater contamination. After reviewing the data collected under the McClellan AFB IRP, the U.S. EPA placed McClellan AFB on the National Priority List (NPL) in 1987.

To date, 257 IRP sites and 25 areas of concern (AOCs) have been identified within the boundaries of McClellan AFB (Radian International, 1999a). In order to effectively manage the IRP, 10 geographic Operable Units (OUs), A-H, B1, and C1, encompassing known or potential sites that covered the entire base (see Figure 3.2) were established. In 1993, a separate Groundwater Operable Unit (GWOU) was established to consolidate the investigation of the groundwater contamination beneath the base. Groundwater data has provided evidence that several contaminated groundwater plumes have migrated beyond geographic OU boundaries, some beyond the base boundaries. In some cases, the contaminant plumes have commingled with plumes from other OUs, such as those beneath OUs B and C. By addressing groundwater contamination as one OU, groundwater strategies and actions could be applied across the entire groundwater medium, regardless of geographic boundaries.

Quarterly sampling of off-base groundwater wells began in 1984. In 1986, the quarterly Groundwater Sampling and Analysis Program (GSAP) was established for long-term monitoring of VOC-contamination in the groundwater beneath McClellan AFB. The GSAP was modified in 1996 and is now referred to as the GWMP. From 1986 to 1997, 21 extraction wells were installed and connected to the groundwater treatment plant (GWTP), located

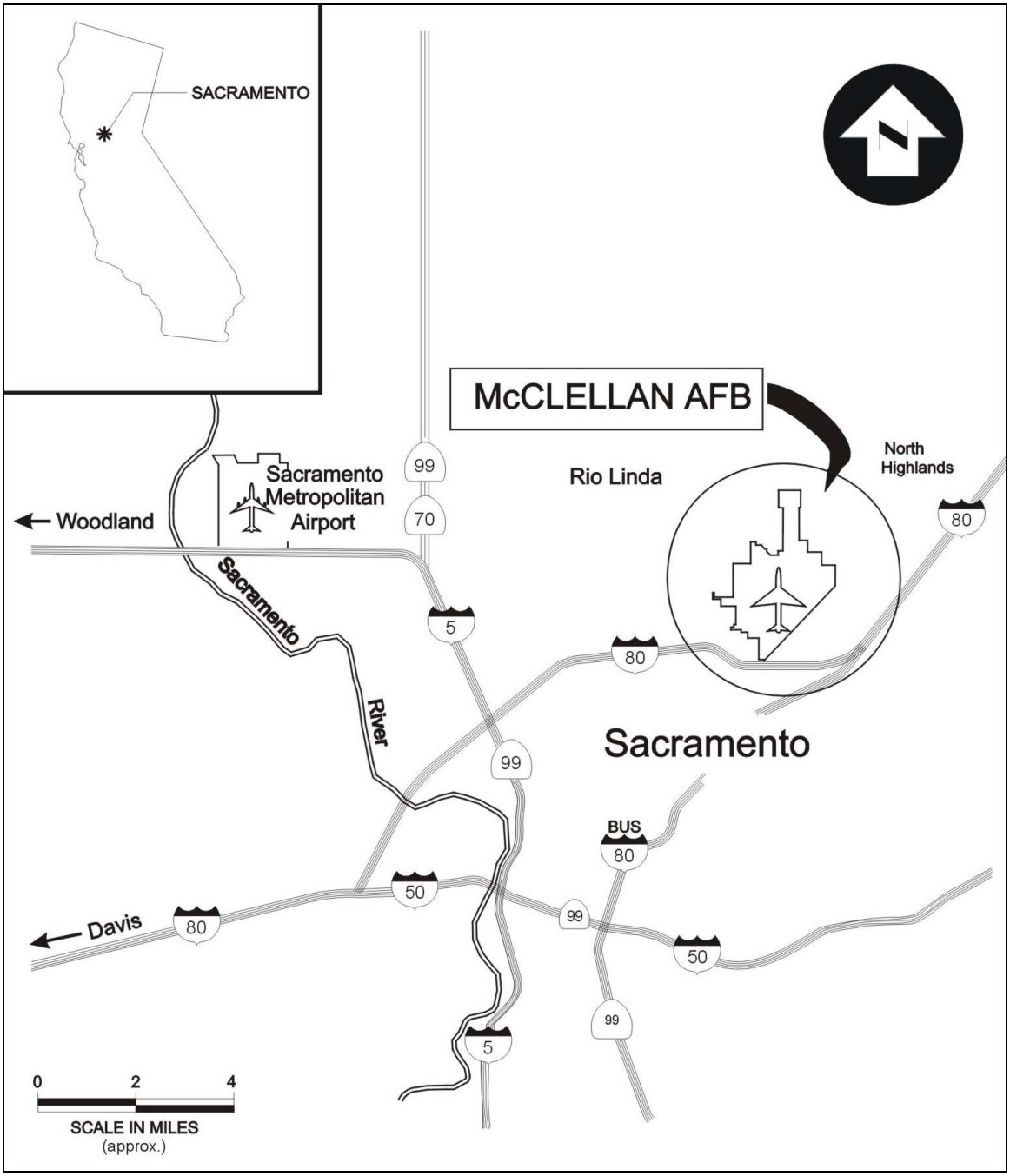

Figure 3.1. Facility Location Map

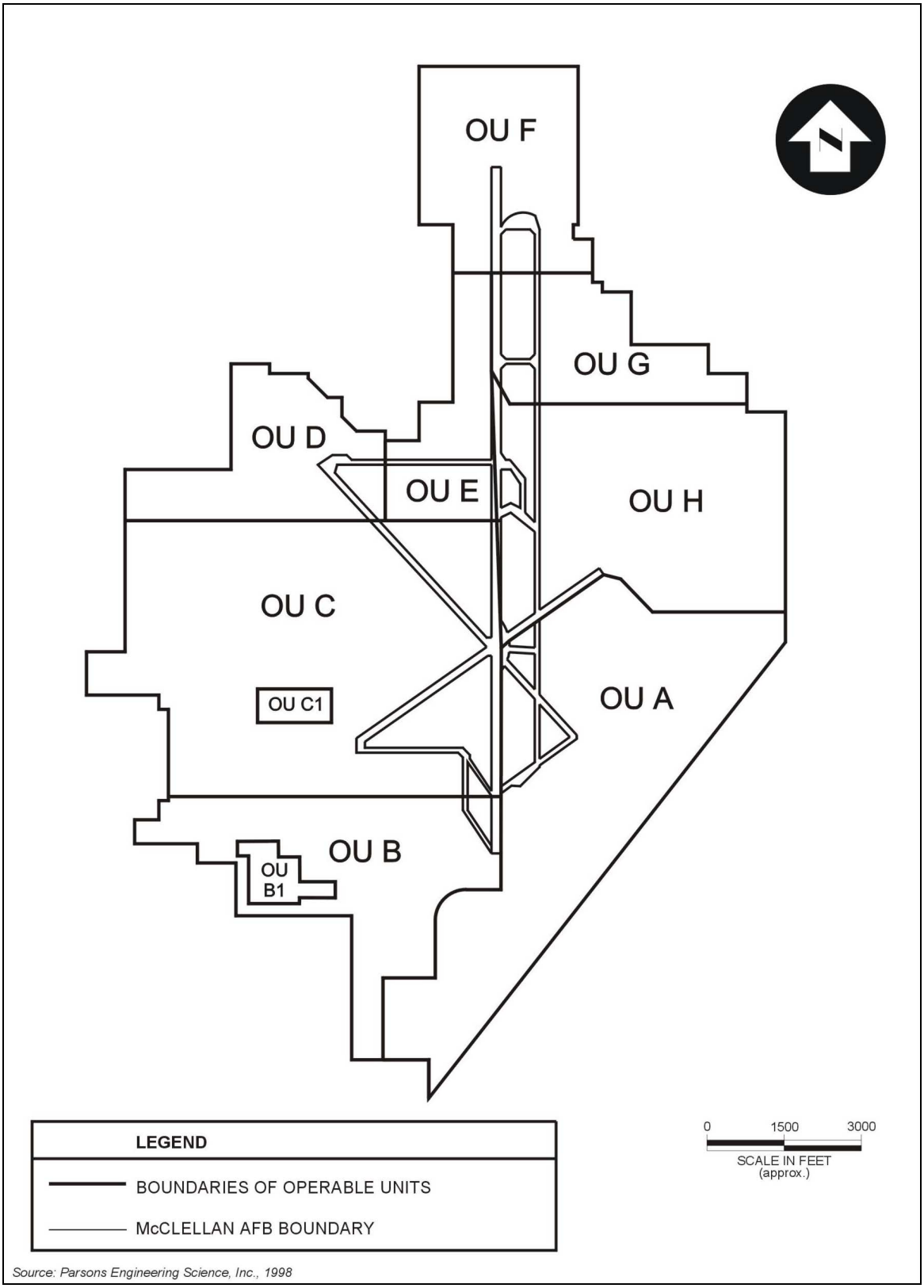

Figure 3.2. Approximate Boundaries of Operable Units

OU C, to remove and treat contaminated groundwater from OUs B, C, and D. A Dual Phase Extraction system in OU A treats contaminated groundwater on the east side of the base. A total of 29 additional groundwater extraction wells were installed and connected to the GWTP along with the six existing OU A wells during GWOU Phase 2 Remedial Design (CH2M Hill, 1997). McClellan AFB currently has over 400 groundwater monitoring wells installed both on- and off-base to monitor the migration of multiple VOC-contaminated groundwater plumes.

3.2 GEOLOGY

From the ground surface to a depth of approximately 450 feet below ground surface (bgs), the subsurface of McClellan AFB consists of alluvial and fluvial sediments eroded from the Sierra Nevada and deposited over the last five million years. Soils found in the vadose zone (*i.e.,* soil above the water table) are composed of interbedded layers of sands, silts, and clays. The thickness of most layers varies from a few inches to 5 feet, particularly in the upper 40 feet of the vadose zone. In some parts of McClellan AFB, layers of one lithology may be 6 to 35 feet thick at depths greater than 40 feet bgs. A discontinuous layers of silica-cemented hardpan, approximately 2 to 4 inches thick, has developed over large, undisturbed areas of the base at 3 to 10 feet bgs. This hardpan may impede, but does not halt the downward percolation of surface water that infiltrates the surface soil. This hardpan has been disturbed or replaced with fill material in many of the industrial sites and disposal pits/landfills during construction activities.

Water and soil gas behavior in the vadose zone is largely determined by the properties of the sediment layers. As a result of the heterogeneity of the vadose zone beneath McClellan AFB, soil permeabilities may increase or decrease by 3 to 4 orders of magnitude where different lithologies (*e.g.,* sands and silts or sands and clays) are in contact. In addition, the poorly sorted condition of most of the layers, grain cementation, and the presence of plant root bores affect the permeability and porosity. The bottom of the vadose zone is determined by the capillary fringe, in which all of the pores between soil particles are filled with water held by capillary forces just above the water table.

3.3 HYDROGEOLOGY

The geologic environment beneath the base is a complex series of alluvial deposits that were laid down, eroded, and re-deposited by actions of streams, rivers, and floods. The alternating layers of unconsolidated sand, silt, clay, and gravel form a single groundwater system. The geologic and hydrologic properties of the aquifer formation vary over short distances, but the aquifer is laterally and vertically interconnected by permeable sand and gravel lenses.

The groundwater table beneath McClellan AFB is typically encountered between 100- and 110-bgs. Historical water level measurements indicate that the water table has declined between 0.09 and 2.0 feet each year between 1955 and 1997. Groundwater levels are expected to continue to decline at rates of 1 to 2 foot per year due to overdrafting of the local aquifers (Radian International, 1997a; CH2M Hill, 1994).

The aquifer system at McClellan AFB has been divided into a series of vertical monitoring zones for investigative purposes. The monitoring zones are layers that together act as preferential pathways for horizontal groundwater flow within the aquifer system. The monitoring zones are not hydraulically independent and groundwater does flow vertically between zones. The Preliminary Groundwater Operable Unit Remedial Investigation defined these zones to assist in determining the potential for

contaminants to migrate horizontally or vertically though the aquifer beneath McClellan AFB (Radian Corporation, 1991). The monitoring zones are designated A through F, from shallowest to deepest.

Generally, the zones thicken and dip across the base from east to west, following the geologic sequence. Figure 3.3 shows a generalized cross-section of these hydrogeologic monitoring zones. However, it is entirely possible for two adjacent wells screened at different depths to be screened within the same zone, or for two wells screened at similar depths to be screened in different zones. These local variations in zone depths are due to the heterogeneity of the deposits beneath McClellan AFB, and to the relative abilities of different deposits to conduct water. At some locations, isolated or intermediate semi-confined zones were identified between the monitoring zones. In OU A, the portion of the current A-monitoring zone that is saturated consists of the fine-grained layers that once formed the aquitard between the now dry (vadose zone), historical A-zone above, and the B-zone below. When fully saturated, the historical A-zone had lateral continuity and provided a conductive pathway for groundwater flow, as it still does in OUs B, C, and D.

The hydraulic conductivity of the aquifer is highly variable. Aquifer tests conducted at McClellan AFB have estimated that the horizontal hydraulic conductivity for the A-zone in the western portion (OUs B and C) of McClellan AFB ranged between 22.5 and 39.7 feet (ft) per day with vertical conductivities between 0.14 and 4.1 ft/day (CH2M Hill 1994).

Groundwater flow beneath McClellan AFB is also controlled by the pumping of groundwater wells. Thirteen water supply wells in the vicinity of McClellan AFB, both on and off base, affect the groundwater flow beneath several OUs. The groundwater extraction systems in OUs C and D exert hydraulic control in the A- and B-monitoring zones on the west side of the base. The local water supply wells historically included (on-base) Base Well (BW) 10 in OU A, BW-18 in OU B, and BW-29 in OU E; and continuing extraction from (off base) Northridge Water District Well (NW) 17 and Arcade Water District Well 16, both of which are east of OU E, and NW-14, which is south of OU A.

3.4 CONTAMINANT DISTRIBUTION

The subsurface beneath McClellan AFB has been divided into the vadose zone and the five saturated groundwater monitoring zones mentioned previously on the basis of hydrogeologic characteristics. These monitoring zones are used to monitor the horizontal and vertical migration of contaminants in groundwater and local variations horizontal and vertical gradients. VOCs have migrated vertically from sources in the vadose zone to the groundwater aquifer. Upon entering the aquifer, these contaminants have migrated laterally via advective and dispersive mechanisms. In some areas of the base, it is also likely that the contaminants continued to migrate vertically to deeper zones due to groundwater pumping from the base supply wells, most notably the former BW-18 in OU B, which had a long, deep well screen and operated at flowrates in excess of 1,000 gallons per minute; thus producing vertical hydraulic gradients that likely drove shallow contamination deeper into the aquifer (Radian International, 1998).

Contaminant concentration data is gathered on a quarterly basis under the McClellan AFB GWMP. These data are used to assess increasing and decreasing trends in concentration and the migration of the VOC plumes in the A-, B-, C-, and D-monitoring zones. Target areas are plan views of contaminated groundwater volumes (*i.e.,* isoconcentration contours) that have concentrations greater than maximum contaminant levels (MCLs). The MCLs, established under the Safe Drinking Water Act (SDWA), specify the allowable concentrations of chemicals in drinking water. “Hot spot” target

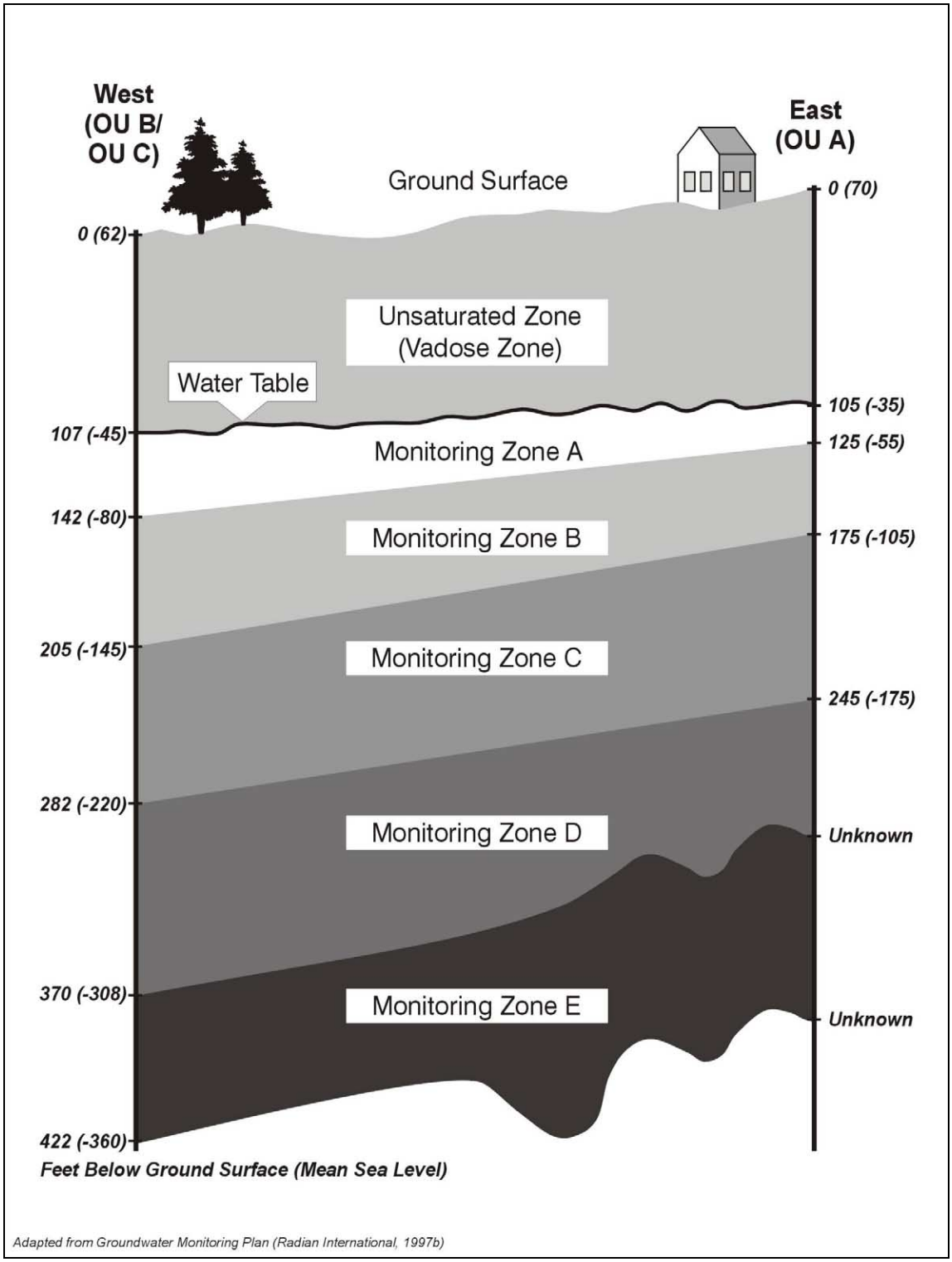

Figure 3.3. Generalized Hydrogeologic Cross Section of McClellan AFB

areas are areas of groundwater contamination where the concentrations of VOCs exceed 100 times their respective MCLs (Radian International, 1997b). The four main contaminants of concern (COCs) in groundwater beneath McClellan AFB are listed below:

- TCE;
- PCE;
- *cis*-1,2-DCE; and
- 1,2-DCA;

MCL and "hot spot" target areas for these COCs in the A, B, and C monitoring zones are shown in Figures 3-4 through 3-7, respectively. Table 3.1 summarizes the MCL and "hot spot" target areas beneath McClellan AFB. These isocontours were derived from VOC concentration data collected through the 2Q99 GWMP sampling event that was conducted concurrently with the diffusion sampling.

