

EXECUTIVE SUMMARY

Parsons Engineering Science, Inc. (Parsons ES) prepared a draft final remedial process optimization (RPO) handbook for the Air Force Center for Environmental Excellence Technology Transfer Division (AFCEE/ERT). The handbook will be used by the Defense Logistics Agency (DLA) and AFCEE to review the performance of existing remediation systems, implement performance enhancements on existing systems, perform 5-year Record-of-Decision (ROD) reviews, and prepare documentation for operating-properly-and-successfully certification for sites at Department of Defense (DOD) facilities. Parsons ES is implementing the approach described in the draft final handbook at multiple sites, including contaminated groundwater associated with waste burial sites at Operable Unit 1 (OU1) and Operable Unit 4, Defense Depot Hill, Utah (DDHU). Lessons learned from the DLA RPO evaluations will be incorporated into the final RPO handbook. The goals for the RPO program are to: 1) assess the effectiveness of particular remedial actions; 2) enhance the efficiency of the remedial actions examined; and 3) when possible, identify annual operating, maintenance, and monitoring (OM&M) cost savings in excess of 20 percent for each system evaluated.

Two groundwater extraction, treatment, and injection (pump-and-treat) systems are currently in operation at DDHU OU1 and OU4, to contain dissolved chlorinated aliphatic hydrocarbon (CAH) plumes. These systems are operated in accordance with the requirements of site-specific RODs established in compliance with the Comprehensive Environmental Restoration, Compensation, and Liability Act (Sections 1 and 3). Each system is intended to contain a plume of dissolved vinyl chloride, and eventually to remove sufficient contaminant mass so that vinyl chloride concentrations are decreased to levels below the cleanup goals established for groundwater at OU1 and OU4 (i.e., the federal maximum contaminant level of 2 micrograms per liter [$\mu\text{g/L}$] for vinyl chloride).

The groundwater extraction and treatment system currently operating at OU1 was installed in 1994, and commenced operation in December 1994. The pump-and-treat system consists of 16 groundwater extraction wells, a single air-stripping tower, and 16 injection wells. The existing treatment system uses sodium hypochlorite and sodium hexametaphosphate pre-treatment for iron and iron bacteria control, and includes transfer pumps, blowers, treated water injection pumps, associated piping, electrical power, and system control and ancillary equipment. The average extraction and treatment rate reported for the system in 1999 was about 100 gallons per minute (gpm). The mean concentrations of vinyl chloride and *cis*-1,2-DCE in water influent to the treatment plant are approximately 1.5 and 3 $\mu\text{g/L}$, respectively. The concentrations of CAH in the treated effluent discharged to the injection wells are below 0.5 $\mu\text{g/L}$.

The groundwater extraction and treatment system currently operating at OU4 was installed in two phases. The first phase (31 extraction wells; two stripping towers; and 25 injection wells) was completed in July 1995. During installation of the OU4 pump and treat system, vinyl chloride was detected in injection wells installed along the western boundary of DDHU. The source of the contamination was traced to a source in the vicinity of an oil holding pit, and possibly three trenches near Buildings 15C and 16C. This area is identified as the OU4 "hot spot". The OU4 ROD was amended in March

2000 to address the “hot spot”, and an extraction trench and treatment system were installed along the DDHU western boundary in 1999. The trench and treatment system for remediation of the OU4 "hot spot" groundwater plume, consisting of a 300-foot-long extraction trench, ozone and hydrogen peroxide reactors, and discharge to a sanitary sewer, went online in April 1999. The current average extraction and treatment rate for the pump-and-treat system is about 100 gpm. The mean concentrations of vinyl chloride and *cis*-1,2-DCE in water influent to the treatment plant were approximately 30 and 100 µg/L, respectively, in December 1999, and the concentrations of CAH in the treatment system effluent are below 0.5 µg/L. The current extraction rate for the trench system at the OU4 "hot spot" groundwater plume is approximately 10 gpm. The mean influent concentrations of vinyl chloride and *cis*-1,2-DCE in water influent to the treatment plant are approximately 0.4 and 4 µg/L, respectively, and their respective concentrations in the treatment system effluent are below 0.5 µg/L.

The following tasks were completed in conjunction with the RPO evaluation at OU1 and OU4:

- Review existing data to evaluate previously completed site characterization activities, intrusive investigations, studies, remedial actions, and remedial designs, and identify data gaps, if any;
- Collect chemical/physical data to fill data gaps, as warranted;
- Prepare a site-specific work plan and a site-specific addendum to the project health and safety plan;
- Develop preliminary conceptual site models;
- Evaluate the existing groundwater extraction/treatment systems, monitoring networks, and long-term monitoring plans (LTMPs) with respect to established remedial action objectives (RAOs);
- Evaluate the remedial decision process leading to the system designs and the current applicability of the established RAOs;
- Evaluate fate and transport in groundwater and estimate rates of natural attenuation;
- Evaluate the biodegradation mechanisms within the source area(s) and dissolved plume(s); and
- Prepare a RPO Phase II Evaluation report, containing conclusions regarding the system evaluations and RPO recommendations for OU1 and OU4.

The RPO evaluation determined that the existing groundwater extraction-and-treatment systems at OU1 and OU4 have reduced efficiency in removing vinyl chloride mass from groundwater. Through December 2000, the groundwater pump-and-treat system at OU1 had recovered approximately 3 pounds of vinyl chloride, at an average cost per pound of about \$793,000. Even though the plume has decreased in size, due in part to groundwater extraction and treatment, vinyl chloride still persists in OU1

groundwater, as a result of continued reductive dechlorination of existing chlorinated solvent mass. Most of the existing extraction wells at OU1 are ineffective at removal of vinyl chloride mass, and most of the extracted water treated by the system contains vinyl chloride at concentrations below the MCL for vinyl chloride (2 µg/L), resulting in the treatment of “clean” water. The mass of vinyl chloride remaining in the groundwater plume is not substantial enough to continue use of the present extraction/treatment system, in its current configuration, or at its current operating rates.

Through July 2000, the OU4 groundwater pump-and-treat and extraction trench systems had December approximately 57 pounds of vinyl chloride, at an average cost per pound of about \$81,300. Even though the plume has decreased in size, due in part to groundwater extraction and treatment, vinyl chloride still persists in OU4 groundwater, as a result of continued reductive dechlorination of existing chlorinated solvent mass. Most of the existing extraction wells at OU4 are ineffective at removal of vinyl chloride mass, and most of the extracted water treated by the system contains vinyl chloride at concentrations below the MCL, resulting in the treatment of “clean” water. The concentration of vinyl chloride in water collected at the OU4 extraction trench, prior to treatment, is below the MCL, indicating that treatment of the water collected in the extraction trench may not be necessary. The mass of vinyl chloride remaining in the groundwater plume at OU4 is probably not substantial enough to continue use of the present extraction/treatment system, in its current configuration, or at its current operating rates at the present operating cost.

There are no current risks to human health or the environment from exposure to soil or groundwater at OU1 and OU4, and future risk, as presented in the RODs for OU1 and OU4, is predicated on extraction of shallow groundwater for potable use under a residential scenario. DDHU is currently undergoing conversion for redevelopment as an industrial area, and institutional controls limiting access to and future use of groundwater at OU1 and OU4 are in place. Assuming that exposures associated with the future industrial use of the facility is similar to those under its past military use, and that current institutional controls restricting groundwater use are maintained, no potential future receptor pathways are likely to be completed.

Based on review of the remedial decision process and system performance to date, recommendations and long-term opportunities were identified to immediately improve system performance, and to provide a framework for the future direction of site remediation. Recommendations for the OU1 pump and treat system include cessation of system operation, with continued monitoring of groundwater conditions for one year. Recommendations for the OU4 pump and treat system include maintaining operation of the system until *cis*-1,2-DCE concentrations fall below MCL and optimize the system by eliminating 14 extraction wells and 16 injection wells. At the OU4 extraction trench, the recommendation is to monitor extracted groundwater quality prior to treatment, and possibly to terminate treatment of extracted groundwater. Groundwater extracted by the trench would be analyzed for VOC concentrations. If the concentrations of VOCs are above MCLs, then water would be directed through the treatment plant prior to disposal. If VOC concentrations are below MCLs, then the water would be disposed directly to the sanitary sewer. If necessary, modified (i.e., reduced number of pumping wells) pump-and-treat systems can be operated at either OU1 or OU4 if necessary to prevent off-site migration of contaminants.