Table 3.1. 2Q99 MCL and Hot Spot Target Area Summary

Contaminant	Monitoring Zone	MCL (µg/L)	Number of MCL Target Areas	Estimated Area (Acres)	Hot Spot Conc. (µg/L)	Number of Hot Spot Target Areas	Estimated Area (Acres)
TCE	A	5	9	535	500	5	49
	B		7	243		2	11
	C		1	0.2		0	
PCE	A	5	9	33	500	0	
	B		2	6		0	
cis-1,2-DCE	A	6	6	199	600	0	
	B		7	0.1		0	
	C		1	0.1		0	
1,2-DCA	A	0.5	11	100	50	0	
	B		9	13		0	

Adapted from *Quarterly Report, Second Quarter 1999* (Radian International, 1999a).

Most wells at McClellan AFB are sampled on a semi-annual, annual, or biennial, basis rather than quarterly. Sampling frequency is determined in accordance with the McClellan AFB Groundwater Monitoring Plan (Radian International, 1997b). Thus all wells are not sampled each quarter. Analytical data collected during the last four GWMP sampling quarters (3Q98 through the 2Q99 event) were used for most wells to generate the figures. However, some of the data used were collected during sampling events prior to the last four quarters. Because every well is not sampled each quarter, the figures represent the most recent data available for each area.

In addition to the four contaminants listed above, the following eight VOCs were reported during the 2Q99 sampling event at concentrations greater than MCLs:

- Carbon tetrachloride;
- 1,1-DCA;
- 1,1-DCE;
- 1,4-dichlorobenzene;
- Benzene;
- Chloroform;
- Methylene chloride; and
- Vinyl chloride.

Carbon tetrachloride, 1,1-DCA, and 1,1-DCE have been detected in groundwater samples collected from wells outside the MCL target areas shown in Figures 3.4 to 3.7. The remaining five compounds listed above were all detected within the target areas for TCE, PCE, *cis*-1,2-DCE, and 1,2-DCA when their concentrations exceeded MCLs. Groundwater elevations in the A, B, C, and D monitoring zones measured during the 2Q99 GWMP event are shown in Figure 3.8. A summary of the sampling and analysis results is presented in the *Quarterly Report, Second Quarter 1999* (Radian International, 1999b).

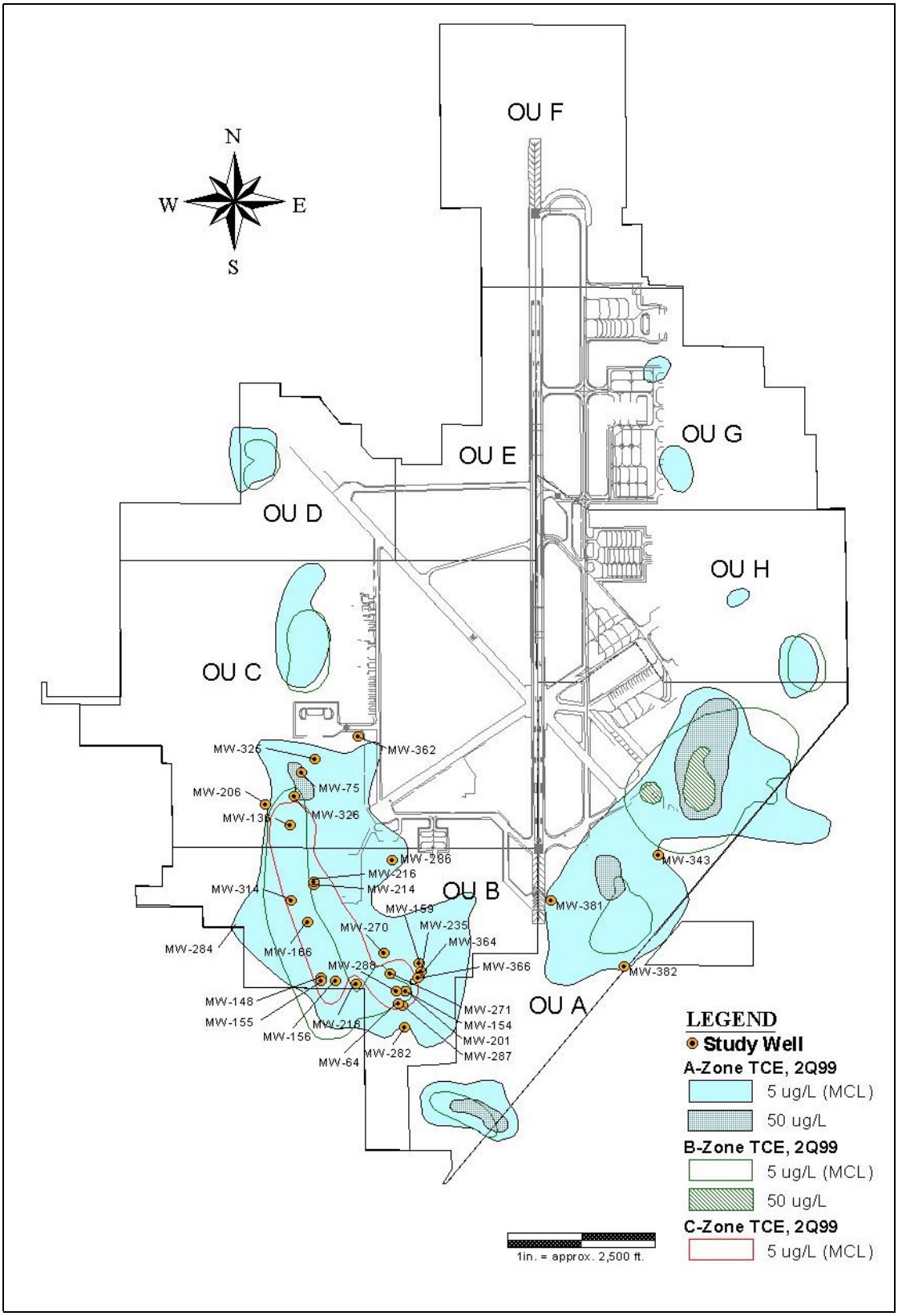

Figure 3.4. 2Q99 TCE MCL Target Areas in the A, B, and C Monitoring Zones

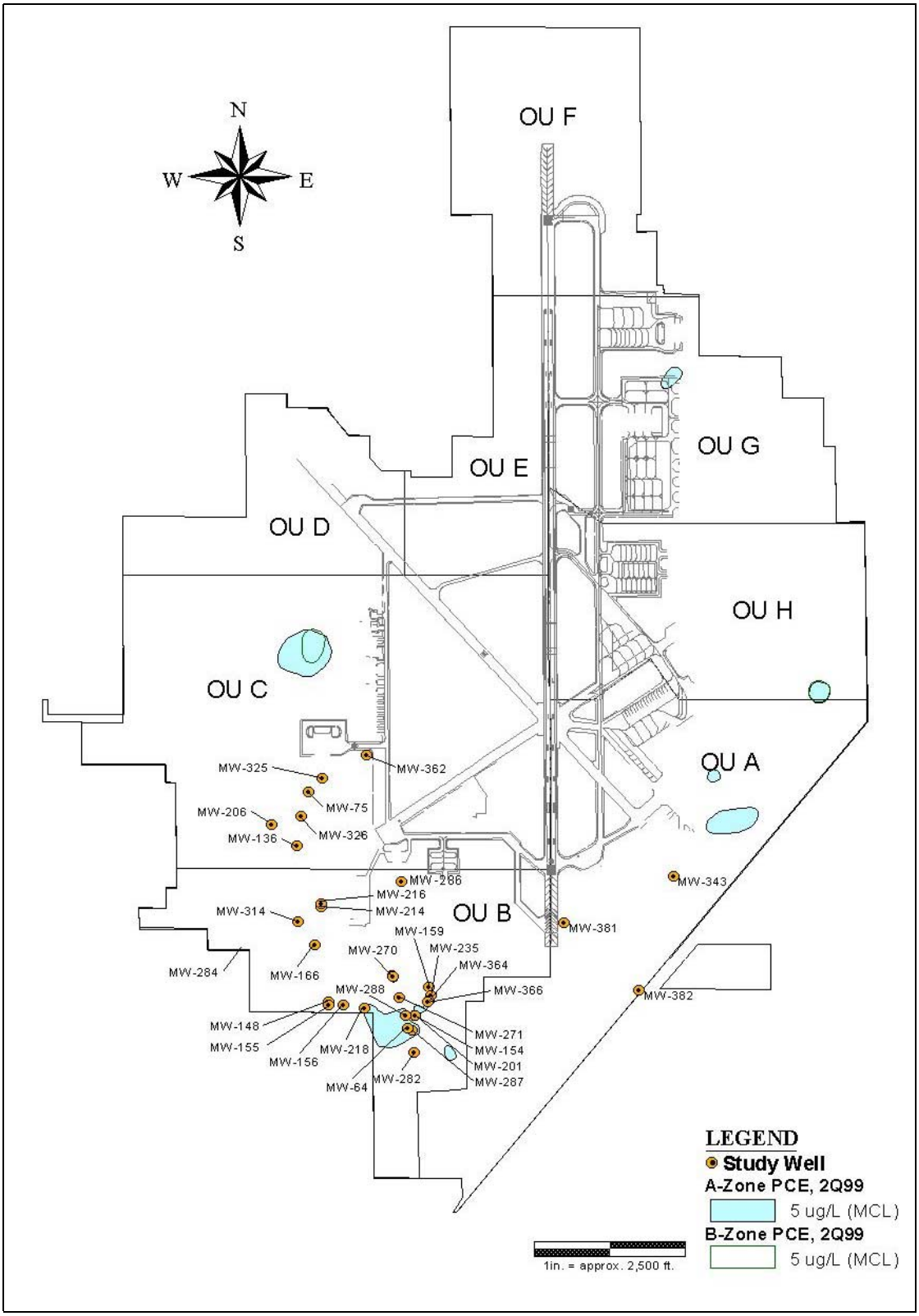

Figure 3.5. 2Q99 PCE MCL Target Areas in the A and B Monitoring Zones

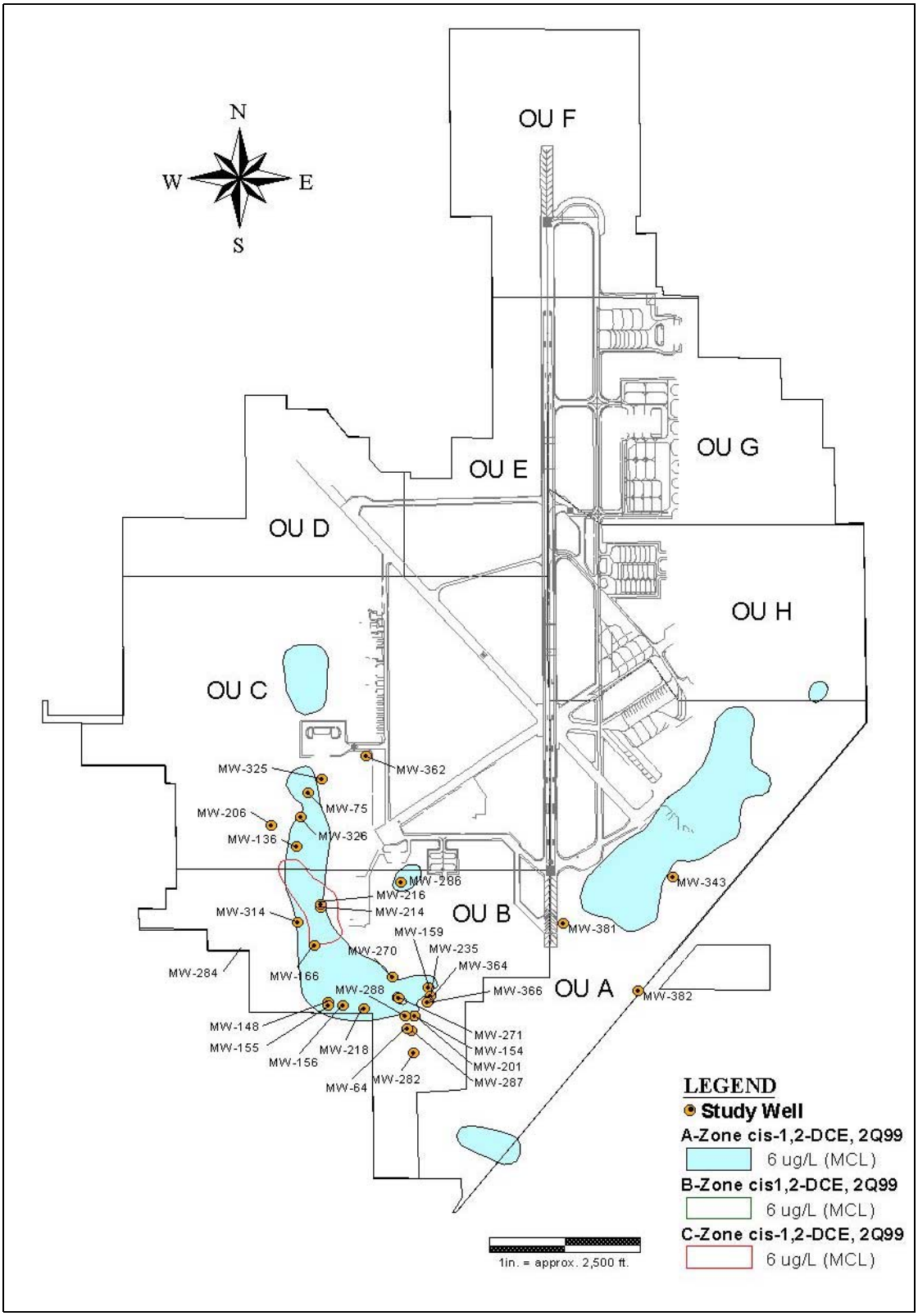

Figure 3.6. 2Q99 *cis*-1,2-DCE MCL Target Areas in the A, B, and C Monitoring Zones