Recommended changes to the monitoring program are minor and include maintaining the current monitoring program at OU1, and removing two of the 17 monitoring wells at OU4. It is recommended that the current frequency of sampling the monitoring wells at OU4 be maintained.

Table ES.1 provides a summary of the short-term recommendations and potential cost savings associated with the recommendations, identified as a result of the RPO evaluation of the OU1 and OU4 extraction and treatment systems at DDHU. If all are implemented, these recommendations could produce an annual cost savings of approximately \$474,000 at both OU1 and OU4.

Long-term opportunities include implementation of monitored natural attenuation at OU1, optimizing the pump and treat system at OU4, and monitoring of groundwater quality at the OU4 "hot spot" extraction trench, including termination of operations, as appropriate, based on monitoring results; and operation of a modified pump and treat system at either OU1 or OU4 if monitoring indicates that CAH concentrations rebound, accompanied by migration of CAHs beyond the facility boundary. Table ES.2 presents a summary of the long-term opportunities.

An RPO implementation plan is included as Section 8 of this document. If so directed by the Contracting Officer's Representative, Parsons ES will advise the Base OM&M contractor on methods of implementing the recommendations provided in Section 7 of this document.

TABLE ES.1
SHORT-TERM RECOMMENDATIONS
OPERABLE UNITS 1 AND 4
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Recommendation	Annual Cost Savings	Cost Savings Over 10-Year Period^{a/}	Reduction in Time to Meet Cleanup Goals	Difficulty of Implementation	Cost to Implement
Recommendation No. 1 – Turn off the existing pump-and-treat system at OU1 and monitor CAHs and natural attenuation parameters in groundwater for 1 year.	\$268 K	\$2.7 M	None	Moderate – Requires regulatory approval.	\$25K
Recommendation No. 2 - Maintain operation of the ETI system at OU4 until <i>cis</i> -1,2-DCE concentrations fall below the MCL and optimize the system by eliminating 14 extraction wells and 16 injection wells.	\$200 K	\$2.0 M	None	Moderate – Requires regulatory approval.	\$25K
Recommendations No. 3 Monitor untreated groundwater from the OU4 hot-spot trench for CAHs Bypass the treatment system if CAH concentrations are below MCLs and discharge directly to the sewer.	\$0 ^{b/}	TBD	None	Low – Requires regulatory concurrence.	\$0
Recommendation No. 4 Maintain the current monitoring frequency and reduce the number of wells sampled by two during long-term groundwater monitoring at OU4.	\$6 K	\$60 K	None	Low – Requires regulatory approval.	\$5K
TOTAL	\$474K	\$4.7 M			\$60K

^{a/} Estimated costs in 2000 constant dollars. Estimated time remaining for reduction of vinyl chloride below 2 micrograms per liter under monitored natural attenuation remedy is 10 years.

^{b/} No short-term savings are estimated for bypassing the treatment system at the extraction trench, because this recommendation requires keeping the treatment system operational in the event that CAH concentrations in pretreated water are above MCLs.

**TABLE ES.2
LONG-TERM OPPORTUNITIES
OPERABLE UNITS 1 AND 4
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH**

Opportunity	Annual Cost Savings	Cost Savings Over 10-Year Period^{a/}	Reduction in Time to Meet Cleanup Goals	Difficulty of Implementation	Cost to Implement
Opportunity No. 1 – Implement monitored natural attenuation at OU1 and optimize the ETI system at OU4.	\$474K	\$4.7 M	None	Moderate – Requires regulatory approval	\$50K
Opportunity No. 2 – Monitor groundwater quality at the OU4 hot-spot extraction trench, and, when appropriate, terminate operations.	\$50 K ^{b/}	\$500 K	None	Moderate – Requires regulatory approval	\$25K
Opportunity No. 3 – Implement modified ETI system operations if monitoring of CAHs in groundwater shows both rebound and continued migration offsite.	\$335 K	\$3.4 M	None	Moderate – Requires regulatory approval	\$50K

^{a/} Estimated costs in 2000 constant dollars. Estimated time remaining for reduction of vinyl chloride below MCL of 2 µg/L under monitored natural attenuation is 10 years.

^{b/} O&M costs for the extraction trench are included in the total O&M costs for OU4, and were not provided to Parsons separately. However, for purposes of this report, Parsons estimated the O&M cost for the extraction trench to be \$50,000.

TABLE OF CONTENTS

	Page
EXECUTIVE SUMMARY.....	ES-1
LIST OF ACRONYMS AND ABBREVIATIONS.....	viii
SECTION 1 - INTRODUCTION	1-1
1.1 Remedial Process Optimization Approach and Objectives.....	1-1
1.2 Report Organization	1-3
SECTION 2 - SITE INFORMATION	2-1
2.1 Site Location and Operational History.....	2-1
2.2 Previous Investigations	2-3
2.2.1 Operable Unit 4.....	2-5
2.2.2 Operable Unit 1	2-7
2.3 Environmental Setting.....	2-10
2.3.1 Physiography.....	2-10
2.3.2 Geology	2-10
2.3.2.1 Bedrock Geology.....	2-10
2.3.2.2 Basin-Fill Geology	2-11
2.3.2.3 Surficial Geology	2-11
2.3.2.4 Operable Unit 4	2-11
2.3.2.5 Operable Unit 1	2-14
2.3.3 Hydrogeology.....	2-14
2.3.3.1 Regional Hydrogeology	2-14
2.3.3.2 Aquifers and Groundwater Flow	2-14
2.3.3.3 Operable Unit 4 Hydrogeology	2-17
2.3.3.4 Operable Unit 1 Hydrogeology	2-22
2.4 Nature and Extent of Contamination.....	2-25
2.4.1 Operable Unit 4.....	2-25
2.4.1.1 Soil.....	2-25
2.4.1.2 Groundwater	2-26
2.4.2 Operable Unit 1	2-27
2.4.2.1 Soil.....	2-28
2.4.2.2 Groundwater	2-30
2.5 Remedial Action Objectives for Groundwater.....	2-32
2.6 Description of Current Remediation Systems.....	2-34
2.6.1 OU4 Burial-Site Plume Groundwater ETI System	2-34
2.6.2 OU4 Northern Lobe Groundwater Treatment System	2-34
2.6.3 OU1 Groundwater Treatment System.....	2-35

TABLE OF CONTENTS (Continued)

	Page
2.7 Current Monitoring Program Description.....	2-36
2.7.1 Monitoring Program at OU4.....	2-36
2.7.2 Monitoring Program at OU1.....	2-38
SECTION 3 - SAMPLE COLLECTION AND NATURAL ATTENUATION EVALUATION.....	 3-1
3.1 Available Data.....	3-1
3.1.1 Monitoring Event of July and August 2000.....	3-1
3.1.2 Groundwater Sampling Procedures.....	3-6
3.2 Occurrence and Movement of VOCS.....	3-6
3.3 Natural Attenuation Evaluation.....	3-6
3.3.1 OU1 Daughter Products.....	3-10
3.3.2 OU1 Redox Couples in Biodegradation.....	3-10
3.3.3 OU1 Electron Acceptors.....	3-11
3.3.4 OU1 Metabolic Byproducts.....	3-13
3.3.5 OU1 Alkalinity and Carbon Dioxide Evolution.....	3-14
3.3.6 Summary of CAH Biodegradation at OU1.....	3-14
3.3.7 OU4 Daughter Products.....	3-15
3.3.8 OU4 Redox Couples in Biodegradation.....	3-15
3.3.9 OU4 Electron Acceptors.....	3-17
3.3.10 OU4 Metabolic Byproducts.....	3-18
3.3.11 OU4 Alkalinity and Carbon Dioxide Evolution.....	3-18
3.3.12 Summary of CAH Biodegradation at OU4.....	3-19
SECTION 4 - REVIEW OF CONCEPTUAL SITE MODEL.....	4-1
4.1 Current Conceptual Model.....	4-2
4.2 Chlorinated Solvents in The Environment.....	4-6
4.2.1 Fate and Transport of Chlorinated Solvents.....	4-6
4.2.1 Concentration Trends in Extracted Groundwater.....	4-6
4.3 Refinement of Conceptual Site Model.....	4-7
SECTION 5 - EVALUATION OF REMEDIATION GOALS.....	5-1
5.1 Key Findings of Historical Documents.....	5-1
5.1.1 Key Findings Related to Contaminants at OU1.....	5-1
5.1.2 Key Findings Related to Contaminants at OU4.....	5-2
5.2 Current Regulatory Framework.....	5-4
5.2.1 State Guidelines.....	5-5
5.2.2 Federal Guidelines.....	5-6
5.3 Evaluation of DDHU Groundwater RAOs and CLEANUP Goals.....	5-7
5.3.1 Appropriateness of Groundwater Cleanup Levels.....	5-7