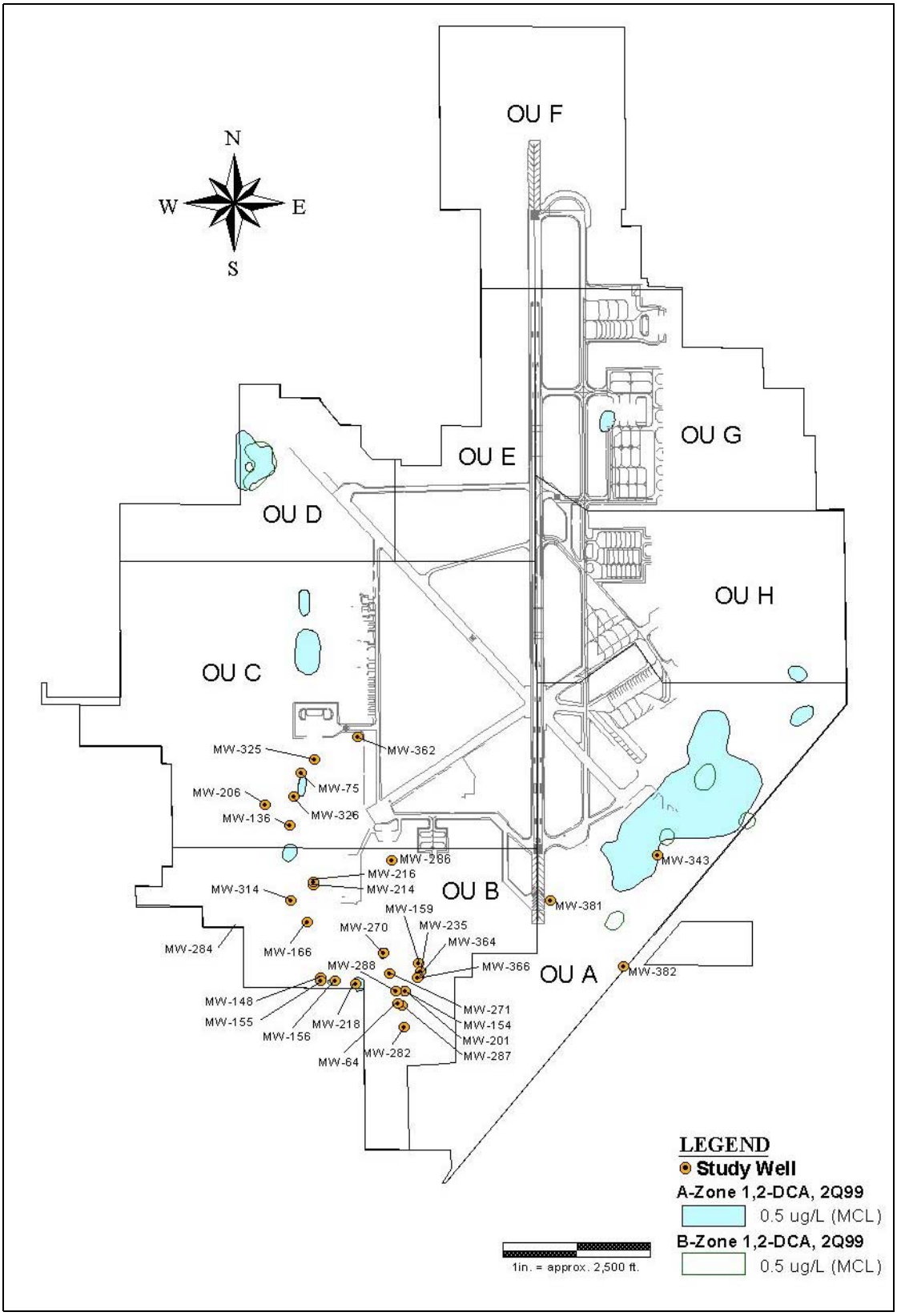

Figure 3.7. 2Q99 1,2-DCA MCL Target Areas in the A and B Monitoring Zones

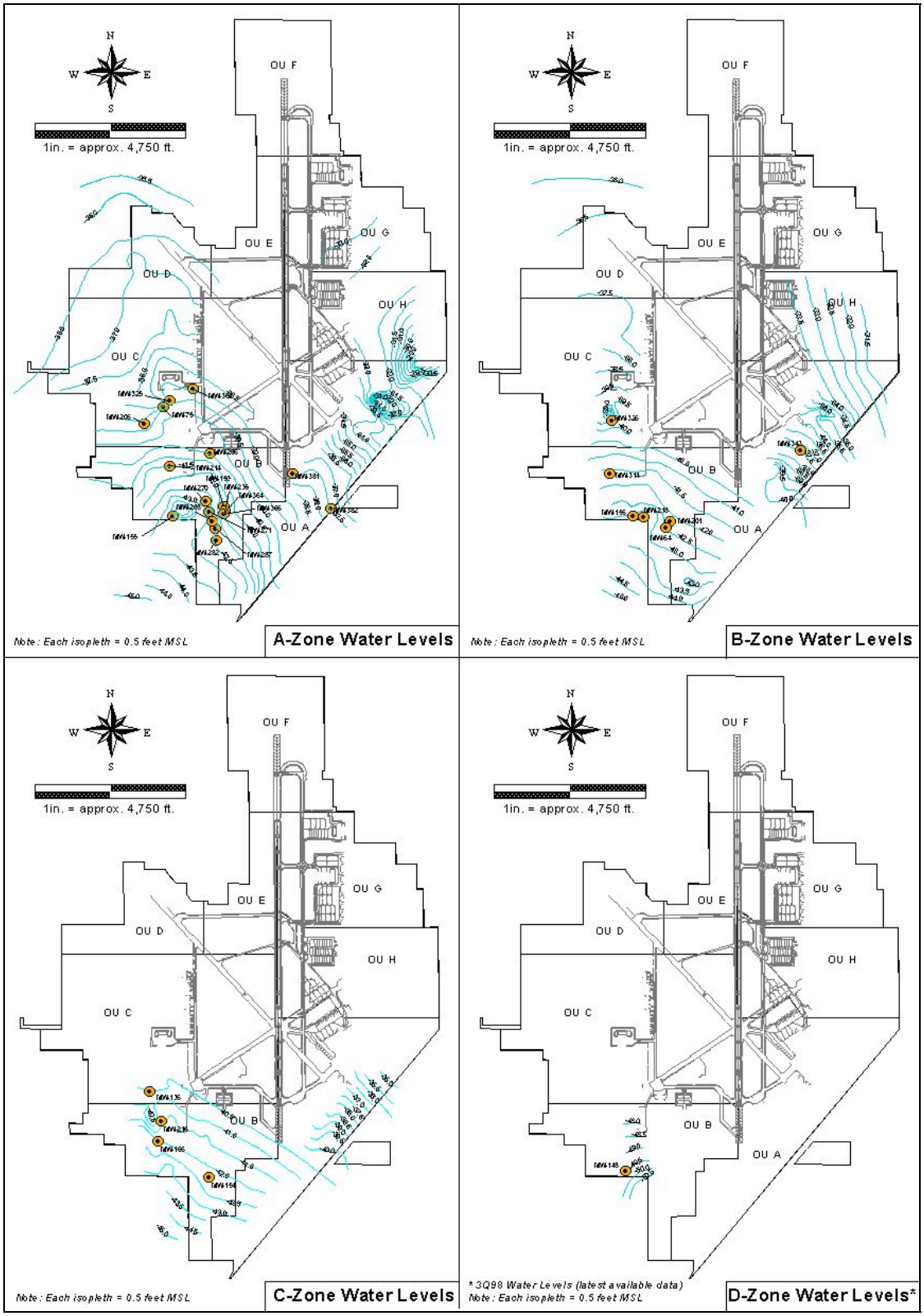

Figure 3.8. 2Q99 Groundwater Elevations in the A, B, C, and D Monitoring Zones

4.0 DEMONSTRATION DESCRIPTION

This section describes the principles of the diffusion sampler technology including the implementation of the sampling protocol. The groundwater sampling strategy QA/QC results are also presented in this section. Additional detail on the diffusion sampling principles and procedures are provided in the *Final Passive Diffusion Membrane Samplers Work Implementation Plan* (McClellan AFB, 1999).

4.1 TECHNOLOGY PRINCIPLES

Monitoring wells are installed in and around known or suspected sources of contamination as a tool to measure the dissolved concentrations of contaminants in the groundwater. The objective of the monitoring well design and construction is to obtain a accurate assessment of the water quality in the formation adjacent to the well screen (Puls and Barcelona, 1989; Vance, 1998). The conventional approach to sampling groundwater monitoring wells for VOC analysis involves purging a minimum of three to five well casing volumes of water from the well and stabilization of water quality parameters such as temperature, pH, and conductance prior to sample collection. The intent of purging prior to sample collection is to evacuate standing well water and access the adjacent formation water (Puls and McCarthy, 1993; Radian International, 1997c; US EPA, 1986). Originally, these purging procedures were developed for assessing inorganic contamination to avoid the disturbance of fines or precipitates which may enter or form in the well due to chemical reactions (*i.e.*, redox conditions) and accumulate inside the well casing (Puls and Barcelona, 1989). Concerns have arisen in regards to the representativeness of samples collected using this method, especially when sampling for trace amounts of organic and inorganic contaminants (Puls and McCarthy, 1993; Robbins, 1993).

Recent studies suggest that purging three to five casing volumes of water prior to VOC sampling is sometimes unnecessary, and in some cases, may produce undesirable effects (Gibs and Imbrigotta, 1990; Powell and Puls, 1993; Kearl *et al.*, 1992; Barcelona *et al.*, 1994). Insertion of sampling devices (*e.g.*, submersible pumps, bailers, etc.) may significantly increase the size and number of suspended colloidal particles (Kearl *et al.*, 1992; Puls *et al.*, 1992) in the sample collected. Since the turbidity decreases with time, this raises the possibility that insertion of a sampling device and subsequent sampling may yield water samples and colloids not representative of the ambient aquifer conditions immediately adjacent to the well screen. The resultant high turbidity of the sample is due to excessive downhole disturbance in the sampling zone including: mixing of stagnant casing water with water in the screened interval and the formation, aeration, degassing, and excessive turbidity due to high pump flowrates (Puls, 1993).

Other studies have demonstrated that mass averaging from differing water qualities along the length of the well screen can lead to misleading results of chemical and physical parameter analysis (Robbins, 1989; Martin-Hayden *et al.*, 1991; Robbins and Martin-Hayden, 1991; and Martin-Hayden, 2000). Other recent research has supported the conclusion that significant physical and chemical heterogeneities can exist over short distances within porous media (Davis *et al.*, 1993; Nikolaidis *et al.*, 1994). Increasing the purge volumes and flowrates may also increase the radius of aquifer (*i.e.*, lateral extent) influenced by the pumping, resulting in a sample that may represent an integration of differing water types. These studies determined that contaminant mass averaging is a function of well screen length, vertical concentration gradients, vertical variations in formation conductivity, well

construction materials (*i.e.*, filter pack in annular spacing between well screen and borehole wall), the amount of water recovered during purging, and the drawdown experienced when purging and sampling. In turn, these artifacts of the sampling procedure can lead to gross misinterpretations of contaminant distribution, fate and transport properties, and other physical, chemical, and biological parameters that influence the overall water quality.

Data from recent investigations suggest the water immediately adjacent to a well screen can be representative of aquifer water prior to purging. Robin and Gillham (1987) showed that ground water at their site traveled through the screened portion of a well with little interaction or mixing with water in the overlying well casing. In three of the four wells examined by Powell and Puls (1993), tracer tests indicated that the water in the screened interval exchanged with formation water and did not significantly mix with overlying casing water unless disturbed. In the fourth well, they found that the casing was constantly replenished with formation water throughout its volume with little or no time available for stagnation of casing water. The results of these studies implied that flow through the well across the screened interval was often horizontal, laminar, and representative of formation water immediately adjacent to the well screen. Kearl *et al.* (1992) used a downhole colloidal borescope to provide visual support of this hypothesis by showing advection of suspended sediment across the borehole. Thus, in a well with horizontal, laminar flow across the screened interval and little interaction or disturbance of the overlying water column, a sampling device in the screened interval potentially could be used to collect a representative sample while minimizing disturbance of the overlying water column in the well.

4.1.1 DIFFUSION SAMPLER SUMMARY

The diffusion sampler technology utilizes a deionized water-filled, low-density polyethylene diffusion membrane to collect water samples from groundwater monitoring wells for VOC laboratory analyses. The sampler membrane allows VOCs in groundwater within the well screen interval to diffuse into the deionized water. Chemical equilibrium between the groundwater and sampler water typically occurs within 14 days resulting in a water sample from the diffusion sampler that is representative of VOC concentrations in the well water. The diffusion samplers can be used to rapidly and inexpensively obtain groundwater samples for VOCs in monitoring wells (Vroblesky *et al.*, 1996; Vroblesky and Hyde, 1997). When used appropriately, representative samples can be obtained without well purging to identify temporal changes in well water chemistry (Vroblesky *et al.*, 1996).

The diffusion samplers also allow collection of samples from discrete depths intervals within the well casing. By placing multiple samplers within a monitoring well's screened interval, it is possible to develop a vertical profile of the VOC contamination along length of the well screen and identify specific geologic formations, if any, that may be contributing the highest concentrations. This methodology eliminates the potential for collecting samples that represent an integration of different water types (*i.e.*, contaminant mass averaging). In addition, once the vertical profile of the well contamination is defined, a sampling program can be developed that monitors only the formation(s) that contribute the highest VOC concentrations. In most cases, one diffusion sampler placed at the midpoint of the well screen may be sufficient to collect a sample that is representative of water in the entire well. Previous field investigations of the methodology showed a close correlation between VOC concentrations in water obtained using the samplers without prior purging and concentrations in water samples obtained from the respective wells using traditional purging and sampling approaches (Vroblesky and Hyde, 1997; Vroblesky *et al.*, 1999).

Furthermore, potentially large cost savings in long-term groundwater monitoring efforts may be realized due to the simplicity of the diffusion samplers compared to traditional purge-and-sample techniques. This methodology significantly reduces or eliminates the costs associated with conventional well purging and micropurging including labor, equipment, and purge water disposal may be substantial.

4.1.1.1 Description of Sampling Device

Samplers are typically constructed from 1.5-feet sections of polyethylene tubing, filled with deionized water, and heat-sealed on both ends. The samplers are placed in "flex-guard" low-density polyethylene mesh tubing for structural support and attached to a weighted rope with nylon cable ties (see Figure 4.1). The rope is lowered into the well until the sampler(s) are located at the appropriate depth(s); and then the rope is then secured at the wellhead (see Figure 4.2).

The diffusion samplers remain undisturbed in the wells until equilibrium between the water in the well casing and water in the diffusion samplers is achieved. VOCs will move from the contaminated groundwater, through the semi-permeable membranes, into the initially uncontaminated deionized water due to the diffusion transport mechanism. Diffusion causes solutes, in this case VOCs, in water to move from an area of high concentration to an area of lower concentration, and typically will occur in the absence of water velocity.

4.1.1.2 Equilibration Period and Sample Collection

Equilibrium time is variable; however, laboratory data indicate the diffusion samplers equilibrate with surrounding water within approximately two to three days, depending on the hydrogeologic characteristics of the aquifer (Vroblesky and Campbell, 1999). An equilibrium time of 14 days was used for this study (McClellan AFB, 1999) in accordance with the draft protocols developed by the USGS (Vroblesky and Campbell, 1999). Periods of longer than 14 days are also acceptable with no adverse impacts on data quality. In that, diffusive transport will allow VOCs in the samplers and the aquifer to remain in equilibrium assuming relatively steady-state conditions are present.

Upon recovery of the diffusion samplers from the wells, the samplers are opened with decontaminated scissors and water samples are transferred into 40-milliliter (mL) VOA bottles. The samples are preserved as required by the analytical method and submitted to a California-certified laboratory for VOC analysis.

4.1.2 ADVANTAGES, DISADVANTAGES, AND LIMITATIONS

Advantages: The diffusion sampler methodology has several potential advantages over currently available sampling protocols, such as:

- Capability of collecting groundwater VOC samples that are representative of concentrations directly adjacent to the well screen;
- Capability of collecting samples from discrete depth intervals of 1.5 ft along the length of the well screen;
- Samples collected do not represent an integration of contaminant concentrations along the length of the well screen where vertically dissimilar contamination profiles exist;

Figure 4.1. Installation of Diffusion Samplers into a Monitoring Well

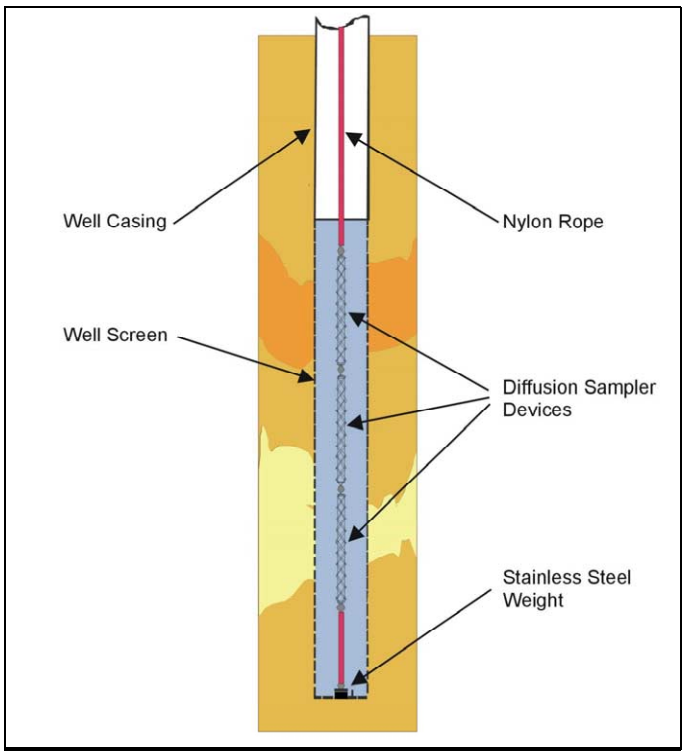

Figure 4.2. Schematic of Diffusion Samplers Installed in a Groundwater Monitoring Well

- Does not require well purging prior to sample collection, thus minimizing labor costs and eliminating costs for purging/sampling equipment and minimizing wastewater disposal;
- No capital and low material costs; and
- No dedicated equipment to maintain.

Disadvantages and Limitations: The diffusion sampler methodology has potential disadvantages and limitations compared to conventional technologies, such as:

- The methodology is not applicable to metals and other contaminants such as SVOCs that do not readily diffuse across the semi-permeable membrane;
- Significant cost savings may not be realized at sites that routinely monitoring groundwater for non-VOC contaminants in addition to VOCs; and
- May not be applicable for sites where water in well casing is stagnant or otherwise not representative of the aquifer adjacent to the well screen.

4.2 MONITORING SYSTEM INSTALLATION AND OPERATION

This section describes the logistics of the installation and operation of the diffusion sampler equipment.

4.2.1 EQUIPMENT INSTALLATION AND OPERATION

The diffusion sampler demonstration was conducted concurrently with the 2Q99 GWMP sampling event at McClellan AFB.

4.2.1.1 Diffusion Sampler Installation

A total of 188 diffusion samplers were installed in 30 groundwater monitoring wells at McClellan AFB (Figure 4.3) between 12 and 18 May, 1999. Multiple samplers were attached end-to-end onto a nylon rope and lowered into the wells. Depending on the saturated length of the well screen, between three and 13 of the 1.5-ft long samplers were installed in each well. Table 4.1 shows the saturated well screen lengths, number of samplers, and depths of samplers installed. A stainless steel weight was attached to the end of the sampler string to insure the rope was taught, and sampler placement at the correct depth. Standard operating procedures for the sampler installation were developed to insure wells were instrumented properly and consistently (McClellan AFB, 1999).

Water level measurements were taken prior to sampler installation to determine the length of the saturated well screen. Of the 18 A-zone monitoring wells in the study, 10 had only partially saturated well screens (*i.e.*, the water table was encountered within the screened interval). Each string of samplers was constructed with an odd number of sample bags so the sampler at the center of the sampler string (see Figure 4.2) could be placed at the midpoint of the saturated screen interval, approximating where the conventional sampling pumps would draw water while ensuring that an equal number of samplers were installed above and below the midpoint. This procedure also allows for the direct comparison between conventional sampling and a single diffusion sampler placed at the