TABLE OF CONTENTS (Continued)

	Page
5.3.2 Development of RBCA-Based Groundwater Cleanup Levels.....	5-8
SECTION 6 - EVALUATION OF REMEDIAL SYSTEMS.....	6-1
6.1 Groundwater Remedial Action Objectives for OU1 and OU4	6-1
6.2 Evaluation of OU1 Remedial System	6-3
6.2.1 Summary of OU1 Groundwater ETI System Operations.....	6-3
6.2.2 Effectiveness of Current Extraction System at OU1.....	6-3
6.2.2.1 Mass Removal	6-5
6.2.2.2 Plume Containment.....	6-12
6.2.3 Evaluation of Effectiveness of Current Treatment System.....	6-18
6.2.4 Evaluation of OU1 Groundwater Monitoring Program	6-24
6.2.4.1 Qualitative Hydrogeologic Evaluation.....	6-24
6.2.4.2 Temporal Statistical Evaluation	6-29
6.2.4.3 Spatial Statistical Evaluation.....	6-34
6.2.4.4 Summary of Evaluation of OU1 Groundwater Monitoring Network.....	6-39
6.2.5 Cost Evaluation	6-42
6.2.6 Alternative Technology Evaluation	6-43
6.3 Evaluation of OU4 Remedial Systems.....	6-48
6.3.1 Summary of OU4 Groundwater ETI System Operations.....	6-48
6.3.1.1 OU4 Main-Plume ETI System	6-48
6.3.1.2 OU4 Hot-Spot ETI System.....	6-48
6.3.2 Effectiveness of Current Extraction Systems at OU4	6-49
6.3.2.1 OU4 Main Plume ETI System.....	6-51
6.3.2.2 OU4 Hot Spot ETI System.....	6-65
6.3.3 Treatment System Evaluation	6-68
6.3.3.1 OU4 Main-Plume Treatment System	6-68
6.3.3.2 OU4 Hot Spot Treatment System.....	6-68
6.3.4 Evaluation of OU4 Groundwater Monitoring Program	6-69
6.3.4.1 Qualitative Hydrogeologic Evaluation.....	6-69
6.3.4.2 Temporal Statistical Evaluation	6-72
6.3.4.3 Spatial Statistical Evaluation.....	6-72
6.3.4.4 Summary of Evaluation of OU4 Groundwater Monitoring Network.....	6-78
6.3.5 Cost Evaluation	6-79
6.3.6 Alternative Technology Evaluation	6-81
SECTION 7 - RECOMMENDATIONS	7-1
7.1 Short-Term Recommendations	7-1
7.1.1 Cost Impact	7-5

TABLE OF CONTENTS (Continued)

		Page
7.2	Long-Term Opportunities	7-5
7.2.1	Costs.....	7-7
SECTION 8 - IMPLEMENTATION PLAN		8-1
8.1	Short Term Recommendations.....	8-1
8.2	Long-Term Opportunities	8-2
SECTION 9 - REFERENCES		9-1
Appendix A Natural Attenuation		
Appendix B Risk-Based Cleanup Levels		
Appendix C Capture Zone Analysis Documentation		
Appendix D Maros Sampling Location Optimization Results		
Appendix E Addendum to Draft Remedial Process Optimization Report		
Appendix F Response to Comments		

LIST OF TABLES

No.	Title	Page
3.1	Sampling Locations and Analyses for Groundwater Samples Collected by Parsons ES, July – August 2000	3-2
3.2	Chlorinated Aliphatic Compounds in Groundwater.....	3-4
3.3	Groundwater Geochemical Data (July - August 2000).....	3-7
5.1	OU1 Groundwater Cleanup Levels	5-3
5.2	OU4 Groundwater Cleanup Levels	5-5
5.3	Alternate Risk-Based Cleanup Goal	5-8
6.1	Remedial Action Objectives and Performance Criteria	6-2
6.2	Recent Production History of Groundwater Extraction Wells in OU1	6-4
6.3	Relative Effectiveness of Individual OU1 Extraction Wells	6-13
6.4	Historic Production Rates of Groundwater Extraction/Injection Wells.....	6-16
6.5	Optimized Groundwater Extraction/Injection Wellfield for the OU1 Plume.....	6-22
6.6	Current Groundwater Monitoring Program at OU1	6-27
6.7	Estimated Costs Associated With Current Monitoring Program at OU1	6-28
6.8	Results of Qualitative Evaluation of Groundwater Monitoring Program at OU1	6-30
6.9	Summary of Temporal Statistical Evaluation of Current OU1 Groundwater Monitoring Program.....	6-35

TABLE OF CONTENTS (Continued)

LIST OF TABLES (Continued)

No.	Title	Page
6.10	Summary of Spatial Evaluation of Current OU1 Groundwater Monitoring Program.....	6-40
6.11	Summary of Evaluation of Current OU1 Groundwater Monitoring Program.....	6-401
6.12	Summary of Capital, Operation, Maintenance, and monitoring costs	6-43
6.13	Recent Production History of Groundwater Extraction Wells/Trench in OU4	6-49
6.14	Relative Effectiveness of OU4 Main Plume Extraction Wells and OU4 Hotspot Interceptor Trench	6-57
6.15	Historic Production Rates of Groundwater Extraction/Injection Wells.....	6-59
6.16	Optimized Groundwater Extraction/Injection Wellfield for the OU4 Main Plume	6-66
6.17	Current Groundwater Monitoring Program at OU4.....	6-70
6.18	Estimated Costs Associated With Current Monitoring Program at OU4	6-71
6.19	Results of Qualitative Evaluation of Groundwater Monitoring Program at OU4	6-73
6.20	Summary of Temporal Statistical Evaluation of Current OU4 Groundwater Monitoring Program.....	6-74
6.21	Summary of Spatial Evaluation of Current OU4 Groundwater Monitoring Program.....	6-79
6.22	Summary of Evaluation of Current OU4 Groundwater Monitoring Program.....	6-80
6.23	Summary of Capital, Operation, Maintenance, and monitoring costs	6-82

LIST OF FIGURES

No.	Title	Page
2.1	Location of Defense Depot Hill, Utah	2-2
2.2	Operable Units.....	2-4
2.3	Operable Unit 4	2-6
2.4	Operable Unit 4 Northern Lobe Groundwater Plume	2-8
2.5	Operable Units 1 and 3 – Waste Disposal Areas	2-9
2.6	Operable Unit 4 Cross-Section A-A'	2-12
2.7	Operable Unit 4 Cross-Section B-B'	2-13
2.8	Operable Unit 1 Structural Contour Map of Top Of Clay	2-15

TABLE OF CONTENTS (Continued)

LIST OF FIGURES (Continued)

No.	Title	Page
2.9	Operable Unit 1 Cross-Section.....	2-16
2.10	Hydrographs for Monitoring Wells AEHA-5 through AEHA-8	2-18
2.11	Operable Unit 4 Shallow Groundwater Elevation Map, April 1991	2-19
2.12	Operable Unit 4 Shallow Groundwater Elevation Map, July 2000.....	2-20
2.13	Operable Unit 4 Measured Hydraulic Conductivities	2-21
2.14	Operable Unit 1 Shallow Groundwater Elevation Map, July/August 1990.....	2-23
2.15	Operable Unit 1 Shallow Groundwater Elevation Map, July 2000.....	2-24
2.16	Operable Unit 4 – April 1991 Isoconcentration Map for <i>cis</i> -1,2-DCE.....	2-28
2.17	Operable Unit 4 – April 1991 Isoconcentration Map for Vinyl Chloride.....	2-29
2.18	Operable Unit 1 – VOCs Detected in Shallow Groundwater.....	2-31
2.19	OU4 Monitoring Well Locations	2-37
2.20	OU1 Monitoring Well Location Map.....	2-39
3.1	VOCs in Groundwater at OU1 July-August 2000	3-7
3.2	VOCs in Groundwater at OU4, July-August 2000	3-9
3.3	Sequence of Microbially Mediated Redox Process.....	3-12
3.4	Sequence of Microbially Mediated Redox Process.....	3-16
4.1	OU1 Conceptual Site Model	4-3
4.2	OU4 Conceptual Site Model	4-4
6.1	Chlorinated Aliphatic Hydrocarbons (CAH) in Groundwater at OU1 – 1993 and 2000	6-6
6.2	Temporal Trends and Projected Cleanup Times for Vinyl Chloride in Groundwater at OU1	6-8
6.3	Removal of <i>cis</i> -1,2-DCE Mass During 2000	6-10
6.4	Removal of VC Mass During 2000.....	6-11
6.5	Capture-Zone Simulation (1,300 ft ² /day Transmissivity).....	6-17
6.6	Capture-Zone Simulation (510 ft ² /day Transmissivity).....	6-19
6.7	Capture-Zone Simulation (1,700 ft ² /day Transmissivity).....	6-20
6.8	Simulated Capture Zone – Two-Well Configuration.....	6-19
6.9	Simulated Capture Zone – Three-Well Configuration.....	6-23
6.10	Conceptual Representation of Temporal Trends and Temporal Variations in Concentrations.....	6-32
6.11	Mann-Kendall Temporal Trend Analysis for Concentrations of TCE6.....	6-36
6.12	Mann-Kendall Temporal Trend Analysis for Concentrations of <i>cis</i> -1,2- DCE.....	6-37
6.13	Mann-Kendall Temporal Trend Analysis for Concentrations of VC.....	6-38
6.14	Cumulative Costs and VC Mass Removal for OU1 ETI System.....	6-45
6.15	Chlorinated Aliphatic Hydrocarbons (CAH) in Groundwater at OU4 – 1993 and 2000	6-50

TABLE OF CONTENTS (Continued)

LIST OF FIGURES (Continued)

No.	Title	Page
6.16	Temporal Trends and Projected Cleanup Times for Vinyl Chloride in Groundwater at OU4	6-53
6.17	Removal of <i>cis</i> -1,2-DCE Mass During 2000	6-55
6.18	Removal of VC Mass During 2000.....	6-56
6.19	Capture-Zone Simulation (525 ft ² /day Transmissivity).....	6-62
6.20	Capture-Zone Simulation (250 ft ² /day Transmissivity).....	6-62
6.21	Capture-Zone Simulation (850 ft ² /day Transmissivity).....	6-64
6.22	Simulated Capture Zone – Recommended Configuration	6-67
6.23	Mann-Kendall Temporal Trend Analysis for Concentrations of TCE.....	6-75
6.24	Mann-Kendall Temporal Trend Analysis for Concentrations of <i>cis</i> -1,2-DCE.....	6-76
6.25	Mann-Kendall Temporal Trend Analysis for Concentrations of VC.....	6-77
6.26	Cumulative Costs and VC Mass Removal for OU4 ETI System.....	6-83

LIST OF ACRONYMS AND ABBREVIATIONS

ACC	Air Combat Command
AFBCA	Air Force Base Conversion Agency
AFCEE/ERC	Air Force Center for Environmental Excellence, Consultant Operations Division
amsl	above mean sea level
ARAR	applicable or relevant and appropriate requirement
ASTM	American Society for Testing and Materials
bgs	below ground surface
BRA	baseline risk assessment
BRAC	Base Realignment and Closure
°C	degrees Celsius
CAH	chlorinated aliphatic hydrocarbon
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CL	cleanup level
cm/s	centimeters per second
CO ₂	carbon dioxide
COC	chemical of concern
CSM	[hydrogeologic] conceptual site model
DCA	dichloroethane
DCE	dichloroethene
DDD	Needs to be expanded in text page 2-37
DDE	Needs to be expanded in text page 2-37
DDT	Needs to be expanded in text page 2-37
DDHU	Defense Distribution Depot Hill, Utah – Ogden Site
DDOU	Defense Distribution Depot, Ogden Utah
DLA	Defense Logistics Agency
DNAPL	dense nonaqueous-phase liquid
DO	dissolved oxygen
ESD	explanation of significant difference
ESE	Environmental Science and Engineering, Inc.
ETI	extraction, treatment, and injection
°F	degrees Fahrenheit
Fe ²⁺	ferrous iron
FFA	Federal Facilities Agreement
FS	feasibility study
ft/day	feet per day
ft/ft	foot per foot
ft/yr	feet per year
GAC	granular activated carbon
gpm	gallons per minute
IT	International Technology Corporation
JMM	James M. Montgomery Consulting Engineers, Inc.
LNAPL	light nonaqueous phase liquid
LTM	long-term monitoring
µg/L	micrograms per liter
MCL	maximum contaminant level
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
MNA	monitored natural attenuation

NAPL	nonaqueous-phase liquid
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
nitrate-N	nitrate as nitrogen
NPL	National Priorities List
OHM	OHM Remediation Services
OM&M	operation, maintenance, and monitoring
O&M	operation and maintenance
OPS	operating properly and successfully
ORC	oxygen-release compound
ORP	oxidation/reduction potential
OU	operable unit
Parsons ES	Parsons Engineering Science, Inc.
PCA	Tetrachloroethane
PCB	polychlorinated biphenyl
PCE	tetrachloroethene
P&T	pump and treat
QA	quality assurance
QC	quality control
RAO	remedial action objective
RBCA	Risk-based corrective action
RCRA	Resource Conservation and Recovery Act
RI	remedial investigation
RNA	remediation by natural attenuation
ROD	Record of Decision
RPO	remedial process optimization
RSV	RPO scoping visit
SARA	Superfund Amendment and Reauthorization Act
SVOC	semivolatile organic compound
TCA	trichloroethane
TCE	trichloroethene
TDS	total dissolved solids
TI	technical impracticability
TOC	total organic carbon
TPH	total petroleum hydrocarbons
UDEQ	Utah Department of Environmental Quality
US	United States
USACE	US Army Corps of Engineers
USAEHA	US Army Environmental Hygiene Agency
USATHAMA	United States Army Toxic and Hazardous Materials Agency
USEPA	United States Environmental Protection Agency
VC	vinyl chloride
VOC	volatile organic compound

SECTION 1

INTRODUCTION

This document was prepared by Parsons Engineering Science, Inc. (Parsons ES) for the Defense Logistics Agency (DLA), as part of Task Order TG03 under Air Combat Command (ACC) contract F44650-99-D0005, RL 72. The United States (US) Air Force Center for Environmental Excellence, Consultant Operations Division (AFCEE/ERC) has provided technical oversight of this task order. The primary objective of this project is to use the remedial process optimization (RPO) approach, described in the US Air Force's draft final RPO Handbook (AFCEE and Air Force Conversion Agency [AFBCA], 1999), to assess the performance of current groundwater remediation systems at Operable Units 1 and 4 (OU1 and OU4) at Defense Depot Hill, Utah (DDHU). Groundwater at these OUs is contaminated primarily with chlorinated aliphatic hydrocarbons (CAHs).

Per the work plan (Parsons ES, 2000b), this RPO evaluation also was to review optimization opportunities at OU2, a third groundwater OU located in the south-central part of DDHU. However, because OU2 has undergone an independent RPO evaluation (Parsons ES, 2000a), it is not evaluated in this report. Based on the results of the separate evaluation, the OU2 groundwater extraction, treatment, and injection (ETI) system was temporarily shut down in late 1998, and alternative, *in situ* treatments for groundwater contaminants are being investigated. A treatability test using injection of vegetable oil into the affected aquifer to enhance biodegradation, and a demonstration of monitored natural attenuation of the dissolved plume, are being implemented. Pending regulatory review of the results of these alternative groundwater treatment studies, the OU2 groundwater ETI system could be permanently taken off-line. The reader is referred to the OU2 alternative groundwater remedy evaluation report (Parsons ES, 2000a) for additional information. The primary focus of this RPO evaluation is the ETI systems operating at OU1 and OU4 to remediate dissolved CAHs in groundwater.

1.1 REMEDIAL PROCESS OPTIMIZATION APPROACH AND OBJECTIVES

The US Air Force initiated the RPO program to develop a systematic means for evaluating and improving the effectiveness and efficiency of site remediation so that maximum risk reduction is achieved for each dollar spent. RPO typically focuses on the optimization of remediation systems and upgrading the technical approach to site cleanup to take advantage of scientific advances. However, changes in the regulatory decision-making framework, such as risk-based cleanup goals and the growing acceptance of monitored natural attenuation, also may be considered during the optimization process. An effective RPO program pursues a wide range of optimization opportunities. The goals for DLA's RPO program are to:

- Assess the effectiveness of remedial actions;
- Improve the efficiency of remedial actions; and
- When possible, identify annual operating, maintenance, and monitoring (OM&M) cost savings in excess of 20 percent for each system evaluated.