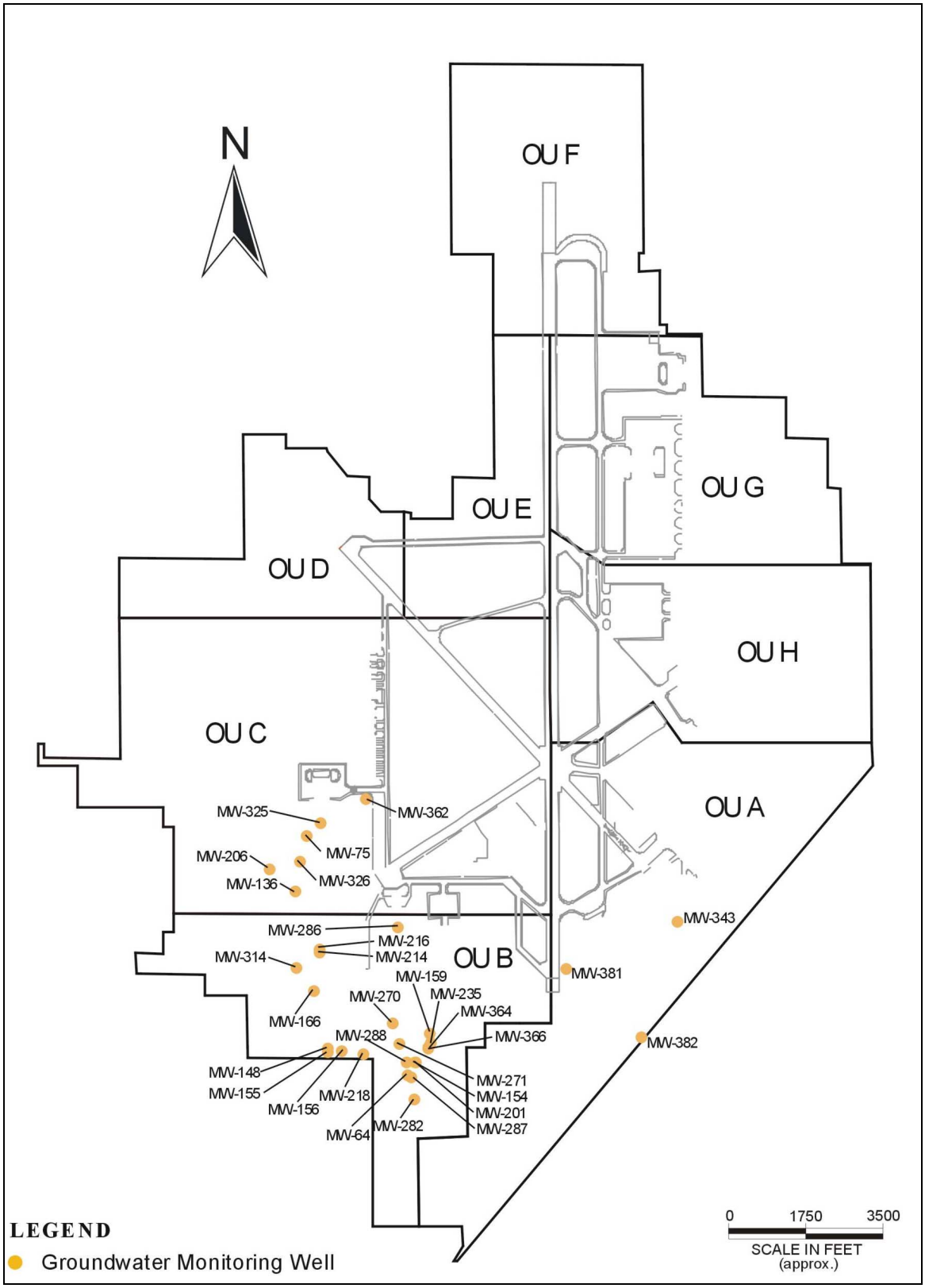

Figure 4.3. Diffusion Sampler Monitoring Well Locations

Table 4.1. Diffusion Sampling Well Locations and Installation Depths

Well Number	Monitoring Zone	Saturated Screen Length (ft)	Number of Samplers	Sampler Depth (ft bgs) A (Shallowest) → M (Deepest)												
				A	B	C	D	E	F	G	H	I	J	K	L	M
MW-155	A	10	5	117.5	119	120.5	122	123.5								
MW-159	A	10	5	109	110.5	112	113.5	115								
MW-206	A	17	9	99.1	100.6	102.1	103.6	105.1	106.6	108.1	109.6	111.1				
MW-214	A	14.5	5	105.9	107.4	108.9	110.4	111.9								
MW-235	A	10	5	108	109.5	111	112.5	114								
MW-270	A	11.4	5	109.3	110.8	112.3	113.8	115.3								
MW-271	A	15	7	113	114.5	116	117.5	119	120.5	122						
MW-282	A	16	7	104.5	106	107.5	109	110.5	112	113.5						
MW-286	A	14.6	9	104.7	106.2	107.7	109.2	110.7	112.2	113.7	115.2	116.7				
MW-287	A	10	5	117.5	119	120.5	122	123.5								
MW-288	A	16.6	9	107.7	109.2	110.7	112.2	113.7	115.2	116.7	118.2	119.7				
MW-325	A	19.6	9	103.22	104.72	106.22	107.72	109.22	110.72	112.22	113.72	115.22				
MW-362	A	10	3	104.4	105.9	107.4										
MW-364	A	8	3	123.5	125	126.5										
MW-366	A	19.2	11	107.1	108.6	110.1	111.6	113.1	114.6	116.1	117.6	119.1	120.6	122.1		
MW-381	A	19.8	13	110.7	112.2	113.7	115.2	116.7	118.2	119.7	121.2	122.7	124.2	125.7	128.7	127.2
MW-382	A	19.6	9	112.7	114.2	115.7	117.2	118.7	120.2	121.7	123.2	124.7				
MW-75	A	10	5	117	118.5	120	121.5	123								
MW-156	B	10	5	177.5	179	180.5	182	183.5								
MW-201	B	10	5	160	161.5	163	164.5	166								
MW-218	B	10	5	178	179.5	181	182.5	184								
MW-314	B	10	5	157	158.5	160	161.5	163								
MW-326	B	10	5	180	181.5	183	184.5	186								
MW-343	B	10	5	162	163.5	165	166.5	168								
MW-64	B	10	5	166	167.5	169	170.5	172								
MW-136	C	15	9	231.5	233	234.5	236	237.5	239	240.5	242	243.5				
MW-154	C	10	5	258.7	260.2	261.7	263.2	264.7								
MW-166	C	10	5	239	240.5	242	243.5	245								
MW-216	C	10	5	232.2	233.7	235.2	236.7	238.2								
MW-148	C/D	10	5	290	291.5	293	294.5	296								
Total Number of Samplers			188													

saturated well screen midpoint. This is the how the diffusion samplers are anticipated to be used widely in the field.

4.2.2 WASTE GENERATION

Two waste streams (*i.e.,* wastewater and solid waste) were generated by the diffusion sampler demonstration:

- **Diffusion Sampler Wastewater:** Because the diffusion sampler technology is a no-purge technique for groundwater sampling, the volume of wastewater generated by the diffusion samplers is orders of magnitude less than the volume generated by conventional purge-and-sample and micropurge techniques. A typical diffusion sampler bag contains approximately 300-mL of water. Of that volume, 160-mL are transferred to four 40-mL VOA vials for shipment to the laboratory. Therefore, each sampler generates less than 140-mL of wastewater. In total, the 188 samplers used in this demonstration generated approximately 4.2 liters, or 1.1 gallons, of wastewater requiring disposal.

- **Conventional Sampling Wastewater:** The volume of wastewater generated by the GWMP sampling crews were not documented during the diffusion sampler demonstration. In general, purging three to five well casing volumes prior to sample collection can generate between 25 to 250 gallons of purge water requiring subsequent disposal. Using this range, the 30 study wells could have produced between 750 to 7,500 gallons of wastewater.

- **Spent Diffusion Membranes:** Since the diffusion sampler membranes were cut open for sampling, they were not suitable for reuse. The 188 spent sampler membranes were placed into plastic bags, scanned with an organic vapor analyzer, and determined to be non-hazardous waste. These samplers were subsequent disposed of as sanitary solid waste.

4.3 THE THREE PHASES OF THE TECHNOLOGY DEMONSTRATION

Field activities conducted to complete the demonstration objectives presented in Section 2.2 proceeded in three phases:

1) Installation of 188 diffusion samplers in 30 groundwater monitoring wells in the southern and western portions of McClellan AFB;

2) Recovery of the diffusion sampler followed by subsequent sampling and analysis of 188 samples, and 18 duplicate samples, for VOC contamination;

3) Collection and analysis of 30 groundwater samples during the 2Q99 GWMP sampling event.

All site activities were conducted in accordance with procedures approved in the McClellan AFB Basewide Remedial Investigation/Feasibility Study (RI/FS) Quality Assurance Project Plan (QAPP, Radian International, 1997c) and the project work plan (McClellan AFB, 1999).

4.4 SAMPLING STRATEGY AND QA/QC RESULTS

This section describes the sampling plan developed to meet the objectives stated in Section 2.2. The analytical results and descriptive statistics of the diffusion sampler data set are contained in Appendix A. Appendix B contains the 2Q99 GWMP analytical results for the 30 study wells. The project work plan (McClellan AFB, 1999) contains the procedures used during this effort.

4.4.1 MONITORING WELL SELECTION

The monitoring wells (MWs) chosen for this field demonstration (see Figure 4.3) were representative of the varying VOC groundwater contamination conditions across the base. Historic quarterly groundwater sampling data were used to identify a set of wells exhibiting a wide range of VOC concentrations, depths, and well screen lengths. Historic VOC concentrations at McClellan AFB range from non-detect (ND) levels to greater than 10,000 µg/L (CH2M Hill, 1994). Therefore, an important factor in assessing the performance of any groundwater sampling technique is to target the wide range of VOC concentrations expected across the base. A majority of the wells sampled in the GWMP report concentrations between MCLs and the "hot spot" concentration (*i.e.,* 100 times the MCL). Table 4.2 provides a qualitative summary of the historic TCE concentrations reported in the monitoring wells chosen for this study.

In addition, 12 of the 30 selected wells have long saturated well screen lengths (*i.e.,* greater than 10 feet of well screen below the water table). Given the heterogeneity of the aquifer matrix beneath McClellan AFB, placing multiple samplers end-to-end along the length of the well screen interval offered the opportunity to investigate whether there are any distinctive variations with depth in concentration data associated with changes in lithology.

Table 4.2. Summary of VOC Contamination in Test Wells

	TCE <MCL	TCE >MCL	Interior Plume[a]
Well Number	MW-64	MW-136[b]	MW-75
	MW-201	MW-148	MW-156
	MW-206[b]	MW-154	MW-159
	MW-218	MW-155	MW-216
	MW-282[b]	MW-166	MW-235
	MW-343	MW-214[b]	MW-270[b]
	MW-362	MW-271[b]	MW-287
	MW-382[b]	MW-286[b]	MW-288[b]
		MW-314	MW-325[b]
		MW-326	MW-364
		MW-381[b]	MW-366[b]
Totals	8	11	11

[a] Interior Plume = Historical TCE concentrations reported in these wells are generally greater than 50 µg/L.
[b] Wells with 15 feet or longer well screens and saturated screen length greater than 10 feet.

4.4.2 DIFFUSION SAMPLER RECOVERY

The samplers remained undisturbed in the wells for 14 days (see Section 4.2.1 for details on sampler installation). The diffusion samplers were recovered from the monitoring wells between 27 May and 4 June, 1999 in the same order of installation. Upon recovery of the diffusion samplers from the wells, the samplers were cut open with decontaminated scissors and water samples immediately transferred into 40-mL VOA bottles. The groundwater sample was carefully poured down the inside

of the VOA bottle to prevent significant aeration of the sample. Sample collection proceeded from the top of the sampler string to the bottom. The sampler string was secured to the wellhead and left hanging in the well casing while individual samples were being collected to minimize any potential disturbance to the sampler water due to agitation, sunlight, or other sources of ambient sample contamination at the surface.

4.4.3 CONVENTIONAL GROUNDWATER SAMPLING

Once all of the samples had been collected from the diffusion samplers at a given well, the well was then sampled as part of the 2Q99 GWMP sampling event. The GWMP sampling crew typically arrived at a given well within two or three hours after the diffusion samplers were removed. All wells were sampled by both methods on the same day. A Grundfos® submersible pump was used to collect groundwater samples from all monitoring wells in accordance with SOP No. McAFB-013 (Radian International, 1997c). Prior to collection, the wells were purged of a minimum of three well casing volumes until temperature, specific conductance, and pH stabilized as required by the Basewide RI/FS QAPP and GWMP (Radian International, 1997b; Radian International, 1997c).

4.4.4 GROUNDWATER SAMPLE ANALYSES

Groundwater samples collected using the diffusion sampling methodology and the conventional purge-and-sample protocols were packaged and shipped to the Radian Analytical Services laboratory in Austin, Texas on a daily basis. These samples were analyzed for VOCs using EPA Method SW8260B in accordance with the Basewide QAPP (Radian International, 1997c). In addition, 19 duplicate samples were collected from the diffusion samplers and shipped to a second California-certified analytical laboratory , Quanterra Laboratory in West Sacramento, California to assess the performance of the primary laboratory.

4.4.5 SAMPLE CONTAINERS AND PACKAGING

Sample containers for each analytical method are listed in Table 4.3. Where noted in Table 4.2, containers were pre-cooled before sampling to minimize loss of volatiles. Samples for VOCs were collected in pre-cooled, 40-mL glass VOA vials fitted with Teflon® septa. To avoid loss of volatiles to the headspace of the VOA vials, it was critical that the vials be completely filled, with zero headspace. Liquid samples destined for off-site analysis were collected in containers supplied by the laboratory with the appropriate preservative already in the container. The appropriate preservative for each analytical method is shown in Table 4.3. The samples were chilled in coolers immediately after collection.

Samples for the laboratory were packed in cleaned coolers with several ice packs. Shock absorbent packing was added to the cooler to prevent breakage of containers. A Chain-of-Custody (COC) form, within a plastic bag to protect it from water, was taped to the lid of the cooler, along with the sample identification number. The samplers relinquished custody of the coolers to an express carrier which delivered them to the off-site laboratory the following morning.

The sampling shipping schedule met all of the holding requirements in Table 4.3 to maintain sample integrity (See 4.4.5). Prompt shipment ensured the laboratory had adequate time to perform analyses before expiration of holding times.

Table 4.3. Sample Storage and Preservation Requirements

Parameter	Method	Holding Time	Container	Preservation	Storage Requirements
Purgeable Organic Compounds	SW8260B	14 days	Four 40-mL glass vials with Teflon liners	pH <2 with HCl	4°C

HCl = hydrochloric acid
°C = degrees Centigrade
mL = milliliters

4.4.6 QUALITY ASSURANCE SAMPLING

To assure the quality of the data collected during this demonstration, personnel took obtained collection duplicates, trip blanks, and field blanks according to the Data Quality Objectives for Definitive Data from the Basewide QAPP (Radian International, 1997c) and the WIP (McClellan AFB, 1999). Primary samples, trip blanks, and field blanks were analyzed by the Radian Analytical Services. Duplicate samples, trip blanks, and field blanks were also sent for analysis to Quanterra Laboratory, for comparison with the Radian Analytical Services analytical results. All sampling personnel had current 40-hour HAZWOPER training according to 29 CFR 1910.120 and were trained in the appropriate, approved sampling techniques as required by WIP (McClellan AFB, 1999).

A cursory evaluation of the data summary and validation conducted by the McClellan AFB contractor as reported in the 2Q99 GWMP report (Radian International, 1999b) revealed anomalies (*e.g.,* failure to note laboratory reporting deviations from the requirements of the Basewide RI/FS QAPP [Radian International, 1997]). Therefore, an additional comprehensive data review and validation was conducted by the contractor preparing this report. This review consisted of a complete, *i.e.,* 100 percent, review of both electronic and raw laboratory data deliverables. Details of this evaluation are included in Appendix C. Table C.1 displays the data that were qualified during the QA/QC review process. Table A.1 presents a master listing of the analytical results for the diffusion sampling. The master log of 2Q99 analytical results and accompanying QA/QC evaluation for the GWMP data can be found in the 2Q99 GWMP report (Radian International, 1999b).

All data produced from the diffusion sampling are valid according the requirements of the Basewide RI/FS QAPP and project-specific Quality Assurance Project Plan (QAPjP). The following is a summary of the QA/QC results for this effort:

- All samples results were useable (*i.e.,* 100% completeness). This meets the completeness requirement for this project;
- A total of 522 results were qualified as estimated and assigned a "J" flag because they were detected between the laboratory practical quantitation limit (PQL) and method detection limit (MDL).
- Of the 12,978 analytical results, 210 were qualified as estimated or non-detect because one or more QA objectives were not met;
- A total of 173 analytical results for acetone were qualified as non-detect and assigned the QA flag "U" due to analytical equipment contamination;

- A total of 25 analytical results for methylene chloride were qualified as non-detect and assigned the QA flag "U" due to analytical equipment contamination;
- The Relative Percent Difference (RPD) pairs for 2 analyses exceed project criterion and the associated data qualified as estimated and assigned a "J" flag;
- For 23 RPD pairs one laboratory reported a concentration while the other laboratory reported the result as not detected. All positive data were qualified as estimated with a "J" flag;
- All laboratory analyses met the accuracy requirements of the QAPjP (*i.e.,* percent recoveries for matrix spike/matrix spike duplicates and laboratory control samples were within the established limits); and
- The sampling data meet the criteria for comparability and representativeness set forth in the QAPjP.

4.4.6.1 Precision

A total of 19 duplicate samples were analyzed for VOCs by EPA Method SW8260B at a second analytical laboratory (Quanterra, West Sacramento, California). Relative percent difference between the diffusion sampler results and the collection duplicates was calculated using Equation 4.1.

Equation 4.1

$$RPD = \left(\frac{(C_1 - C_2)}{(C_1 + C_2)/2} \right) \times 100\%$$

where: RPD = relative percent difference
C_1 = the larger of the two observed values
C_2 = the smaller of two observed values

Except as noted below, all primary (Radian Analytical Services) and secondary laboratory RPD samples met project RPD criteria. The analysis of RPD values shows that there is good intercomparability between laboratories, thus the primary laboratory analysis results are appropriate for use. Samples from location MW-156E had an RPD of 38% for 1,1-DCE. This is within the 50% maximum accepted RPD for samples analyzed by differing laboratories and is due to laboratory dilution performed on the sample analyzed by the secondary laboratory. Similarly, *cis*-1,2-DCE results from location MW-366E had an RPD of 49.6%.

Cis-1,2-DCE samples from location MW-64-B had an RPD of 130.7%. Both samples had reported concentrations less than the laboratories PQL and were flagged as estimated. The RPD for TCE in samples from location MW-64B was calculated at 101.5%. The secondary laboratory report TCE at concentrations above the PQL, while the primary laboratory reported values of less than PQL. *Cis*-1,2-DCE and TCE samples from locationMW-64-B were flagged as estimated due to the high RPDs.

In 23 other instances, RPD values were not calculated as one laboratory reported values near the MDL while the other laboratory reported concentrations as non-detect. In these cases, a UJ flag was added to all non-detect values.

4.4.6.2 Accuracy

Accuracy is determined from the formula of Equation 4.2.

Equation 4.2
$$\%R = \frac{C_i - C_o}{C_t} \times 100$$

where:
%R = percent recovery
C_I = measured concentration of spiked sample aliquot
C_o = measured concentration of unspiked sample aliquot
C_t = actual concentration of spike added

During the 100% data review, data from laboratory control samples and matrix spike/matrix spike duplicate pairs were compared to requirements of the QAPjP and Basewide RI/FS QAPP. The percent recovery for all laboratory control samples and matrix spike/matrix spike duplicate pairs were verified as being within the acceptable range for the specific compound analyzed. In that, all data meet the accuracy requirements of the QAPjP.

4.4.6.3 Completeness

Completeness was calculated for the data using the formula in equation 4.3:

Equation 4.3
$$\%\ Completeness = {}^{VDP}\!/_{TDP} \times 100$$

where:
VDP = number of valid data points
TDP = number of total samples obtained

Following the 100% review of the data, completeness was calculated as 100%. In that, all data were found to be suitable for their intended use. This exceeds the project completeness requirement of 95%.

4.4.6.4 Comparability and Representativeness

Comparability refers to the confidence with which one data set can be compared to another. Comparability is essential for the evaluation of technology performance compared to that of similar technologies. Comparable data was generated during this project by following standard SW-846 and U.S. EPA protocols for all laboratory analyses, and by following manufacturers' instructions for all field meters and measurement devices. A review of the field log books and field QA inspections indicate that data meets the project requirements for this qualitative quality indicator and is considered comparable to other data sets.

Representativeness is a measure of the degree to which data accurately and precisely represent the conditions of the parameter represented by the data. Collected samples must be representative of the matrix characteristics and contamination concentrations of the aquifer. Representativeness is affected by errors introduced through the sampling process, field contamination, preservation, handling, sample preparation, and analysis.

Representativeness was ensured through the following practices:

- using the necessary number of samples, sample locations, and sampling procedures that depicted, as accurately and precisely as possible, the matrix and conditions measured;
- utilizing SOPs and protocols for storage, preservation, and transport that preserved the representativeness of the collected samples;
- documenting that protocols have been followed and that samples were properly identified to maintain integrity and traceability; and
- using standard, well-documented analytical procedures that ensured consistent, representative data.

While none of the above practices can be quantified as a measure of representativeness, QC samples were collected to indicate factors that may affect representativeness. The QC samples to be used for this purpose include:

- field duplicates to indicate variations caused by sampling techniques;
- equipment blanks to indicate contamination caused by incomplete decontamination;
- trip blanks to indicate contamination of samples during transport; and
- field blanks to indicate contamination introduced through ambient conditions.

Results of the field duplicates have been previously discussed. Equipment blanks, trip blanks, and field blanks are discussed in subsequent sections. Overall, the project data were determined to meet the representativeness criteria of the QAPjP.

4.4.6.5 Equipment Blanks

Equipment blanks were obtained for off-site analysis. One equipment blank, MW-235-EB, reported 1,1-DCE concentrations of 9.97 µg/L. After a careful review of the laboratory data from the sample, the laboratory data from surrounding samples, and field log books it was determined that the source of contaminants was not due to field equipment or as a result of laboratory preparation or analytical carryover. As the source of the water for the equipment blank was an unused diffusion sampler, the probable cause of the contamination was improper storage of the diffusion sampler in the field. Improper sample labeling in the field was discounted as this sample had dissimilar contaminant profiles from those included within that days sampling. Because of this, no flags were assigned to the corresponding data set.