The RPO evaluation for DDHU OU1 and OU4 was conducted based on guidance presented in the draft final RPO Handbook (AFCEE and AFBCA, 1999). The handbook describes a three-phased approach for implementing the RPO program and provides guidelines for reviewing the performance of existing remediation systems, enhancing the performance of existing systems, performing 5-year Record of Decision (ROD) reviews, and preparing documentation for "Operating Properly and Successfully" (OPS) certifications.

This report presents the results of the RPO Phase II evaluation conducted at DDHU. The specific objectives of this evaluation, and the tasks completed by Parsons ES under this effort, are described in the *Final Work Plan for Remedial Process Optimization Evaluation at Defense Depot Hill, Utah* (Parsons ES, 2000b), and are summarized below. Objectives of this RPO Phase II evaluation at DDHU included:

- Evaluate the accuracy of the conceptual hydrogeologic site model (CSM), and the appropriateness of cleanup goals;
- Review decision trees for performance and effectiveness evaluations;
- Make recommendations for optimizing remedial systems operations, and long-term monitoring;
- Streamline and standardize data management;
- Assess the effectiveness of the current remediation systems in relation to existing performance criteria;
- Recommend short-term modifications to OM&M of the groundwater remediation systems that will generate future cost savings;
- Identify long-term opportunities for the direction of future remedial decision making; and
- Provide a plan for implementing appropriate short-term recommendations and long-term opportunities.

Specific tasks that were completed during this RPO Phase II evaluation for DDHU OUs 1 and 4 included:

- Conducting a preliminary site visit and literature search of DDHU records;

- Reviewing available data generated during site investigations, studies, remedial actions, and monitoring, and identify data gaps, if any;
- Preparing a site-specific work plan (Parsons ES, 2000b);
- Collecting chemical/physical data to fill data gaps, as warranted;
- Refining the CSM, if appropriate, based on new data;
- Evaluating the existing groundwater ETI systems, monitoring networks, and long-term monitoring plans with respect to established remedial action objectives (RAOs);
- Evaluating the monitoring well network and determining if the network could be optimized with respect to sampling locations, frequencies, analytes, and sampling and analysis techniques;
- Evaluating the remedial decision process that formed the basis for system designs and the current applicability of the established RAOs;
- Evaluating fate and transport of contaminants in groundwater and estimating rates of natural attenuation;
- Evaluating biodegradation mechanisms operating within source areas and dissolved contaminant plumes; and
- Preparing this RPO Phase II evaluation report and presenting conclusions regarding the system evaluations and RPO recommendations for OU1 and OU4.

1.2 REPORT ORGANIZATION

This report is organized into nine sections, including this introduction, and three appendices. Section 2 provides a review of the site history and background information and a description of current site conditions, including the site environmental setting, nature and extent of contamination, current RAOs, remedial systems, and monitoring programs. Section 3 provides an evaluation of natural attenuation processes that are occurring at DDHU. A review of the current CSM is presented in Section 4. Section 5 provides an evaluation of groundwater cleanup goals, and Section 6 presents an evaluation of remedial system effectiveness. Section 7 presents recommendations for short- and long-term RPO opportunities, and Section 8 provides an RPO implementation plan. Section 9 lists the references cited in this document. Appendix A presents a discussion of natural attenuation. Appendix B presents risk-based exposure assumptions and alternative cleanup-goal calculations. Appendix C presents capture-zone analysis data for the extractions systems. Appendix D presents the statistical analysis, including the Mann-Kendall temporal trend analyses.

SECTION 2

SITE INFORMATION

This section provides a review of the operational history and previous investigations conducted at OU1 and OU4 at DDHU. A description of current site conditions also is presented, including the site environmental setting, nature and extent of contamination, RAOs, remedial systems, and monitoring programs.

2.1 SITE LOCATION AND OPERATIONAL HISTORY

DDHU is located in northern Utah approximately 30 miles north of Salt Lake City in the northwestern portion of Ogden City in Weber County (Figure 2.1). Land uses on adjoining properties include open space/recreational, agricultural, light industrial, and residential. DDHU occupies 1,128 acres and has approximately 155 buildings that have been used for covered storage, administration, vehicle maintenance, or family housing. Originally called the Utah General Depot, the site was purchased by the Department of Defense in 1940, and was activated on 15 September 1941. At that time, the Quartermaster Corps Chemical Warfare Service, Medical Corps, Corps of Engineers, and Signal Corps occupied the facility. In 1964, the facility was renamed the Defense Depot Ogden for operation by DLA. Recently, DDHU has been decommissioned through the Base Realignment and Closure (BRAC) process, and property is being transferred for non-military uses, as determined suitable. The primary use of this facility was as a supply depot.

Liquid and solid waste materials were generated and disposed of at DDHU in the past. Oily liquids and combustible solvents and fuels were burned in burning pits, and solid wastes were burned and buried. Early site assessments and investigations performed during the 1980s identified and preliminarily characterized waste disposal areas and the environmental conditions of the Depot (US Army Toxic and Hazardous Materials Agency [USATHAMA], 1980; US Army Environmental Hygiene Agency [USAEHA], 1981, 1984, 1985, and 1987; US Environmental Protection Agency [USEPA], 1984 and 1985a; and Environmental Science and Engineering, Inc. [ESE], 1986). As a result of these investigations, the former Depot was placed on the National Priorities List (NPL) in 1987 as a federal facility requiring investigation. A Depot-wide Phase I remedial investigation (RI) was conducted in 1988 (James M. Montgomery Consulting Engineers, Inc. [JMM], 1989). Based on the findings, a Federal Facilities Agreement (FFA) was signed on 30 November 1989, in accordance with the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) as amended by the Superfund Amendments and Reauthorization Act (SARA). The FFA divided the waste disposal sites into four OUs.

Figure 2.1 Location of Defense Depot Hill, Utah

OUs 1 and 4 are regions of contaminated groundwater underlying the former waste burn/burial sites. The pre-remediation dissolved CAH plumes associated with these OUs, as determined from previous investigations, are shown on Figure 2.2. OU3 is an area of soil contamination that lies within the areal extent of the OU1 dissolved CAH plume, and was not the focus of this RPO evaluation. OU1 is located at the southwestern corner of the former Depot, and OU4 is located in the northwestern part. Burn/burial sites are the confirmed source areas for the CAH plumes. Dissolved CAH plumes at OUs 1 and 4, which are the subjects of this RPO evaluation, predominantly contain *cis*-1,2-dichloroethene (DCE) and vinyl chloride (VC).

Subsequent to the Depot-wide Phase I RI (JMM, 1989) and designation of the OUs, additional phased investigations were conducted at the facility, and RI/feasibility study (FS) reports were prepared (JMM, 1990, 1991a, and 1991b; Montgomery Watson, 1996). RODs were implemented for OUs 1 and 4 by the end of 1992 (DLA, 1992a and 1992b). Source excavation/removal of soils, and shallow groundwater extraction, CAH treatment by air stripping, and reinjection were the remedies originally selected in the RODs for OUs 1 and 4. A provision for treatment of dioxins and furans in groundwater using granular activated carbon (GAC) also was made in the OU1 ROD (DLA, 1992a). Soil removal was the remedy selected for OU 3. The ETI systems at OU1 and OU4 began operation in December 1994 and July 1995, respectively. Since that time, dissolved CAH concentrations in groundwater have been reduced to low levels (Klienfelder Inc., 1999; OHM Remediation Services Corporation [OHM], 1999 and 2000). These decreases may be attributed to the permeability of the shallow aquifer, which allows high extraction/injection rates, and to favorable rates of natural attenuation (including biological degradation) of the dissolved CAHs.

2.2 PREVIOUS INVESTIGATIONS

Numerous studies have been conducted at the DDHU OUs. The information summarized below was drawn from the following reports:

- Defense Depot Ogden, Utah (DDOU) installation assessment (USATHAMA, 1980);
- DDOU hydrogeological characterization (ESE, 1986);
- DDOU Phase I and II RI reports (JMM, 1989 and 1990);
- OU1 and OU4 draft final RI/FS reports (JMM, 1991a and 1991b);
- OU1 and OU4 RODs and Responsiveness Summaries (DLA, 1992a and 1992b);
- OU4 100-Percent remedial design report (JMM, 1993c);
- OU4 Phase II Geoprobe[®] investigation report (JMM, 1994);
- Phase III Geoprobe[®] investigation report (JMM, 1995);
- Environmental baseline survey and CERFA reports (Parsons ES, 1995 and 1996);

Figure 2.2 Operable Units

- OU4 hotspot investigation and alternatives analysis report (Montgomery Watson, 1996);
- Final OU4 groundwater remediation system design concept (Montgomery Watson, 1997b);
- OU1 and OU4 5-year ROD reviews (DDHU, 1998a and 1998b);
- OU4 ROD explanation of significant difference (ESD) (Montgomery Watson, 1999);
- Fourth year operations and maintenance (O&M) report for OU4 groundwater ETI systems (OHM, 1999);
- Final OU4 hotspot remediation closure report (International Technology Corporation [IT], 1999);
- Final OU4 ROD amendment (Montgomery Watson, 2000); and
- Final OU2 groundwater plume evaluation for treatment alternative (Parsons ES, 2000a).

2.2.1 Operable Unit 4

OU4 is located at the northern end of DDHU, immediately adjacent to the Weber County Fairgrounds (Figures 2.1 and 2.2). The source area for the main OU4 plume is composed of Burial Sites 4A through 4E (Figure 2.3). Site 4A contained two shallow burning pits that were used from the 1950s until 1975. Materials disposed of included solid wastes and petroleum products. Site 4B was reportedly used for disposal of fluorescent tubes. Site 4C consisted of four shallow trenches that were used as a sanitary landfill from 1969 to 1972. Site 4D was reportedly used from the mid-1940s to mid-1960s as a burial site for cylinders of methyl bromide, but cylinders were not encountered during the RI (JMM, 1989 and 1990). However, large quantities of bottles containing water purification tablets were found. Site 4E consisted of a shallow trench that was used as an oil holding/burning pit in the 1950s and 1960s. Reportedly, waste oils, solvents, and industrial wastes were disposed of in the trench several times a year. Results of investigations conducted from 1988 through 1991 indicated that Burial Site 4E is the primary source of groundwater contamination, and Burial Site 4A is a potential secondary source. Contamination was not detected at the Fire Training/Oil Burning Pit located west of the disposal sites (Figure 2.3), suggesting that the existence of a burn pit here is doubtful. Remediation of soils in these OU4 source areas was conducted in June 1995. Soils were removed to a depth corresponding with the bottom of the disposal trenches (approximately 8 feet below ground surface [bgs]) and the depth of shallow groundwater.

During installation of the primary groundwater ETI system at OU4, VC was detected at injection wells located at the western property boundary, beyond the perceived distal extent of the plume as defined during the RI. As a result, 3 proposed injection wells were installed as extraction wells in this area. Groundwater quality in this area was further

Figure 2.3 Operable Unit 4

investigated to delineate the extent of contamination (JMM, 1994). During the BRAC environmental baseline survey conducted at roughly the same time, a potential source of the contamination was identified from a 1950 aerial photograph (Parsons ES, 1996). The potential source appeared to be an oil holding pit and possibly three trenches between Buildings 15C and 16C. After further investigation this potential source was confirmed, and the OU4 plume was expanded to include the newly identified source area and associated groundwater contamination (JMM, 1995). This area became known as the northern lobe of the OU4 plume (Figure 2.4), and also is referred to as the OU4 “hotspot” and “hotspot plume.”

The OU4 groundwater extraction system was considered incapable of capturing the northern lobe plume, and the OU4 groundwater treatment system was determined to be incapable of treating flow from additional extraction wells (Montgomery Watson, 1996). Consequently, an Explanation of Significant Difference (ESD), which was later revised and resubmitted in March 2000 in the form of a final ROD Amendment, was issued (Montgomery Watson, 1999 and 2000), and alternatives were evaluated to address this northern lobe. A system that includes a groundwater extraction trench, treatment of extracted water by chemical oxidation, and discharge of treated water to the sanitary sewer was designed and installed (Figure 2.4). The extraction trench was placed at the downgradient tip of the northern lobe near the western Depot boundary. Recent sampling of off-Depot wells downgradient from the extraction trench, however, indicates that dissolved VC may now be migrating off-site, possibly due to artificial groundwater mounding created at the OU4 injection wells.

Source-removal operations at the OU4 hotspot were conducted during October through November 1998. Approximately 4,775 tons of soil and debris, contaminated primarily with motor-oil-range petroleum, was removed to a depth of 7 feet bgs, which was 1 foot below the water table at that time (IT, 1999). Some contamination was left beneath the buildings to preserve the integrity of the structures. Approximately 3,000 pounds of oxygen-release compound (ORC) was placed in the open excavation at the water table in an attempt to promote biodegradation of the residual hydrocarbons left in place (IT, 1999). The nature and extent of soil and groundwater contamination in the OU4 source areas are discussed in Section 2.3.

2.2.2 Operable Unit 1

OU1 is located in the southwestern portion of DDHU and is composed of Burial Sites 1, 3-B, 3-C, and material in the backfilled Plain City Canal (Figure 2.5). Groundwater underlying the OU3 source areas is included in OU1. The Plain City Canal and Burial Site 3A (OU 3) were identified as sources of groundwater contamination (JMM, 1991a), and contaminated soils and debris from these sites have been removed and disposed off-Depot.

Burial Site 1 reportedly was used for the disposal of riot-control agent and white smoke containers (1945). Only non-toxic materials were placed in Burial Site 3-B. Site 3-C was the burial location for several thousand water-purification-tablet bottles. Burial Site 3-A and the World War II Mustard Storage Area (Figure 2.5) were designated OU3 based on the similarity of chemicals managed at the sites. Burial Site 3-A occupied an area slightly larger than 1 acre and had six distinct burial areas that contained various

Figure 2.4 Operable Unit 4 Northern Lobe Groundwater Plume

Figure 2.5 Operable Units 1 and 3 – Waste Disposal Areas

items. The Plain City Canal, which flowed northwest through OU1, reportedly was backfilled with debris from Burial Site 4-A (in OU4) from 1969 through 1973.

The OU1 ROD was signed in June 1992 (DLA, 1992a). Approximately 8,951 tons of soil and debris were removed from OU1 during removal actions that were completed by August 1994. More recently, additional soil and debris were removed from a west-trending segment of the Plain City Canal within OU1, as well as from a north-trending segment that paralleled the western Depot boundary (IT, 1999). Groundwater extraction at OU1 began in December 1994. More recently, an apparent source of TCE in soil has been identified at Burial Site 3-C (previously thought to be free of contamination) (Smith, 1999 personal communication).

2.3 ENVIRONMENTAL SETTING

2.3.1 Physiography

DDHU is at the eastern edge of the Basin and Range Province in a topographically flat area within the Great Salt Lake Valley, between the western margin of the Wasatch Range and the eastern shore of the Great Salt Lake. The Wasatch Mountains, about 3 miles to the east, rise as much as 5,000 feet above the valley floor, with the altitude of the highest peaks equal to approximately 9,700 feet above mean sea level (amsl) (Feth *et al.*, 1966). The shoreline of the Great Salt Lake is about 7 miles west of DDHU. The altitude of the valley floor ranges from 5,000 feet amsl near the Wasatch Range to about 4,200 feet amsl at the eastern edge of the Great Salt Lake. Surface elevations within the boundary of DDHU range from 4,247 feet amsl to 4,292 feet amsl, a difference of 45 feet. The higher elevations are in the northern portion of DDHU.

Distinct eastern and western physiographic units are present regionally (Feth *et al.*, 1966). The eastern unit is a foothills area of terrace lake deposits that form hill-and-valley topography paralleling the Wasatch Range. The terraces were formed during the Pleistocene Period by Lake Bonneville (Gilbert, 1890). Since the recession of Lake Bonneville approximately 12,000 years ago, closely spaced mountain-front streams have dissected these terraces. The western physiographic unit is a valley/lowland plain of little relief. This area extends from the western edge of the terraces to the shores of the Great Salt Lake. This plain was formed partially by deposition from Lake Bonneville during its recession, and partially by deposition from the Weber River as it meandered across the valley. DDHU is situated within this lowland plain.

2.3.2 Geology

2.3.2.1 Bedrock Geology

The Wasatch Range east of DDHU is composed of metamorphic and sedimentary rocks that range from Precambrian to Paleozoic in age (Hintze, 1988). The Precambrian rocks are of the Farmington Complex, which is composed of quartz monzonite, migmatite grading into quartz monzonite, schist, gneiss, quartzite, and amphibolite. The Paleozoic rocks are quartzites, limestones, dolomites, and shales (Feth *et al.*, 1966).