4.4.6.6 Trip Blanks

Trip blank samples were prepared in the field and included with each shipment to an analytical laboratory. Acetone was detected in 3 trip blanks and chloroform in one trip blank. All acetone and chloroform results were flagged as J due to field contamination.

4.4.6.7 Field Blanks

An ambient field blank sample was taken and analyzed during the diffusion sampling effort. No contaminants were reported in the sample and, therefore, no data flags were applied.

4.4.6.8 Quantitation Limits

The PQL for all primary laboratory samples met the project requirements as specified in the WIP and QAPP. The secondary laboratory did not meet the PQL for all compounds due to required dilutions. This did not adversely effect the quality of the data or impact the use of the data for its stated purpose.

4.4.6.9 Field Audit

A field audit was performed during the 2Q99 field effort. Results of the field audit are included in 2Q99 GWMP report (Radian International, 1999). No significant problems were identified during the audit.

4.4.6.10 Other Quality Assurance Indicators

During the data validation and assessment, two deviations from project requirements were noted. First, the primary laboratory did reported the MDL and PQL as the same value although the PQL was typically two to five times greater than the MDL. The McClellan AFB subcontractor that performed the sampling applied the appropriate PQL to the laboratory data following receipt in its local offices and the applied PQL was not included within the data deliverable. This project had a specific requirement that the laboratory report both the MDL and PQL for each compound for each analysis.

Lastly, the secondary laboratory did not always report the MDL (*i.e.,* only reported the PQL) for the analysis as dictated by project requirements. Therefore, it was not always possible to verify the accuracy of the data flags assigned by the laboratory.

While both of these discrepancies require corrective action, neither is indicative a systemic quality assurance problem and do not adversely effect the quality of the project data.

5.0 TECHNOLOGY PERFORMANCE EVALUATION

This section summarizes the results of the diffusion sampler demonstration with respect to monitoring effectiveness and system performance. The demonstration objectives are presented in Section 2.2 and, the principles of the diffusion sampler technology are described in Section 4.1.

5.1 PERFORMANCE DATA

This section presents the data generated from groundwater samples collected during the demonstration sampling activities. These data have been compiled for use in evaluating the diffusion sampler performance. The diffusion sampler analytical results from the 30 wells were compared to data collected during the 2Q99 GWMP sampling event using conventional purge-and-sample procedures. This comparison included both qualitative and statistical analyses of the data sets to evaluate the representativeness of the diffusion sampler data and its comparability to the GWMP data. The complete set of diffusion sampler data is presented in Appendix A. Appendix B contains the analytical results from the 30 study wells collected during the 2Q99 GWMP sampling event.

The first step in the evaluation process was to determine the acceptable level of variability between the two data sets due to inherent variations in the sampling procedures and analytical methods. The next step was to use the VOC concentration data from the diffusion sampler data set to develop vertical contamination profiles for each of the study wells. These profiles were used in conjunction with available lithologic data to assess any potential relationships between variations in VOC concentrations with depth and the geologic formations adjacent to the well screen sampling interval.

Once these profiles were developed, statistical analyses were used to evaluate the comparability of the two data sets. The comparability of the data sets were evaluated under two different scenarios to determine the optimal placement of one diffusion sampler to be representative of the highest contamination in a given well. The first set of tests compared the GWMP results to the entire diffusion sampler contamination profile (*i.e.*, mean diffusion sampler concentrations). These data were also used to determine if environmental conditions such as well depth, proximity to source areas, or geology might influence the diffusion sampler results. The second scenario evaluated the comparability of the GWMP results to VOC concentrations in the diffusion sampler installed at the midpoint of the saturated well screen interval. In wells that have significant vertical contamination profiles, one sampler placed at the midpoint of the well screen may not capture the highest zone of contamination.

5.1.1 HYDROGEOLOGIC CONSIDERATIONS

As mentioned in Section 4.1, the diffusion samplers require that the formation water travel through the well screen interval (*i.e.,* the technique is not suitable for wells with stagnant water in the screened interval). While no criteria for sufficient flow through the well screen has been established to date, the water level maps shown in Figure 3.8 suggest that even when the groundwater extraction wells are not in operation at McClellan AFB, the natural groundwater gradients are sufficient for allow formation water to exchange with the water in the well screens without pumping.

5.1.2 DERIVATION OF ACCEPTABLE LEVEL OF VARIABILITY IN ANALYTICAL DATA

Before one can make comparisons between or drawn conclusions from chemical data derived from any environmental samples, it is essential to quantify the acceptable degree of variability of the data. As discussed previously, stringent QA/QC measures are implemented in the McClellan GWMP to produce a data set of known and acceptable "quality" for use in decision making. Given the high degree of heterogeneity of subsurface conditions beneath McClellan AFB and the numerous artifacts of groundwater sampling and analysis concentration data should be viewed as an estimate of the true contamination rather than a concrete numerical value. A well-implemented QA/QC program is necessary to quantify the errors introduced during the sampling and analysis of environmental samples (*i.e.*, to determine the quality of the data set).

In an effort to determine the quality of data collected, the Basewide RI/FS QAPP (Radian International, 1997c) establishes a variety of quality assurance parameters to measure the precision and accuracy of a data set. Field duplicate samples are often collected during sampling events and sent to the same analytical laboratory as the normal samples to evaluate the ability of a sampling crew and procedures to collect samples with repeatable results. The acceptable variability in analytical results between a normal environmental sample and it's paired field duplicate is typically an RPD value less than 30% (Radian International, 1997c). Split samples are collected in the same manner as field duplicates, but are sent to a second laboratory for confirmation purposes. Acceptable RPD values for split samples are typically greater than those for field duplicates. Yet, since no formal QA/AC criteria have been established for split samples, the 30% RPD is used as a conservative starting point. This is a relatively high degree of variability and was used as a general rule.

An evaluation of the split samples collected during the diffusion sampling study (see Appendix D) suggests that the expected analytical variability due to sample collection is significantly less than 30%. A total of 19 split samplers were collected during the study and sent to a second analytical laboratory for confirmation purposes. From these samples, 39 sample/analyte matches between the normal and split sample data sets were identified. These data showed that the average RPD between the split sample results was 10.4%, but only 44% of the sample pairs had RPD values less than 10%. However, 32 of the 39 pairs (82%) had an RPD value of less than 15%, while 92% of the pairs were less than 20% different. Based on this distribution of data, it was concluded that a RPD value of 15% or less was a reasonable standard to use as acceptable variability between the diffusion sampler and GWMP samples.

5.1.3 UNMATCHED ANALYTES IN DIFFUSION SAMPLERS

While comparison of the concentration data is the key factor in assessing sampler performance, the frequency of analyte detection is also an important factor to consider. Review of the data sets concluded that groundwater samples collected using the diffusion sampler were likely to report the presence of VOC species that were not reported in the GWMP samples. In fact, while there were 140 instances where the same contaminant was reported in samples from both data sets, in nearly half of the study wells, analytical results from the diffusion samplers indicated the presence of at least one, and often several, contaminants that were not reported in the GWMP sample (Table 5.1). As discussed in Section 4.1 these results are not surprising, given the inherent potential for conventional purge-and-sample protocols to bias VOC sampling results. TCE and PCE were the only VOCs that did not report unmatched results between the two data sets. Of the 22 cases where contaminants were reported in the diffusion samplers only, the unmatched VOCs typically had a lower molecular weight and/or were more soluble in water than TCE and PCE. In addition, these contaminants were reported

Table 5.1. Unmatched VOCs Reported in Diffusion Samplers Only

Contaminant	Unmatched Incidents	Range (µg/L)	Molecular Weight[b] (grams/mole)	Water Solubility[b] (mg/L)	@(°C)
No. of monitoring wells	14				
1,1-DCA	3	0.365-0.553	98.96	5,500	20
1,2-DCA	1	0.433	98.96	8,690	20
1,1-DCE	2	0.314-0.387	96.94	2,250	20
1,1,2-TCA	1	0.111	133.4	4,500	20
Carbon tetrachloride	3	0.164-0.735	153.81	800	20
cis-1,2-DCE	1	0.057	96.94	800	20
Chloroform	4	0.112-0.940	119.37	8,000	20
Freon 113	1	3.78	187.37	17	20
Toluene	2	0.228-0.235	92.15	515	20
trans-1,2-DCE	4	0.116-0.371	96.94	600	20
PCE	0		165.82	150	25
TCE	0		131.38	1,100	25
Total	22				

[a] Unmatched Incidents = analytes reported in diffusion samplers while not detected in the GWMP samples.
[b] LeGrega *et al.*, 1994
mg/L = milligrams per liter
°C = degrees Centigrade

at concentrations between the MDL and PQL. This suggests that the conventional purge-and-sample method may be agitating the samples enough to volatilize the lighter molecular weight compounds or drawing in water from geologic formations other than those immediately adjacent to the well screen, in effect diluting the true contamination of the formation water. While none of the additional VOCs reported in the diffusion samplers would have impacted any regulatory decisions, their presence suggests that the diffusion samplers may provide samples that are more representative of groundwater quality in the formations immediately adjacent to the monitoring well screen.

5.1.4 WELL CONTAMINATION PROFILES

One advantage of the diffusion samplers is the ability to install multiple samplers at different depths within the monitoring well to collect samples from discrete intervals. Once all the data from the diffusion samplers were compiled, well contaminant profiles were developed to assess whether individual geologic formations along the length of the well screen interval had differing water qualities. The profiles were developed by plotting the VOC concentrations versus the depth at which the samplers were installed. Since the samplers are approximately 1.5-ft long, the sample depth was identified as the depth of the midpoint of the sampler. The profiles were then overlaid onto the lithologic logs to assess whether any changes in VOC concentration could be attributed to changes in lithology (Appendix E). Figure 5.1 is an example of the lithologic log and well contamination profile prepared for each monitoring well. These sheets (Figures E.1 to E.30 in Appendix E) also show the well construction details, diffusion sampler placement, and water level measured in the well casing at the time of sample collection.

Dixon's Extreme Value Test (US EPA, 1998) was used to identify potential statistical outliers in the diffusion sampler data set that may be indicative of a significant difference in VOC concentrations along the length of the well screen (*i.e.*, distinctive contaminant profile). Any data that were

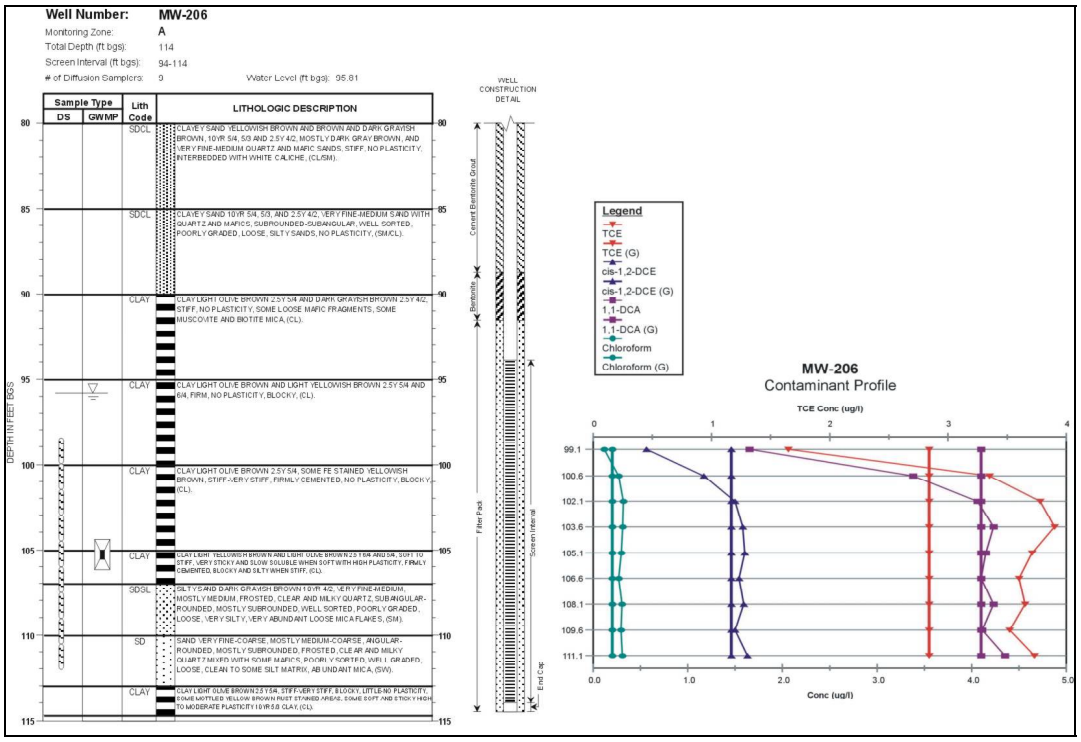

Figure 5.1. Example of Lithologic Log and Well Contaminant Profile

identified as potential outliers were further evaluated to determine if the concentrations were within the acceptable range of analytical variability (Table E.1 in Appendix E). Of the 30 monitoring wells instrumented with diffusion samplers, nine wells exhibited a statistically significant difference in VOC concentrations along the length of the well screen. The other 21 wells did not appear to have any distinctive vertical profile. Seven of the nine wells that exhibited apparent differences in concentration with depth were screened in the A monitoring zone. Furthermore, five of the 12 long-screened (*i.e.,* saturated screen lengths greater than 10 feet) wells exhibited distinct VOC concentration gradients along the length of the screened interval.

It appears that most of the variations in concentration are either a function of change in lithology or, in the case of Monitoring Well (MW)-206 (see Figure E.9), potential loss of VOCs into the vadose zone due to off-gassing from the water table into the capillary fringe. A brief description of the wells exhibiting these vertical concentration gradients is presented in Table 5.2.

The implication of the presence of these vertical concentration gradients is that conventional purge-and-sample results may not be representative of the true nature of contamination in the immediate vicinity monitoring well screen. In some cases, the data suggests that conventional GWMP sampling may be diluting the true contamination by vertically mixing waters from zones of higher and lower contamination. In other cases, preferential flow through coarse formations (*i.e.,* sands and gravels) may introduce contaminants, or clean water, into the sample stream that have traveled a significant lateral distance to the monitoring well; thus, integrating water quality over a large portion of the aquifer. When purging the long-screened wells, the potential effects of lateral and vertical averaging appear to increase. In general, when there was a significant difference in concentrations along the length of the saturated well screen, the lower concentrations appeared to be associated with fine-grained geologic formations (*i.e.*, silts and clays) or, in the case of several shallow wells, the close

Table 5.2. Monitoring Wells with Distinctive Vertical Concentration Gradients

Well Number/ (Zone)	Screen Length (ft)	No. of Samplers	Figure Reference[a]	Lithology Type[b]	Mean TCE Conc[c] (μg/L)	Description
MW-148 (C/D)	10	5	Figure E.2	High Low	16.6 NA	Bottom 2 samplers (294.5 and 296 ft bgs) adjacent to coarser sand layer reported significantly higher concentrations. May be geology related.
MW-154 (C)	10	5	Figure E.3	High Low	23.4 NA	Concentration spike (~30%) in 2nd sampler at 260.2 ft bgs. Entire screen located within same sandy gravel formation.
MW-155 (A)	10	5	Figure E.4	High Low	19.6 11.1	Increasing trend in concentration (~30%) with depth. Top 5 feet of screen located in silty clay formation. Remainder of screen in fine sand formation underlain with a clay layer at the bottom of well, 125 ft bgs.
MW-206 (A)	20	9	Figure E.9	High Low	3.63 3.33	Increasing trend in top 3 samplers. Top sampler located within 3 ft of water table. Trend likely due to proximity to water table.
MW-235 (A)	10	5	Figure E.13	No lithologic data available		Significant decrease in concentrations in 4th sampler at 112.5 ft bgs. No lithologic description available.
MW-271 (A)	15	7	Figure E.15	High Low	58.0 51.9	60% lower in concentrations in top sampler (113 ft bgs) located in clayey silt. Remainder of well screened in sand units beneath clayey silt formation.
MW-288 (A)	20	9	Figure E.19	High Low	166.5 169.5	7th sampler, 116.7 ft bgs concentrations 40% lower than other samplers. Bottom 5 samplers all placed within the same silty sand layer, thus low result not likely a function of lithology.
MW-381 (A)	20	13	Figure E.27	High Low	23.6 NA	Increasing trend in top 5 samplers (110.7-116.7 ft bgs) associated with silty sand layer in upper portion of well screen. Concentrations relatively stable in silty sands between 119-130 ft bgs (bottom of well screen interval).
MW-382 (A)	19.6	9	Figure E.28	High Low	4.5 NA	Increasing trend in top 3 samplers (112.7 to 115.7 ft bgs). Top sampler located within 3 ft of water table. Trend likely due to proximity to water table.

[a] Lithologic Logs and Well Contaminant Profile sheets are contained in Appendix E
[b] High = sands and gravels; Low = silts and clays
[c] TCE used as an indicator for VOC concentration trends
NA = Not Applicable (no geologic formation fitting this description)

proximity to the water table. Conversely, the higher concentrations were typically associated with coarse-grained materials (*i.e.*, sands and gravels).

5.1.5 STATISTICAL EVALUATION OF DIFFUSION SAMPLER DATA

The comparison between the diffusion sampler data and the purge-and-sample data gathered during the 2Q99 GWMP event was conducted under two scenarios. Given that the diffusion sampler data set

includes multiple sampling points per well, the first scenario compared the GWMP results from each individual well to that of the entire sample population of the diffusion sampler data set (*i.e.*, mean and standard deviation) for that well. The second comparison scenario evaluated whether one diffusion sampler placed at the midpoint of the saturated well screen was representative of the entire well (*i.e.*, statistically equivalent or superior to the GWMP data). Descriptive statistics were calculated for the diffusion sampler data including the mean, minimum, maximum, 95% confidence interval for the mean, standard error of the mean, standard deviation, variance, skewness, kurtosis, median, and 95% confidence interval for the median (see Table A.31 in Appendix A).

5.1.6 COMPARISON OF DIFFUSION SAMPLER POPULATION TO GWMP DATA

Several statistical tests were applied to evaluate the comparability of the diffusion sampler and GWMP data sets. Tests of means were used to determine if the VOC concentrations reported in the diffusion samplers were comparable to conventional purge-and-sample results from the 2Q99 McClellan AFB GWMP sampling event on a well-by-well basis. Paired t-tests were used to evaluated the basewide comparability of the data sets. In addition, the data were segregated and analyzed using non-parametric statistical and graphical methods to evaluate whether environmental variables (*e.g.,* well depth, geology, and proximity to source areas) may influence the results from diffusion samplers.

5.1.6.1 Well-By-Well Comparison (Test of Means)

A test of means was first used to determine if the analytical results of the diffusion samplers and the GWMP sample from individual wells represent a single statistical population. As previously mentioned, analytical results that were within ±15% of the mean were considered within the expected variability for samples analyzed by EPA Method 8260B (see Appendix D). Normality tests were performed on the diffusion sampler data using the Ryan-Joiner test (Ryan and Joiner, 1976) to ensure the data were appropriate for use in the following parametric tests. The test of means was performed on each well/analyte pair between the two data sets using one-sided approximate t-tests described in detail below.