2.3.2.2 Basin-Fill Geology

A major north/south-trending, normal fault zone, referred to as the Wasatch fault zone, defines the Wasatch Range (Feth *et al.*, 1966). Successive displacement along this fault zone has allowed the accumulation of as much as 9,000 feet of basin fill. During Pleistocene Lake Bonneville and pre-Bonneville times, material eroded from the Wasatch Mountains and infilled the basin or graben (Feth *et al.*, 1966). This fill is composed of unconsolidated and semi-consolidated sediments in a series of interbedded alluvial and lacustrine deposits. Coarse-grained sediments dominate the eastern edge of the graben near the mouths of the canyons where deltas, alluvial fan, and mudflow materials predominate. The sediments become progressively finer grained to the west.

2.3.2.3 Surficial Geology

In the area encompassing DDHU, the Pleistocene deposits are covered by Holocene sediments deposited and reworked by the Weber and Ogden Rivers (ESE, 1986). Poorly to moderately well-drained soils of probable floodplain origin are present at the near surface in depressions and along abandoned stream courses (JMM, 1989). Some near-surface soils are formed from moderately coarse, mixed alluvium.

2.3.2.4 Operable Unit 4

Based on numerous investigations at OU4, the depositional sequence to the bottom of the shallow unconfined aquifer can be characterized as interfingering lenses of clay, silt, and fine sand underlain by saturated sand and gravel. A dark silt and clay aquitard underlies the shallow saturated zone at an average depth of about 30 feet bgs. Based on the logs for three deeper exploratory wells at OU4, this basal clay is 60 feet to 80 feet thick. The thickness of this basal aquitard between the shallow unconfined aquifer and the deeper, confined aquifer zone may vary, but the basal clay is ubiquitous at DDHU. There is an inferred strong upward hydraulic gradient from the deep confined aquifer to the shallow unconfined aquifer (JMM, 1991b). A prominent northwest/southeast-trending depression in the clay surface beneath DDHU is evident as shown from Phase I RI data (JMM, 1989). A north-trending lobe or small trough in this clay surface depression is evident at OU4, and allows for a local thickening of the saturated sands and gravels comprising the shallow unconfined aquifer. The structural trough at OU4 was better defined during the Phase II, III, and IV activities reported in the RI/FS (JMM, 1991b). The impacts of this trough on the pattern and magnitude of groundwater flow at OU4 are discussed in Section 2.3.3.

The depth to the surface of the basal clay beneath OU4 (designated Unit 3), and the depths and thicknesses of the water-bearing sands and gravels (Unit 2) and near-surface fine-grained sediments (Unit 1), are shown on Figures 2.6 and 2.7. Cross-section A-A' is oriented along the downgradient flowpath of the plume (Figure 2.6). Cross-section B-B' is oriented approximately perpendicular to groundwater flow (Figure 2.7). The average depth to the top of the basal clay is approximately 22 feet bgs (JMM, 1991b). The average thickness of the saturated zone appears to be about 15 feet, depending on water levels. Figures 2.6 and 2.7 illustrate the discontinuous nature of the upper silt and clay of Unit 1. In general, the aquifer material (Unit 2) is about 20 to 25 feet thick in this area.

Figure 2.6 Operable Unit 4 Cross-Section A-A'

Figure 2.7 Operable Unit 4 Cross-Section B-B'

At the OU4 hotspot, the depth to the basal clay is a little shallower, and the aquifer thins slightly to the west from this source area.

2.3.2.5 Operable Unit 1

Similar to conditions described for OU4, the depositional sequence at OU1 to the bottom of the shallow unconfined aquifer can be characterized as interfingering lenses of clay, silt, and fine sand underlain by saturated sand and gravel. The basal clay aquitard is present below the saturated zone; however, the clay surface has a relatively steep slope to the northwest beneath OU1, as shown on Figure 2.8. The depth of the clay is much shallower to the southeast of (hydraulically upgradient from) the site, as shown on the figure. The thickness of the clay aquitard at OU1 is not known, but likely is similar to that observed at OU4.

The depth to the surface of the basal clay beneath OU1, and the depths and thicknesses of the water-bearing sands and gravels and near-surface fine-grained sediments, are shown on Figure 2.9. This cross-section is oriented along the downgradient flowpath of the OU1 plume (see Figure 2.2). The depth to the top of the basal clay (Unit 3) increases by approximately 20 feet along this 1,500-foot cross-section (Figure 2.9). Likewise, the thickness of the saturated zone increases along the section line, and is up to 25 feet downgradient from the Plain City Canal source area, depending on water levels. This saturated thickness is slightly greater than that observed at OU4 (Figures 2.6 and 2.7).

2.3.3 Hydrogeology

2.3.3.1 Regional Hydrogeology

The large thickness of basin fill creates a regional hydrologic unit referred to as the East Shore unit (Thomas and Nelson, 1948). This regional unit is about 40 miles long and 3 to 20 miles wide. The Weber Delta district, a sub-region within the East Shore, is divided into six subdistricts (Feth *et al.*, 1966). DDHU is located in the Ogden-Plain City subdistrict (Feth *et al.*, 1966).

The Ogden-Plain City subdistrict is mostly underlain by unconsolidated lacustrine and fluvial deposits that form confining layers and aquifers. The artesian (confined) aquifer system supplies much of the water for the region (Feth *et al.*, 1966). The lithology of the various deposits largely determines the areas of recharge and natural discharge of groundwater, and is important in determining the chemical quality of the water in the district, which varies laterally and vertically (Feth *et al.*, 1966). High total dissolved solids (TDS) and sodium content in certain areas make this water unsuitable for irrigation.

2.3.3.2 Aquifers and Groundwater Flow

The East Shore unit contains two deep, confined (artesian) aquifers: the Sunset and Delta aquifers. The Sunset aquifer lies at a depth of 200 to 400 feet bgs, and the Delta aquifer lies between 500 and 700 feet bgs, depending on the location (Feth *et al.*, 1966). Large transmissivities are observed at certain locations within the Delta Aquifer, with lower values typical near the western edge of the valley near the Great Salt Lake. The

Figure 2.8 Operable Unit 1 Structural Contour Map of Top Of Clay

Figure 2.9 Operable Unit 1 Cross-Section

uppermost aquifer, comprised of reworked sands and gravels (ESE, 1996) and referred to as the shallow unconfined aquifer, was the focus of this RPO evaluation. Generally, lower yields and naturally poor groundwater quality characterize this uppermost aquifer in the area incorporating DDHU (Feth *et al.*, 1966).

Regionally, groundwater in the aquifers moves from the Wasatch Range (east) to topographically lower areas near the Great Salt Lake (west). Recharge to shallow groundwater is by seepage from the Weber River, canals, and small streams, and by infiltration of precipitation and excess irrigation water. In the southern part of DDHU, the inferred groundwater flow direction is northwest; at the northern end of the Depot, groundwater flow is to the southwest (JMM, 1989; Montgomery Watson, 1997c). A groundwater depression is evident in the west-central portion of DDHU, resulting in a groundwater sink that controls this pattern of flow.

2.3.3.3 Operable Unit 4 Hydrogeology

Based on water-level data for USAEHA monitoring wells collected during the 10-year period from 1981 to 1991, groundwater levels in the shallow aquifer at OU4 fluctuate 3 to 5 feet seasonally, depending upon location (Figure 2.10). The USAEHA wells, all located near the burial-site source area, and all monitoring wells installed during the RI, are shown on Figure 2.11. Groundwater levels are consistently higher during the summer and lower in winter. This general seasonal pattern of fluctuation in the shallow unconfined aquifer is exhibited Depot-wide (Montgomery Watson, 1997c). Based on April 1991 measurements, the average hydraulic gradient across the site was 0.0023 foot/foot (ft/ft) to the southwest, as shown on Figure 2.11 (JMM, 1991a). Figure 2.12 is a groundwater elevation map of OU4 for July 2000, which represents the configuration of the water table during groundwater extraction and injection. Comparison of Figures 2.11 and 2.12 shows that groundwater flow direction and gradient do not appear to have changed significantly during groundwater extraction and reinjection.