The null hypothesis (H_o) for this test of means was:

> H_o: *The difference between the mean (u)concentration of specific VOCs detected above the analyte's method detection limit by the diffusion samplers and the analyte concentration reported in the 2Q99 GWMP sample is less than 15% of the GWMP concentration at the 95% confidence level.*

A one-sided approximate t-test was performed as the statistical test for this hypothesis using the following equation:

Equation 5.1:
$$t' = \frac{|x_1 - x_2| - d_o}{\sqrt{s_1^2/n_1 + s_2^2/n_2}}$$

where: H_o: $|u_1 - u_2| \leq d_o$
H_1: $|u_1 - u_2| > d_o$
t' = approximate t-statistic
x_1 = mean of the diffusion sampling concentrations

x_2 = GWMP sampling concentration
d_o = 15% difference (*i.e.,* 0.15 x GWMP concentration)
s_1 = standard deviation of the diffusion sampler concentrations
s_2 = standard deviation of the GWMP concentrations (0)
n_1 = number of diffusion samplers in the well
n_2 = number of GWMP samples from the well (1)

Since there was only one GWMP sample collected from each well, the standard deviation of the GWMP data (s_2) is zero and the n_2 value is 1. Thus, substituting these values reduces Equation 5.1 to:

Equation 5.2:
$$t' = \frac{|x_1 - x_2| - d_o}{\sqrt{s_1^2 / n_1}}$$

Since the t-test was performed at the 95% confidence level (*i.e.*, probability of a Type I error, α, equal to 5%), the following decision criteria was used to accept or reject the null hypothesis:

- Accept null hypothesis: $t' \leq t_{5\%}$; or
- Reject null hypothesis: $t' > t_{5\%}$

where: $t_{5\%}$ is the t-statistics determined for n_1-1 degrees of freedom where s_2 is zero and the n_2 value is 1as determined below:

Equation 5.3:
$$\nu = \frac{\left(s_1^2/n_1 + s_2^2/n_2\right)^2}{\frac{\left(s_1^2/n_1\right)^2}{n_1 - 1} + \frac{\left(s_2^2/n_2\right)^2}{n_2 - 1}} \Rightarrow \frac{\left(s_1^2/n_1\right)^2}{\frac{\left(s_1^2/n_1\right)^2}{n_1 - 1}} \Rightarrow n_1 - 1$$

5.1.6.1.1 Test of Means Results

Results of the test of means are presented in Table F.1 of Appendix F. Overall, 60% of the sample pairs reported concentrations statistically equivalent between the two methods, while 21% of the pairs indicated the diffusion sampler results were statistically greater than the GWMP data. Conversely, 19% of the diffusion sampler data was determined to be biased low, when compared to the GWMP results. Figure 5.2 presents a summary of these results for each analyte.

Table 5.3 summarizes the conclusions drawn from these tests of means for each of the study wells. In general, where the diffusion sampler results were statistically higher or lower than the GWMP, lithologic data and contamination profiles (see Appendix E) provided evidence of that the GWMP samples were either an integration of differing water qualities near the well screen, or drawing water laterally from formations not in contact with the well screen. Thus, the diffusion sampler data were typically considered to be more representative of the true contamination in most of the wells. In cases where analyte concentration in the diffusion samplers were determined to be statistically greater than or less than the GWMP data, approximately 71% of these pairs differed by less than 1.0 µg/L.

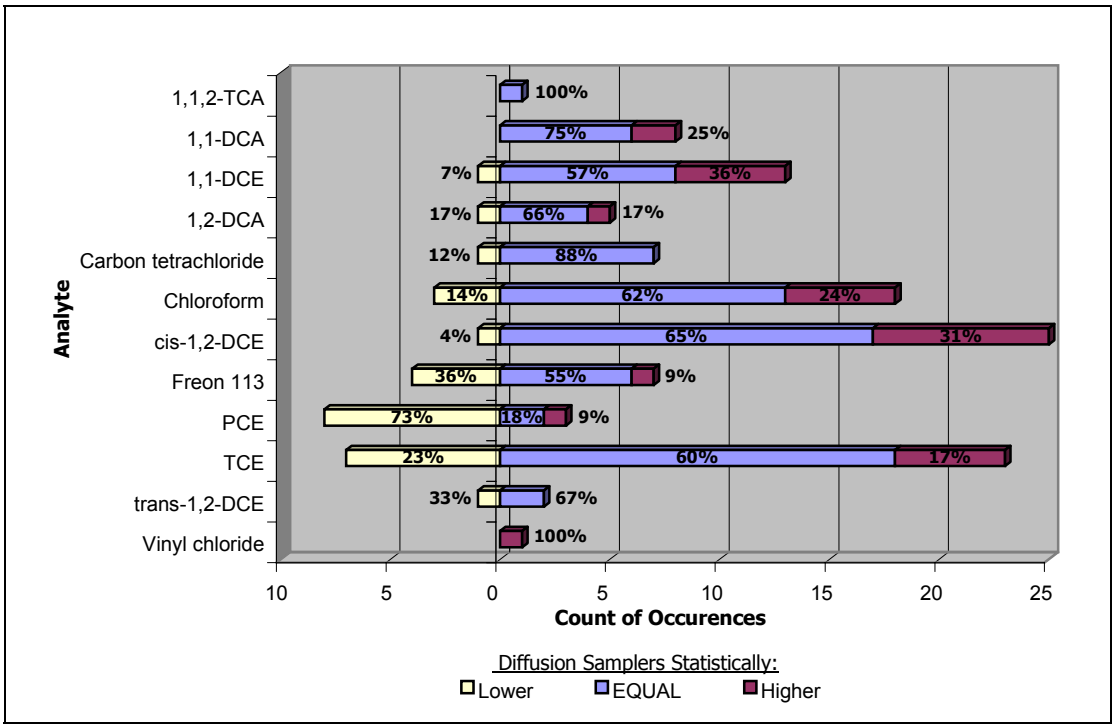

Figure 5.2. Analyte-Specific Test of Means Results – Diffusion Sampler Data versus GWMP

Table 5.3. Conclusions from Test of Means: Diffusion Samplers vs. 2Q99 GWMP

Well Number/ Zone	Screen Length (ft)	Distinct Contaminant Profile?	Conclusion
MW-136 (C)	15	No	3 of 4 analytes were statistically equivalent. TCE results from diffusion samplers were statistically lower than the GWMP ±15% range. The RPD value for this data pair was 26% which is within the acceptable range for field duplicates established in the Basewide QAPP. Therefore, the difference between the two data sets is likely insignificant.
MW-148 (D)	10	Yes	Both TCE and *cis*-1,2-DCE were statistically equivalent.
MW-154 (C)	10	Yes	All 3 analytes results were statistically higher in the diffusion samplers. This was likely due to GWMP sampling pulling less contaminated water laterally (see Figure 2.4) through sandy gravel in the screened interval.
MW-155 (A)	10	Yes	All 7 analytes were statistically equivalent.
MW-156 (B)	10	No	1,2-DCA and TCE were statistically equal. The other 5 analytes were statistically higher than the GWMP samples. For these 5 compounds, the differences between the two data sets were either less than 1 µg/L or the RPD was less than 20%. Thus the differences were likely insignificant.
MW-159 (A)	10	No	3 of 4 analytes were statistically equal. PCE was statistically lower in the diffusion samplers, but the difference was only 1.6 µg/L.

Table 5.3. Conclusions from Test of Means: Diffusion Samplers vs. 2Q99 GWMP (continued)

Well Number/ Zone	Screen Length (ft)	Distinct Contam. Profile?	Conclusion
MW-166 (C)	10	No	*cis*-1,2-DCE and TCE were statistically higher in the diffusion samplers. This was likely due to GWMP sampling pulling less contaminated water laterally (see Figure 3.4) through gravelly sands in the screened interval.
MW-201 (B)	10	No	All 3 analytes were statistically equivalent.
MW-206 (A)	20	Yes	1,1-DCA, *cis*-1,2-DCE, and TCE were statistically equivalent. Chloroform was statistically higher in the diffusion samplers by more than ±15%.
MW-214 (A)	20	No	8 of 9 analytes were statistically equivalent, *trans*-1,2-DCE was statistically lower in the diffusion samplers, but the difference between the two data sets was only 0.143 μg/L.
MW-216 (C)	10	Yes	All 5 analytes were statistically higher in the diffusion samplers. Of the 5, only *cis*-1,2-DCE and TCE had differences in concentrations greater than 0.2 μg/L.
MW-218 (B)	10	No	TCE was statistically equivalent, while *cis*-1,2-DCE was higher in the diffusion samplers. The difference between the *cis*-1,2-DCE data sets was only 0.333 μg/L
MW-235 (A)	10	Yes	5 of 7 analytes were statistically equal, while Freon 113 and PCE was statistically lower in the diffusion samplers.
MW-270 (A)	15	No	Only 3 of 7 analytes were statistically equivalent. 1,2-DCE was higher, while 1,2-DCA, Chloroform, and PCE concentrations were statistically lower in the diffusion samplers.
MW-271 (A)	15	Yes	4 of 5 analytes were statistically equal, while PCE was statistically lower in the diffusion samplers with a difference of 0.450 μg/L.
MW-282 (A)	20	Yes	3 of 4 analytes were statistically equal, while Freon 113 was statistically lower in the diffusion samplers.
MW-286 (A)	20	No	6 of 8 analytes were statistically equal, while 1,1-DCA was higher and PCE statistically lower in the diffusion samplers. The difference in PCE concentrations was only 0.73 μg/L.
MW-287 (A)	10	No	All 6 analytes were statistically higher in the diffusion samplers. GWMP sampling may be diluting true contamination with cleaner water not adjacent to the well screen.
MW-288 (A)	20	Yes	All 7 analytes were statistically equal.
MW-314 (B)	10	No	All 3 analytes were statistically equal.
MW-325 (A)	20	No	1,1-DCE was statistically equal, while Freon 113 and TCE were lower in the diffusion samplers. These analytes had RPD values less than 30%. Thus, the differences are likely insignificant.
MW-326 (B)	10	No	3 of 4 analytes were statistically equivalent. TCE was statistically higher in the diffusion samplers. This well is located near the edge of the MCL target area (Figure 3.4) and screened mostly in sand. The GWMP sample likely represents a lateral integration of clean and contaminated groundwater. Thus, the diffusion sampler results are likely more representative of the contamination adjacent to the well screen.
MW-343 (B)	10	No	3 of 4 analytes were statistically equivalent. *cis*-1,2-DCE was statistically higher in the diffusion samplers, though the concentrations were near the method detection limit.

Table 5.3. Conclusions from Test of Means: Diffusion Samplers vs. 2Q99 GWMP (continued)

Well Number/ Zone	Screen Length (ft)	Distinct Contam. Profile?	Conclusion
MW-362 (A)	20	No	Freon 113 was statistically equivalent. TCE was statistically lower in the diffusion samplers, though both methods reported TCE less than 1 μg/L, thus the difference is likely associated with analytical variability near the practical quantitation limit.
MW-364 (A)	10	No	Only 2 of 6 analytes were statistically equivalent. The other 4 analytes were statistically lower in the diffusion samplers. The data from this well appear to be anomalous. Similarities in lithology between MW-364 and MW-366 suggest a sand lens near the bottom of the well may provide a preferential flowpath for high contaminated water to enter the well while purging. Furthermore, the groundwater extraction wells in the vicinity were not operating during the study. Historical concentration data report TCE concentrations significant higher in MW-364 and MW-366 (Radian International, 1998). Operation of these extraction wells may transport contamination laterally through these monitoring wells.
MW-366 (A)	20	Yes	Only 3 of 7 analytes were statistically equivalent. The other 4 analytes were statistically lower in the diffusion samplers. The same issues affecting MW-364 may occur in this well also.
MW-381 (A)	20	Yes	6 of 7 analytes were statistically equivalent. PCE concentrations were statistically lower in the diffusion sampler results, but the mean difference the two methods was only 0.44 μg/L.
MW-382 (A)	19.6	Yes	Both TCE and carbon tetrachloride were statistically equivalent.
MW-64 (B)	10	No	TCE was statistically lower in the diffusion samplers that reported in the GWMP, while *cis*-1,2-DCE were equivalent. No lithologic data is available for this well.
MW-75 (A)	10	No	Only 1 of 6 analytes were statistically equivalent. 2 were lower and 3 higher in the diffusion samplers. All variations are likely analytical method error, with the exception of TCE and vinyl chloride. This well is located on the edge of the TCE hot spot are shown in Figure 3.4. It is likely that the GWMP sampling introduces some contaminant mass into the well laterally from this hot spot area.

5.1.6.2 Basewide Comparison (Paired t-Tests)

A second statistical test was performed to determine if the results of diffusion sampling for VOCs are accurate and representative of groundwater concentrations on a basewide basis. This was accomplished by arranging the data from all 30 study wells into analyte-specific groups (*i.e.*, TCE, PCE, *cis*-1,2-DCE, etc.). A two-sided, paired t-test was used to compare the following hypothesis:

H_o: *Basewide, the mean concentration of specific VOCs detected above the analyte's method detection limit by diffusion sampling is equal to that determined by conventional sampling at the 95% confidence level.*

The following equation was used to compute the t-statistic in the paired t-test.

Equation 5.4: $$t = \frac{\bar{d} - d_o}{s_d / \sqrt{n}}$$

where: H_o: $\bar{d} - d_o = 0$
H_1: $\bar{d} - d_o \neq 0$
t = t-statistic
$\bar{d}$ = mean of the difference between diffusion and conventional sample analytical results
d_o = hypothesized mean difference of reference populations (which is zero based on null hypothesis)
s_d = standard deviation of the differences
n = number of sample pairs

Since the t-test was performed at the 95% confidence level, the following decision criteria was used to accept or reject the null hypothesis:

- Accept null hypothesis: $t_{-2.5\%} < t < t_{2.5\%}$; or
- Reject null hypothesis: $t > t_{2.5\%}$ or $t < t_{-2.5\%}$

where: $t_{-2.5\%}$ and $t_{2.5\%}$ are the t-statistics determined for n-1 degrees of freedom

The mean analyte concentrations in the diffusion samplers were paired with the GWMP results from each well. These pairs were then grouped with data from other wells on an analyte-specific basis. The Ryan-Joiner test for normality (Ryan and Joiner, 1976) was used to determine if these analyte-specific data sets were normally distributed. With the exception of *trans*-1,2-DCE, the concentration pairs for all other contaminant were log-normally distributed. Thus, these data were log-transformed prior to testing.

5.1.6.2.1 Results of Paired t-tests

Overall, the paired t-tests indicated that the diffusion sampling results were statistically equivalent to the GWMP data for each of the VOCs tested. Concentration data from the diffusion samplers and the GWMP were paired for the following VOCs:

- 1,1-DCA,
- 1,1-DCE,
- 1,2-DCA,
- Carbon tetrachloride,
- Chloroform,
- *cis*-1,2-DCE,
- Freon 113,
- PCE,
- TCE, and
- *trans*-1,2-DCE.

Table F.2 in Appendix F summarizes the results of the 10 paired t-tests conducted on the mean diffusion sampler concentrations. Each analyte passed the two-sided paired t-test. Therefore, it can be concluded that basewide, the concentrations of specific VOCs detected in the diffusion sample are comparable to conventional purge-and sample results.

5.1.6.3 Influences Due to Well Depth

The objective of this evaluation was to determine if there were any systemic (*i.e.,* basewide) differences between the two data sets based on well depth. These differences were evaluated by first grouping the data by monitoring zones (*i.e.*, A-, B-, and C/D-zones) and analyte, then pairing the individual diffusion sampler results with the corresponding GWMP data. The Ryan-Joiner test (Ryan and Joiner, 1976) was used to determine if each of the grouped (monitoring zone- and analyte-specific) data sets were normally or log-normally distributed. Since only the *trans*-1,2-DCE data in the A-zone wells were determined to be normally or log-normally distributed, a nonparametric test was required. The Wilcoxon Signed-Rank Test was selected to evaluate the equality of the paired diffusion sampler and GWMP data sets (Walpole and Myers, 1993).

The results of these tests are presented in Tables F.3 through F.5 of Appendix F and summarized in Table 5.4. Seven of the 10 analytes reported in the A-zone monitoring wells exhibited statistically significant differences (*i.e.,* five lower and two higher) concentrations in the diffusion samplers compared to the GWMP data sets. Likewise, the concentrations reported in six of the eight analyte groups in the B-, C-, and D-zone wells were statistically higher in the diffusion samplers. The trend of lower diffusion sampler concentrations reported in the shallow A-zone wells presents further evidence that these wells are susceptible to contaminant mass averaging along the length of the long well screens or off-gassing of VOCs into the annular space of the well casing above the groundwater table. Furthermore, the propensity of the diffusion samplers to reported higher concentrations in the deeper wells suggest that the conventional sampling protocols may be introducing water vertically or laterally from formations not immediately adjacent to the well screen.

Table 5.4. Summary of Wilcoxon Signed-Rank Tests Grouped by Well Depth

	A-Zone Wells		B-Zone Wells		C/D-Zone Wells	
Analyte	Count	Conclusion	Count	Conclusion[a]	Count	Conclusion[a]
TCE	124	DS Lower	44	Equal	19	DS Higher
cis-1,2-DCE	96	Equal	44	Equal	19	DS Higher
Chloroform	100	DS Lower	19	DS Higher	10	DS Higher
1,1-DCA	37	DS Higher	19	DS Higher	--	--
1,1-DCE	58	DS Higher	19	DS Higher	--	--
PCE	77	DS Lower	--	--	--	--
1,2-DCA	30	Equal	--	--	--	--
Carbon tetrachloride	51	DS Lower	--	--	--	--
Freon 113	77	DS Lower	--	--	--	--
trans-1,2-DCE	15	Equal	--	--	--	--

[a] Diffusion sampler concentrations statistically equal to, lower than, or higher than GWMP concentrations
DS = diffusion samplers

5.1.6.4 Effects Due to Proximity to Source Areas

The test of means results (see Section 5.1.6.1.1) indicated that 40% of the concentration differences between the diffusion sampler and GWMP data sets were statistically significant. While the monitoring well depth appears to have some systemic influence on the data comparability, the

summary of results presented in Table 5.3 also suggests that the well screened length may influence the comparability of the two data sets. The location of the monitoring wells in relation to contamination source areas or hot spots is important in assessing the potential for contaminant mass averaging in the GWMP samples, especially in wells with long screen intervals that cross several difference geologic formations.

TCE results from the test of means were evaluated graphically with respect to the MCL target areas in Figure 3.4. The wells were segregated by monitoring zone (*i.e.,* A, B, and C/D) and identified as reporting diffusion sampler concentrations statistically equivalent to, greater than, or less than the TCE concentration reported in the GWMP sample. TCE was used as the compound of interest because it was reported at the highest frequency and in the widest range of concentrations.

There does not appear to be any particular area of the base where the diffusion sampler performance was consistently biased either high or low. However, many of the monitoring wells that reported statistically significant differences between the two data sets are located near the boundaries of the MCL and hot spot target areas rather than in the middle of the diffuse VOC plume (see Figure 5.3). This may suggest that the well purging could be introducing water laterally into the well through preferential horizontal flow paths from areas where the VOC concentrations are significantly higher or lower than the concentrations in the formation adjacent to the well screen. In that, the VOC concentrations reported in the GWMP samples may be a function of the well's proximity to zones of high VOC concentrations and the surrounding hydrogeology; providing further evidence that the GWMP samples may represent an integration of different water qualities from a portion of the aquifer significantly larger than that immediately adjacent to the well screen.

5.1.6.5 Effects Due to Adjacent Geologic Formations

The objective of this evaluation was to determine if there were any basewide systemic differences between the two data sets due to changes in lithology along the length of the well screen interval. These differences were evaluated by first grouping the diffusion sampler data based on the properties of the geologic formation immediately adjacent to the well screen at the depth each sampler was installed. Each diffusion sampler was associated with a with a geologic description using the lithologic logs and well construction details in Appendix E. These logs also indicate the depth interval for each sampler installed in the wells. To simplify the evaluation, the geologic formations were categorized as either high or low permeability units. High permeability units were defined as sands and gravels, while the low permeability units consisted of silts and clays. The data management was completed by pairing the individual diffusion sampler results with the corresponding GWMP data similar to how the well depth evaluation was performed.

The Ryan-Joiner test (Ryan and Joiner, 1976) determined that each of the grouped (*i.e.,* geologic unit- and analyte-specific) data sets were not normally or log-normally distributed. Therefore, the nonparametric Wilcoxon Signed-Rank Test was performed to evaluate the comparability of the grouped diffusion sampler data to the GWMP results.

The results of these tests are presented in Tables F.6 and F.7 of Appendix F and summarized in Table 5.5. With the exception of PCE, VOC concentrations reported in diffusion samplers were generally statistically equivalent to or greater than the concentrations reported in the GWMP samples. Three of nine analytes reported significantly higher concentrations in the diffusion samplers when the samplers were installed adjacent to high permeability soils. The small P-value (0.068) and point

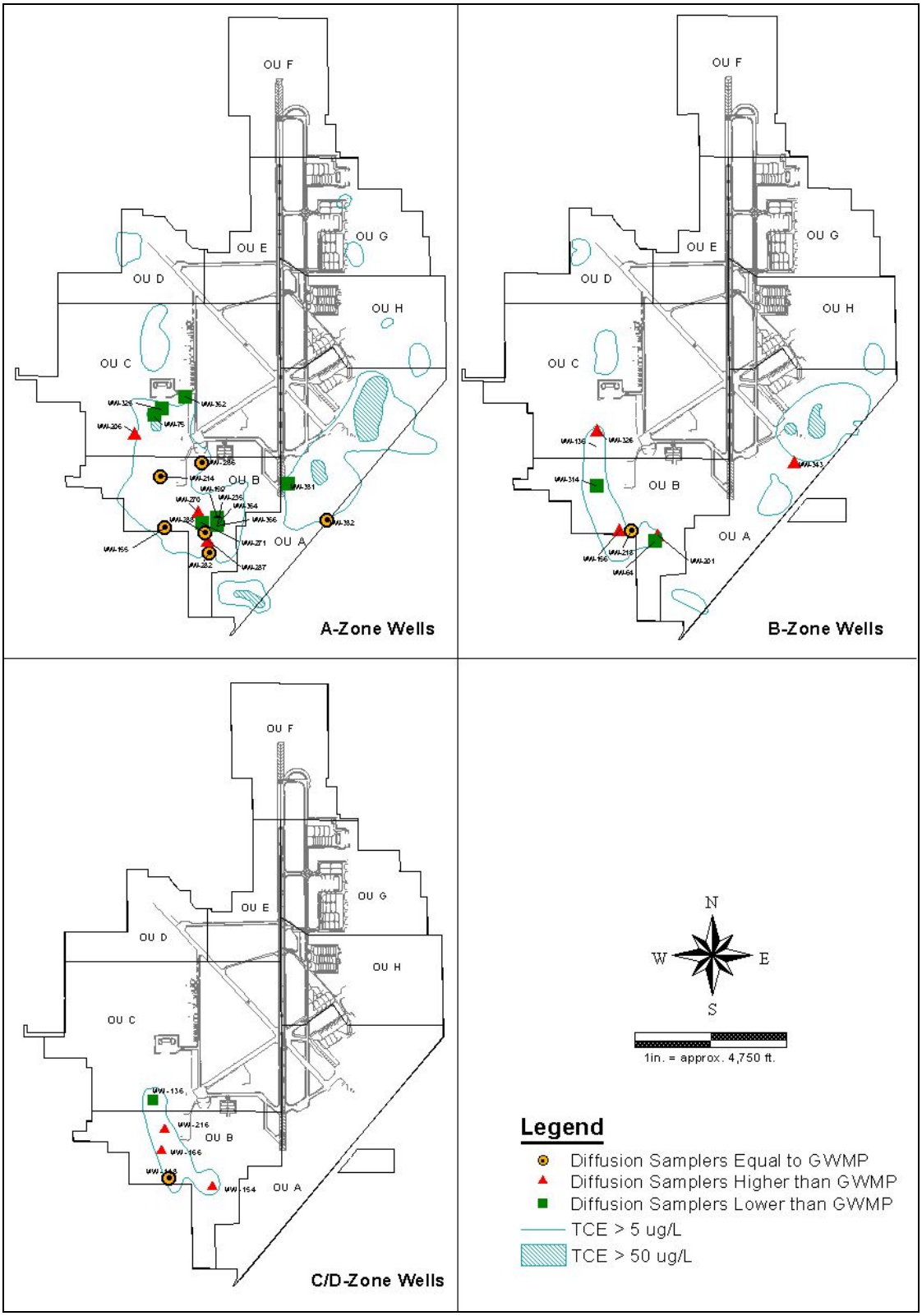

Figure 5.3. Comparison of TCE Concentrations in Diffusion Samplers to 2Q99 GWMP Samples

estimate of the median difference (1.2) for TCE in the high permeability soils (Table F.6) suggests that TCE may be a fourth analyte reported at higher concentrations when diffusion samplers are installed near high permeability soils. This implies that the conventional purge-and-sample protocol used in the GWMP may be diluting the true contamination in the formation immediately adjacent to the well screen. Thus, the results from these signed-rank tests indicate that a systemic (*i.e.*, basewide) difference may exist between the diffusion sampler and GWMP data sets, and that difference may be related to the geology immediately adjacent to the diffusion sampling interval.

5.1.7 COMPARISON OF MIDDLE DIFFUSION SAMPLER CONCENTRATION TO GWMP DATA

The intent of the diffusion sampling protocol in meeting the long-term monitoring needs is to place one diffusion sampler in a well that is representative of the VOC concentrations at that location. The simplest method would be to install one diffusion sampler at the midpoint of the saturated well screen interval. Thus, the wells in this study were instrumented such that the middle sampler was placed at the midpoint of the saturated screen interval. The VOC concentrations reported in the middle diffusion sampler were compared to the GWMP data in a manner similar to how the entire diffusion sampler population was analyzed in Section 5.1.6. A one-sided approximate t-test of conducted to determine if the middle diffusion sampler was representative of the entire vertical well profile. The middle diffusion sampler results were then compared directly to the GWMP results using the RPD value as a measure of comparability. Finally, a paired t-test was conducted on the data from the middle sampler and 2Q99 GWMP event.

Table 5.5. Summary of Wilcoxon Signed-Rank Tests Grouped by Geology

	High Permeability Soils		Low Permeability Soils	
Analyte	Count	Conclusion[a]	Count	Conclusion[a]
TCE	110	Equal[b]	54	Equal
PCE	41	DS Lower	29	DS Lower
cis-1,2-DCE	93	DS Higher	43	Equal
1,2-DCA	30	Equal	8	DS Higher
1,1-DCA	22	DS Higher	23	DS Higher
1,1-DCE	40	DS Higher	23	Equal
Carbon tetrachloride	27	DS Lower	23	Equal
Chloroform	71	Equal	47	Equal
Freon 113	34	Equal	36	DS Lower

[a] Diffusion sampler data statistically equal to, lower than, or higher than GWMP data
[b] P-value (0.068) and median point estimate (1.2) suggest the diffusion sampler data may be higher than GWMP data
DS = diffusion samplers

5.1.7.1 Well-by-Well Comparison (Test of Means)

One-sided approximate t-tests were performed to determine if the VOC concentrations reported in the middle diffusion sampler were representative of the population of concentrations along the length of the well screen. This test of means was performed in a manner similar to the test described in Section 5.1.6.1 except that the GWMP data (x_2, s_2, and n_2) in Equations 5.1, 5.2, and 5.3 were replaced with the concentration of the specific VOC reported in the middle diffusion sampler at each well. Thus, the null hypothesis for this test was:

H_o: *The difference between the mean concentration of specific VOCs detected above the analyte's method detection limit by the diffusion samplers and the analyte concentration reported in the middle diffusion sampler is less than 15% of the concentration in the middle diffusion sampler at the 95% confidence level.*

5.1.7.1.1 Test of Means Results

A total of 162 well/analyte pairs were evaluated. This number is greater than the 140 data pairs evaluated in Section 5.1.6 when comparing the diffusion sampler data to the GWMP results. Recall in Section 5.1.3 that there were an additional 22 cases where VOCs were reported at low concentrations, between the MDL and PQL, in the diffusion samplers while not detected in the GWMP samples.

Given the acceptable level of analytical variability (d_o) of 15%, all 162 data pairs passed the test of means (*i.e.*, the null hypothesis was accepted). Therefore, it was concluded that the VOC concentrations in the middle diffusion samplers were representative of the entire well screen interval. Table F.8 in Appendix F contains the test of means calculations for the middle diffusion sampler-to-the entire diffusion sampler data set comparison.

5.1.7.2 Comparison of RPD values

Since VOC concentrations in the middle diffusion samplers were considered representative of the average concentration along the well screen interval, they were then compared directly to the 2Q99 GWMP data for each of the 30 wells. As described in Section 5.1.6, 140 well/analyte pairs were compared. Nearly 70% of the data pairs had a RPD value less than 15%. A closer inspection of the data revealed that 84% of the data had an RPD value less than 30% and/or a concentration difference less than 1.0 ug/L. Given the inherent variations in groundwater sample results, these results suggest that the quality of the diffusion sampler data is at least equivalent to the quality of conventional purge-and-sample data. The comparison of RPD values is shown on Table F.9. Based on these first test of means (*i. e.,* the mean diffusion sampler concentration versus GWMP data) and these results, in most cases it could be inferred one diffusion sampler placed at the midpoint of the saturated well screen would provide equivalent, if not more representative, results compared to standard purge-and-sample techniques. This result is somewhat surprising given the fact that nine of the study wells exhibited significant vertical gradients along the lengths of the well screens. Given that, it is likely that this test of means may have averaged out the true (*i.e.,* highest level of) contamination in those wells.

5.1.7.3 Basewide Comparison (Paired t-Tests)

The final set of statistical tests conducted in the study were tests of differences, paired t-test, to assess the basewide (analyte-specific) comparability of the concentrations in the middle diffusion samplers to the 2Q99 GWMP data. These tests of differences were conducted in a manner similar to that described in Section 5.1.6.2. The only variation from the paired t-test described by Equation 5.4 is that the $\bar{d}$ value was the mean difference between the middle diffusion sampler concentration and the GWMP data, rather than the mean difference between the mean diffusion sampler concentrations and the GWMP data. Thus, the null hypothesis for this test was:

H_o: Basewide, the concentration of specific VOCs detected above the analyte's method detection limit in the middle diffusion sampler is equal to that determined by conventional sampling at the 95% confidence level.

5.1.7.3.1 Results of Paired t-test

The paired t-test described in the Section 5.1.6.2 concluded that there was no difference between the mean diffusion sampler concentration and the 2Q99 GWMP data. The two-sided paired t-tests on the midpoints indicated that 1,1-DCA, *cis*-1,2-DCE, and PCE concentrations in the middle diffusion samplers were not statistically equivalent to the GWMP results (Table F.10). One sided t-tests were performed to assess whether the diffusion sampler concentrations were statistically high or lower that the GWMP data. The one-sided tests concluded that 1,1-DCA and *cis*-1,2-DCE concentrations were statistically higher in the middle diffusion samplers while the PCE concentrations were statistically lower.

Based on results from the previous statistical tests, these differences may be a function of analytical variability (especially when VOC concentrations are less than 2 µg/L), incomplete equilibration times, or contaminant mass averaging during well purging. In fact, while the PCE results appear to be biased low based on these paired t-tests, the average difference between the two data sets was approximately 1.5 µg/L. But recall in Section 5.1.4, that approximately one-third of the study wells exhibited a statistically significant concentration gradient along the length of the well screen interval. The concentration and lithologic data suggested that in heterogeneous soils, the highest VOC concentrations along the length of the well screens were associated with coarse-grained material (*i.e,* sands and gravels). Using the average VOC concentrations from the diffusion samplers along the length of the well screen for statistical comparison (see Section 5.1.6) appears to have masked this lithologic effect; thus, diluting the true nature of contamination in the well similar to the conventional sampling.

In general, the results of the paired t-tests described in this section suggest that the midpoint of the saturated well screen interval may not be the optimal depth for one diffusion sampler. Other factors such as proximity to the groundwater table, well screen length, and type of geologic formation adjacent to the sampling interval play an important role in determining optimal placement of a single diffusion sampler to best represent the true contamination in a given monitoring well. These results support the conclusions drawn in Section 5.1.4, that suggest targeting coarse-grained layers within the well screen interval will likely provide data most representative of the true contamination in the well. In general, these tests indicate that there are a variety of factors that bring into question the representativeness of groundwater samples collected using conventional techniques.

5.2 REMEDIATION EFFICIENCY

RESERVED

5.3 PROCESS FLOW EFFICIENCY

RESERVED

6.0 OTHER TECHNOLOGY ISSUES

This section covers demonstration considerations other than the cost of the technology and technical performance. Regulatory requirements, personnel health and safety issues, and community acceptance issues all affect the degree of future success for any environmental remediation technology. This section discusses these subjects below.

6.1 ENVIRONMENTAL REGULATORY REQUIREMENTS

This section discusses the regulatory requirements pertinent to the diffusion sampler technology for monitoring VOC concentrations in groundwater monitoring wells. Regulations applicable to a particular application of this technology will depend on the logistics of site-specific remediation and the type of contaminated groundwater being monitored.

6.1.1 COMPREHENSIVE ENVIRONMENTAL RESPONSE, COMPENSATION, AND LIABILITY ACT (CERCLA)

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended by the Superfund Amendments and Reauthorization Act (SARA) of 1986, provides federal funding to respond to releases of hazardous substances, pollutants, or contaminants to the air, water, and land that may present an imminent and substantial danger to public health or welfare (Federal Register, 1990). Section 121 of SARA, Cleanup Standards, states a strong statutory preference for remedies that are highly reliable and provide long-term protection. It strongly recommends that remedial actions use on-site treatment that "…permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances."

CERCLA remedial actions also must address these general factors:

- Long-term effectiveness,
- Short-term effectiveness,
- Implementability, and
- Cost.

The diffusion sampler technology may be appropriate for monitoring VOC groundwater contamination at a large number of sites exhibiting the proper hydrogeologic and contaminant distribution conditions. This technology may prove to be a valuable tool in assessing the performance and effectiveness of *in situ* groundwater treatment systems.

6.1.2 RESOURCE CONSERVATION AND RECOVERY ACT

The Resource Conservation and Recovery Act (RCRA), as amended by the Hazardous and Solid Waste Amendments of 1984, is the primary federal legislation governing hazardous waste activities. Subpart C of RCRA contains requirements for the generation, transport, treatment, storage, and disposal of hazardous waste, and most of them would be considered applicable to NPL sites.

There is no hazardous waste generated by the diffusion sampler technology except potentially the excess volume of the sampler not sent to the laboratory for analysis. Inherent to the diffusion sampler technology is the considerable reduction of wastewater (*i.e.,* elimination of purgewater) generated during groundwater sampling activities.

6.2 PERSONNEL HEALTH AND SAFETY

Occupational Safety and Health Administration (OSHA) regulations, contained in 29 CFR Parts 1900 through 1926, are designed to protect worker health and safety. Both Superfund and RCRA corrective actions must meet OSHA requirements, particularly Part 1910.120, Hazardous Waste Operations and Emergency Response. Part 1926, Safety and Health Regulations for Construction, applies to any on-site construction activities. Personnel safety and health issues associated with the diffusion sampling technology are no greater than those required for conventional groundwater sampling at VOC-contaminated sites. Each site where the technology is to be implemented must review all activities to ensure compliance with state-specific OSHA and site-specific health and safety requirements.

6.3 COMMUNITY ACCEPTANCE

Because the diffusion sampler technique requires no well purging prior to sample collection, the technology generates an extremely small volume of wastewater, less than 140 mL (4.7 ounces) per well. By eliminating the generation of wastewater requiring disposal, the technology significantly reduces the possibility of worker exposure to contaminants in the groundwater while also eliminating the potential for uncontrolled spills of extracted groundwater. In addition, the technology generates no chemical or particulate air emissions from the sampling devices or any auxiliary equipment such as portable generators that are often used to power pumps and other conventional groundwater sampling equipment. The above, coupled with high sample accuracy, should lead to community acceptance of this technology.

7.0 COST ANALYSIS

The purpose of this economic analysis is to estimate costs for the diffusion sampler technology for use in full-scale monitoring of groundwater for VOCs[1]. The cost estimates presented in this section are derived from data compiled during the demonstration at the McClellan AFB NETTS location. Costs have been placed in the Hazardous, Toxic, Radioactive Waste (HTRW) Remedial Action Work Breakdown categories applicable to HTRW remedial action activities at Superfund and RCRA sites. The RA-WBS level 1 (federal action) number for all these activities is 33. Twenty level 2, or project phase, cost categories are used to separate demonstration costs under federal action number 33.

The RA-WBS system hierarchy has four levels of detail, as follows:

- Level 1: Federal action, in this case remedial action, 33.
- Level 2: Pre-, post-, and demonstration operations (20 categories, see bulletized list below).
- Level 3: Subtasks pre-, post- and demonstration operations.
- Level 4: Subtasks pre-, post- and demonstration operations.
- Level 5: Subtask elements primarily for demonstration operations (distinguishes portable versus permanent treatment units).

Each RA-WBS level adds more detailed cost information. The cost estimate is based on fiscal year 1999 dollars. The cost estimate has an estimated accuracy of plus or minus 25 percent.

7.1 BASIS OF COST ANALYSIS

A number of factors affect the estimated monitoring costs for implementing diffusion sampling for VOCs in groundwater. These factors include, but are not limited to: number of diffusion samplers placed per well, contractor labor rates, wastewater disposal, and cost of diffusion sampler devices.

7.2 COST CATEGORIES

Cost data have been assigned to the following 20 RA-WBS categories, which fall under the HTRW Remedial Action Account, 33:

Pre-Demonstration Cost Elements:

- (33.01) Mobilization and Preparatory Work;
- (33.02) Monitoring, Sampling, Testing, and Analysis (pre-, post-, and demonstration sampling analysis are included in this category, unlike full-scale cleanup projects);

[1] It should be noted that this cost estimate assumes that semi-volatile and nonvolatile compounds are not part of the routine groundwater sampling program as is the case at McClellan AFB.

- (33.03) Site Work;
- (33.05) Surface Water Collection and Control;
- (33.06) Groundwater Collection and Control;
- (33.07) Air Pollution/Gas Collection and Control;
- (33.08) Solids Collection and Containment;
- (33.09) Liquids/Sediments/Sludges Collection and Containment; and
- (33.10) Drums/Tanks/Structures/Misc. Demolition and Removal.

Demonstration Cost Elements:

- (33.11) Biological Treatment;
- (33.12) Chemical Treatment;
- (33.13) Physical Treatment;
- (33.14) Thermal Treatment; and
- (33.15) Stabilization/Fixation/Encapsulation.

Post-Demonstration Cost Elements:

- (33.17) Decontamination and Decommissioning;
- (33.18) Disposal (other than commercial);
- (33.19) Disposal (commercial);
- (33.20) Site Restoration;
- (33.21) Demobilization (includes reporting);
- (33.9x) User Defined (replace "x" with numbers 0-8); and
- (33.99) Distributive Costs.

Overall Demonstration Cost Elements:

Categories 33.99, Distributive Costs, are costs that are not attributed to any specific RA-WBS activity but apply to the whole project. Examples of Distributive Costs at RA-WBS level 3 are:

- (33.99.01) Supervision/Management;
- (33.99.02) Administration;
- (33.99.03) Office management;
- (33.99.04) Engineering;
- (33.99.05) Purchasing and Construction Services;
- (33.99.06) Security;
- (33.99.07) Equipment Maintenance and Motor Pool;
- (33.99.08) Temporary Construction Facilities;
- (33.99.09) Utilities - Operation/Maintenance;
- (33.99.10) Facility Operations;
- (33.99.11) Operating Supplies/Services;
- (33.99.12) Computer and Data Processing;
- (33.99.13) Vehicles for Personnel;
- (33.99.14) Winterization;
- (33.99.15) Health and Safety;
- (33.99.16) Miscellaneous Costs;
- (33.99.17) Insurance Premiums;

- (33.99.18) Money Costs; and
- (33.99.19) Home Office Costs.

Each task and subtask has certain repeating elements, such as labor, capital equipment costs, materials, and subcontractor costs. These are not typically identified separately at the RA-WBS level, but are considered as part of each cost element.

7.2.1 MOBILIZATION AND PREPARATORY WORK (33.01)

Mobilization and Preparatory Work includes all preparatory work required. This includes: mobilization of equipment and facilities; mobilization of personnel; setup and construction of temporary facilities; temporary utilities; temporary relocations; and setup of decontamination facilities.

7.2.1.1 Mobilization of Demonstration Equipment and Facilities

Equipment mobilization costs for the diffusion sampling technology consisted of:

- Procurement and shipping the diffusion samplers and weights from the USGS Water Resources Division in Columbia, South Carolina;

  Note: Diffusion samplers can be readily constructed on site and were provided by USGS as part of the previous cooperative demonstration effort with AFCEE and the McClellan AFB NETTS location.

- Procurement and shipping of pre-cleaned, pre-preserved VOA vials, shipping coolers, polyethylene rope, and “flex guard” mesh, and standard plastic rope ties; and

- Rental of a standard 2 wheel drive pick-up truck for use by the sampling team.

7.2.1.2 Mobilization of Personnel

There were no specific costs for the mobilization of personnel that are specific to the diffusion sampling technology. These travel costs are specific to the site and, as they are the same as for conventional sampling, they have been discounted for this cost estimate.

7.2.1.3 Pre-demonstration Submittal

Not applicable to this technology.

7.2.1.4 Setup and Construction of Temporary Facilities

Not applicable to this technology.

7.2.1.5 Construct Temporary Utilities

Not applicable to this technology.

7.2.1.6 Temporary Relocations of Roads/Structures/Utilities

Not applicable to this technology.

7.2.1.7 Demonstration Plant Erection

Not applicable to this technology.

7.2.2 MONITORING, SAMPLING, TESTING, AND ANALYSIS: PRE-DEMONSTRATION, DEMONSTRATION, AND POST-DEMONSTRATION (33.02)

This category provides for all demonstration costs associated groundwater sampling, monitoring, testing, and analysis. It includes collecting, shipping and analyzing samples.

Analytical costs associated with the GWMP include laboratory analyses, data reduction and tabulation, QA/QC, and reporting. For long-term monitoring programs using either diffusion sampling and conventional purge-and-trap, these costs are identical. The costs reported are those typically experienced by the GWMP and NETTS location. As noted in Appendix B, shipping costs have been discounted from the estimate due to the variability of lab locations, shipping strategies, and shipping methods that could be used[1].

In both cases, this cost estimate assumes that one VOC sample is tested per monitoring well exclusive of QA/QC samples. Further it assumes that a total of 500 monitoring wells per year are sampled, evenly distributed through 4 calendar quarters (*i.e.,* 125 wells are sampled per quarter). Further, field duplicate samples are taken at a rate of 5% (*i.e.,* 7 samples per quarter); a trip blank is included with each sample shipment; and that ambient blanks and equipment blanks are taken twice during each sample event.

7.2.3 SITE WORK (33.03)

Not applicable to this technology.

7.2.4 SURFACE WATER COLLECTION AND CONTROL (33.05)

Not applicable to this technology.

7.2.5 GROUNDWATER COLLECTION AND CONTROL (33.06)

Not applicable to this technology.

7.2.6 AIR POLLUTION/GAS COLLECTION AND CONTROL (33.07)

Not applicable to this technology.

7.2.7 SOLIDS COLLECTION AND CONTAINMENT (33.08)

Not applicable to this technology.

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[1] For example, for a site such as McClellan AFB that ships samples each day, the 15 day reduction in overall sampling duration would result in a savings of approximately $600 per event.

7.2.8 LIQUIDS/SEDIMENTS/SLUDGES COLLECTION AND CONTAINMENT (33.09)

Not applicable to this technology.

7.2.9 DRUMS/TANKS/STRUCTURES/MISCELLANEOUS DEMOLITION AND REMOVAL (33.10)

Not applicable to this technology.

7.2.10 BIOLOGICAL TREATMENT (33.11)

Not applicable to this technology.

7.2.11 CHEMICAL TREATMENT (33.12)

Not applicable to this technology.

7.2.12 PHYSICAL TREATMENT (33.13)

Not applicable to this technology.

7.2.13 THERMAL TREATMENT (33.14)

Not applicable to this technology.

7.2.14 STABILIZATION/ FIXATION/ENCAPSULATION (33.15)

Not applicable to this technology.

7.2.15 DECONTAMINATION AND DECOMMISSIONING (33.17)

Excess groundwater, decontamination fluids, and personal protective equipment (PPE) are produced during both diffusion and conventional sampling efforts. The wastewater produced (*i.e.,* groundwater and decontamination fluids) require treatment prior to discharge. The volumes of wastewater are based upon those observed during the diffusion sampling demonstration and 2Q99 GWMP event at McClellan AFB. Used PPE are identical between sampling methods and have been discounted from the cost estimate due the variability of PPE requirements based on well contamination levels.

7.2.16 DISPOSAL (COMMERCIAL) (33.19)

The diffusion sampling technology generates small quantities of wastewater that requires further processing, handling, or disposal.

7.2.17 SITE RESTORATION (33.20)

Not applicable to this technology.

7.2.18 DEMOBILIZATION (33.21)

Demobilization from a sampling event includes decontamination of sampling equipment, return of rental equipment used during the effort, and storage of reusable sampling equipment and materials. This cost estimate assumes that except for the diffusion sampler, all equipment and materials are reusable after appropriate decontamination. Costs for demobilization for conventional sampling are based on those documented during the diffusion sampling event.

7.3 RESULTS OF COST ANALYSIS

A comparison of the costs of diffusion sampling, conventional purge-and-sampling techniques, and micropurging[1] are summarized in Tables 7.1, 7.2, and 7.3 respectively. The costs show the one-time capital costs and associated annual recurring costs for sampling. The basis of the cost estimate is included in this Chapter and Appendix G.

Table 7.1. Diffusion Sampling Cost Summary

Cost Element	Unit Cost	Subtotal
Capital Expenditures		
Weights	$10 each	$5,000
Other materials	$8 each	$4,000
One-time Costs		
Sampler location	$65/hr	$32,500
Annual Recurring Costs		
Sampler Installation		
Labor	$45/hr	$14,850
Transportation	$62/day	$1,240
Samplers	$5/sampler	$12,500
Misc. materials	$2 /well	$9200
Sampler Recovery		
Labor	$45/hr	$14,850
Transportation	$62/day	$1,240
Materials	$92/event	$368
Materials	$7/sampler	$3,680
Waste Disposal	$7 /gal	$5
Demobilization	$45/hr	$1,440
VOC Analysis		
Laboratory	$85/analysis	$42,500
QA/QC samples	$85/analysis	$4,505

[1] Note that although micropurging was not evaluated in this study, costs have been included for reference as McClellan AFB had stated its intent to switch to this method at a future date.

Table 7.2. Conventional Sampling Cost Summary

Cost Element	Unit Cost	Subtotal
Capital Expenditures		
Pumps	$950 each	$2,850
Other equipment	$750 each	$1,500
Sampling vehicle	$7,500 each	$7,500
Annual Recurring Costs		
Sampling		
Mobilization	$45/hr	$360
Equipment maintenance	$300/event	1,200
Labor	$45/hr	$112,500
Transportation	$55/day	$4,400
Materials	$182/sample	$91,000
Materials	$472/event	$1,887
Waste Disposal	$7 /gal	$175,000
Demobilization	$45/hr	$1,440
VOC Analysis		
Laboratory	$85/analysis	$42,500
QA/QC samples	$85/analysis	$11,645

Table 7.3. Micropurge Sampling Cost Summary

Cost Element	Unit Cost	Subtotal
Capital Expenditures		
Pumps	$1,175 each	$3,525
Other equipment	$750 each	$1,500
Sampling vehicle	$7,500 each	$7,500
One-time Costs		
Sampling Location	$65/hr	$32,500
Annual Recurring Costs		
Sampling		
Mobilization	$45/hr	$360
Equipment maintenance	$825/event	$3,300
Labor	$45/hr	$135,000
Transportation	$55/day	$4,400
Materials	$182/sample	$91,000
Materials	$472/event	$1,887
Waste Disposal	$7 /gal	$87,500
Demobilization	$45/hr	$1,440
VOC Analysis		
Laboratory	$85/analysis	$42,500
QA/QC samples	$85/analysis	$11,645

Overall there is an estimated one time capital cost of $9,000 for diffusion sampling equipment. This compares with an $11,850 estimated capital cost for conventional purge sampling and $12,525 capital cost for micropurge sampling. These costs are generalized estimates and should be evaluated on a site-by-site basis for accuracy. In that, some sites rent conventional sampling equipment, use dedicated pumps within monitoring wells, or rent sampling vehicles.

A one-time cost of has been included for the diffusion sampling and micropurge sampling methods to account for technical reviewer time to review well lithologic and contaminant details to determine optimal sample position. This 1-hr per well labor correlates to a one-time cost of $32,500 for a site with 500 wells. Each site will need to evaluate these assumptions carefully as factors such as availability of well information and total number of wells could greatly influence the actual cost.

The major costs differences between the methods are in the annual recurring costs. It is estimated that diffusion sampling would cost approximately $98,098 per year as compared to $411,572 for conventional purge sampling and $378,672 for micropurge sampling. However, it should be noted that off-site wastewater disposal accounted for $175,000 of recurring costs for conventional sampling and $87,500 for micropurging. In many cases, this cost will be much lower as on-site remedial action systems will be capable of treating this waste stream. Nonetheless, even if the costs of wastewater disposal are discounted, the use of diffusion samplers would result in large estimated cost savings over both the micropurge and conventional sampling methods. Table 7.4 presents a comparison of estimated costs for the diffusion, conventional, and micropurge sampling methods.

Table 7.4 Cost Comparison Summary

Method	Capital Costs	One-time Costs	Annual Recurring Costs
Diffusion sampling	$9,000	$32,500	$98,098
Conventional sampling	$11,850	$0	$411,572 *$236,572 (w/o purge water disposal costs)*
Micropurge sampling	$12,525	$32,500	$376,672 *$289,172 (w/o purge water disposal costs)*

Overall, sites where routine groundwater sampling does not include semi-volatile or nonvolatile compounds, the use of diffusion sampling could result in annual savings of at least 50% over conventional or micropurge sampling. Specifically, diffusion sampling is estimated to save between $275 to $600 per well sampled. The majority of this savings is from decreased labor associated with purging during sampling events.

8.0 RECOMMENDATIONS

Based on the results of the diffusion sampler demonstration project and the associated cost analysis, the following recommendations are presented concerning the application of diffusion samplers for monitoring of VOC contamination in groundwater:

8.1 GENERAL RECOMMENDATIONS

- Initial pilot testing should be conducted at each site to determine if the diffusion sampler approach is appropriate for hydrogeologic and contaminant transport conditions of the aquifer(s) to be monitored. During the initial sampling event, it may be appropriate to perform a side-by-side comparison of diffusion sampling with the site's current sampling protocol using the recommendations provided below.

- An initial evaluation of hydrogeology aquifer should be conducted prior to diffusion sampler implementation. Diffusion samplers should only be used at sites where there groundwater gradients are sufficient to allow water to pass through the monitoring well screens without purging (*i.e.*, water within the well screen is not stagnant). Longer-screened wells may also be affected by vertical flow within the well casing.

- An initial evaluation of the lithology adjacent to the well screen should be conducted to identify zones of coarse- (*i.e.*, sands and gravels) and fine- (*i.e.*, silts and clays) grained materials. Results of this study suggests that the highest concentrations within a well are generally associated with the coarser-grained materials. This is likely a site-specific condition and may not be applicable to all sites, especially those with wells screened in fractured media.

- Each site should evaluate the appropriate equilibrium period for the diffusion samplers. Unless site-specific testing is completed, the diffusion samplers should be left in the wells for a minimum of 14 days prior to sample collection. It may be reasonable to increase this time in colder climates where diffusion rates may be slower.

- Further studies on the effects of long-term placements of the diffusion samplers is warranted. In that, are the samplers suited to be left in the wells for long periods of time (*e.g.,* placed in wells at the end of one sampling event to be retrieved at the next sampling round).

8.2 MCCLELLAN AFB-SPECIFIC RECOMMENDATIONS

- One diffusion sampler placed adjacent to a coarse-grained geologic formation nearest to the midpoint of the saturated well screen interval should provide data representative of the highest contamination within the well.

- The diffusion samplers should be left in the wells for a minimum of 14 days prior to sample collection. Further site-specific evaluations are warranted should a shorter equilibrium time be deemed desirable.

- Further studies on the effects of long-term placements of the diffusion samplers is warranted. In that, to determine if the samplers suited to be placed in wells at the end of one sampling event to be retrieved at the next sampling round.

9.0 CONCLUSIONS

The conclusions presented in this section are based on an in-depth scientific and engineering evaluation of the cost and performance of the diffusion sampler technique for monitoring VOC contamination in groundwater aquifers.

Conventional purge-and-sample protocols for collection of samples from groundwater monitoring wells have the potential to introduce a variety of artifacts into the sampling process that may compromise the quality of the sample collected. Recent studies have shown that conventional well purging is susceptible to vertical mass averaging from different geologic formations, with differing water qualities, along the length of the screen, introduction of water from formations above or below the well screen through vertical preferential flowpaths along the annular spacing between the well casing and the formation, or introduction of waters of differing quality laterally through preferential horizontal flowpaths. In that, conventional sampling often represents an integration of different water qualities over a portion of the aquifer larger than that immediately adjacent to the well screen.

9.1 COST AND PERFORMANCE

Results from this and previous studies (Vroblesky and Hyde, 1997; Vroblesky *et al.*, 1999) have shown a close correlation between VOC concentrations in the diffusion samplers and concentrations in water samples obtained from wells using conventional purge-and-sample approaches. The following conclusions can be drawn from the results of this and previous studies:

- The diffusion sampler protocol is a passive approach to monitoring VOC concentrations in groundwater. The technology may only be appropriate for monitoring wells with hydraulic gradients sufficient to allow the water within the well casing to exchange with formation water without purging. Thus, the diffusion samplers may not be appropriate for sites where groundwater is stagnant (*i.e.,* no horizontal or vertical flow through the well screen interval);

- Statistical analysis of the demonstration data indicates that the diffusion sampler technique produces sample results that are comparable to the conventional samples collected during the McClellan AFB 2Q99 GWMP sampling event;

- In a number of wells, the combination of lithologic data, well construction details, and VOC contamination profiles developed from the diffusion sampler results indicate that the conventional sampling is indeed susceptible to the representativeness issues mentioned above. In many of the wells, the diffusion samplers provided data that appears to be more representative of the true nature of contamination in the geologic formation immediately adjacent to the monitoring well screen; and

- The diffusion sampler devices are not appropriate when sampling groundwater for non-VOC contaminants such as toxic metals and some semi-volatile organic compounds that do not readily diffuse through the membranes. The McClellan GWMP does not routinely sample for these analytes.

Optimal placement of the diffusion samplers along the length of the well screen appears to be an issue that remains unresolved. Ideally, a groundwater monitoring program would only require one diffusion sampler placed in the well to represent the contamination along the length of the entire screen. The results of this study suggest that blindly placing one sampler at the midpoint of the saturated well screen may not be sufficient. In the nine wells that exhibited significant variations in VOC concentrations along the well screen, the higher concentrations were typically associated with coarse-grained materials (*i.e.*, sands and gravels). One diffusion sampler placed near the midpoint of the saturated well screen interval and adjacent to a coarse-grained formation, will likely yield results representative of the highest degree of contamination in the well. For long-screened wells, more in-depth and site-specific studies, such as using multiple samplers during an initial sampling event or borehole flowmetering (Vroblesky *et al.*, 1999) to investigate the hydraulics of the monitoring well, may be necessary to determine optimal placement of the a single diffusion sampler along the length of the saturated well screen interval.

Finally, the diffusion sampling technique has the potential to dramatically reduce the costs associated with long-term monitoring of VOCs in groundwater. The primary conclusions that can be drawn regarding cost are:

- This technology does not require the purchase of expensive equipment that must be continually maintained or replaced;
- The volume of wastewater generated and requiring disposal is also significantly reduced by eliminating well purging;
- Furthermore, the technique is extremely simple and does not require any special training, and reduces the potential for human error to compromise the integrity of collected samples;
- The passive diffusion membrane sampling technique requires very little labor to implement, allowing fewer field personnel to sample the a larger number of groundwater monitoring wells in a significantly shorter period of time compared to conventional groundwater sampling and micropurging techniques; and
- Programs that routinely monitor groundwater for both VOC and non-VOC contaminants may not realize a significant cost savings using the diffusion samplers since non-VOC samples would be collected with conventional or micropurge sampling protocols. But these programs could potentially benefit from more accurate representation of the VOC contamination with the diffusion samplers.

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