The hydraulic conductivity adjacent to the screened intervals of monitoring wells was estimated from slug tests conducted during the 1991 RI/FS. Monitoring wells measured for this parameter during the RI/FS phase are shown on Figure 2.13. Although order-of-magnitude variability is evident, the hydraulic conductivity from the Burial Site source area along the downgradient flowpath or main plume centerline (e.g., at wells JMM-45, JMM-9, JMM-58, JMM-34, and JMM-46; Figure 2.13) is relatively high. This higher hydraulic conductivity is associated with the thicker, more coarse-grained portions of the shallow aquifer (i.e., in the trough in the surface of the basal clay), and appears to be a controlling factor for plume morphology and the direction and magnitude of contaminant transport (see Figures 2.2 and 2.6 and Section 2.3).

The average hydraulic conductivity of wells along the main plume centerline (exclusive of JMM-34, which is considered an outlier) is 1.5×10^{-2} centimeters per second (cm/s) or 42 feet per day (ft/day). Using this average centerline hydraulic conductivity, the average hydraulic gradient of 0.0023 ft/ft, and an effective porosity of 0.25 for sands and gravels, the average advective groundwater velocity in the horizontal direction (parallel to stratigraphy) is approximately 140 feet per year (ft/yr) along the downgradient flowpath. This rate was calculated using the following equation:

Figure 2.10 Hydrographs for Monitoring Wells AEHA-5 through AEHA-8

Figure 2.11 Operable Unit 4 Shallow Groundwater Elevation Map, April 1991

Figure 2.12 Operable Unit 4 Shallow Groundwater Elevation Map, July 2000

Figure 2.13 Operable Unit 4 Measured Hydraulic Conductivities

$$V_h = K_h \times \frac{dh/dl}{n_e}$$

where

V_h = average horizontal velocity of groundwater movement [ft/day],

K_h = average horizontal hydraulic conductivity [ft/day],

dh/dl = average horizontal hydraulic gradient [ft/ft], and

n_e = effective porosity [percent].

As shown on Figure 2.13, the hydraulic conductivity west of the main plume is greatly reduced. The “hotspot” and associated northern lobe plume (Figure 2.4) appear to be located in these zones of lower hydraulic conductivity. *In situ* tests for hydraulic conductivity were not conducted during hotspot investigations (Montgomery Watson, 1996).

2.3.3.4 Operable Unit 1 Hydrogeology

Groundwater in the shallow aquifer at OU1 fluctuated as much as 4 feet over the 10-year period from 1981 to 1991, based on water-level data for monitoring wells AEHA-9 and AEHA-10. The AEHA wells, and all monitoring wells installed during the RI, are shown on Figure 2.14. Similar to OU4 and Depot-wide, groundwater levels are consistently higher in the summer and lower in winter; however, hydraulic gradients are not significantly affected by the fluctuating water levels. The average hydraulic gradient across the site, established in August 1990 during the RI/FS (JMM, 1991a), was 0.0023 ft/ft to the northwest (Figure 2.14). However, the gradient from JMM-19 (source area) along the flowpath to downgradient well JMM-17 is about 0.0015 ft/ft. As shown on Figure 2.14, the hydraulic gradient flattens from southeast to northwest, probably because of the increased saturated thickness of the shallow aquifer in the direction of groundwater flow. The RI/FS report states that the flow direction can vary slightly from northwest to north-northwest depending on the season, and that this may result from the seasonal effects of recharge to the shallow aquifer from Mill Creek (JMM, 1991a). Mill Creek flows near the property boundary south of the site. Figure 2.15 is a groundwater elevation map of OU1 for July 2000, which represents the configuration of the water table during groundwater extraction and injection.. Comparison figures 2.14 and 2.15 shows that groundwater extraction and reinjection at OU1 do not appear to have much influence on local groundwater flow direction or gradient.

The hydraulic conductivity adjacent to the screened intervals of monitoring wells was estimated from slug tests conducted during the 1991 RI/FS. Some variability is evident; however, most values are in the 10^{-2} to 10^{-3} cm/s range. The average hydraulic conductivity of monitoring wells along the plume centerline from the primary Plain City Canal source area (e.g., JMM-19, JMM-47, JMM-51, JMM-2, JMM-22, and JMM-17; Figure 2.15) is 1.17×10^{-2} cm/s, or 33 ft/day. Wells JMM-1 (highest value) and JMM-3 (lowest value), located near JMM-2, were excluded from the average. The average

Figure 2.14 Operable Unit 1 Shallow Groundwater Elevation Map, July/August 1990

Figure 2.15 Operable Unit 1 Shallow Groundwater Elevation Map, July 2000

flowpath hydraulic conductivity of 33 ft/day is similar to that estimated for the shallow aquifer at OU4 (42 ft/day), and to the value of 48 ft/day calculated and used by Parsons ES (2000a) in their fate and transport modeling simulations for the OU2 plume. Using this average centerline hydraulic conductivity, the average hydraulic gradient of 0.0015 ft/ft, and an effective porosity of 0.25 for sands and gravels, the average advective groundwater velocity was approximately 73 ft/yr along the downgradient flowpath prior to groundwater extraction and reinjection (see Section 2.3.3.3 for equation). Lower values of hydraulic conductivity (<10 ft/day) are evident in the distal portion of the plume near wells JMM-4, JMM-5, and JMM-6. As a result, the rate of groundwater flow, and contaminant transport, in this downgradient area of the plume is gradually reduced.

2.4 NATURE AND EXTENT OF CONTAMINATION

2.4.1 Operable Unit 4

Both soil and groundwater contamination have been documented at OU4. The results of previous investigations at the burial-site and hotspot source areas (Figures 2.3 and 2.4) indicate that the contaminants associated with soil at Burial Sites 4-A through 4-E were volatile organic compounds (VOCs), polychlorinated biphenyls (PCBs), lead, arsenic, and total petroleum hydrocarbons (TPH). Contaminants associated with soil at the OU4 hotspot were VOCs, semivolatile compounds (SVOCs), lead, and arsenic. The contaminants associated with groundwater are primarily VOCs (particularly CAHs) and TPH. Low concentrations of dioxins, furans, pesticides, and PCBs also were detected near Burial Sites 4-A through 4-E.

2.4.1.1 Soil

Remedial actions to remove contaminated soil and debris at both OU4 source areas to cleanup levels established in the ROD (DLA, 1992b) were conducted. Removal operations at Burial Sites 4-A through 4-E were completed in June 1995 (DDHU, 1998b). A reported 23,440 tons of contaminated soil and debris were removed and disposed offsite. Removal and offsite disposal for the OU4 hotspot were completed in November 1998 (IT, 1999). Approximately 4,775 tons of contaminated soil and debris were removed from the oil pit and trenches at this source area. At both source areas, contaminated soil and debris were excavated to or slightly below the shallow water table (7 feet bgs at the hotspot and approximately 8 feet bgs at the Burial Sites).

During investigations of the OU4 hotspot conducted from 1994 through 1996, CAHs, petroleum-related VOCs, and diesel range-TPH were detected in vadose zone soil samples collected within the Oil Pit. All VOC concentrations were less than 10 milligrams per kilogram (mg/kg) (Montgomery Watson, 1996). The maximum concentrations of VC and total 1,2-DCE each were 3.2J mg/kg (“J” indicates the values were estimated); 3.2 mg/kg is the soil cleanup level for VC established in the ROD (DLA, 1992b). Diesel-range petroleum hydrocarbons were detected at a maximum concentration of 9,700 mg/kg. Lower concentrations of TPH and CAHs were detected in the saturated zone at some locations. *cis*-1,2 DCE was detected at two locations at or slightly above the level of the basal clay at a maximum concentration of 0.052 mg/kg.

During source removal operations conducted in 1998, contaminated soil and debris beneath the buildings were left in place, and the buildings, concrete floors were considered by DDHU to be low-permeability caps. Confirmation samples from excavation sidewalls of the trenches and oil pit indicated that TPH (mostly motor-oil range), lead, and arsenic contamination remained. Concentrations of TPH approached 10,000 mg/kg. Free-phase petroleum product was reported to be present in the oil pit (IT, 1999). Some petroleum-related VOCs also were detected at low concentrations. No CAHs were detected in confirmation soil samples collected at the hotspot; however, PCE, TCE, and *cis*-1,2-DCE were detected in soil samples and waste characterization samples of material excavated from the oil pit. Confirmation samples were not collected from the bottom of the excavations during the removal actions. Approximately 3,000 pounds of ORC was placed in the bottom of the excavation to promote biodegradation of residual petroleum hydrocarbons (IT, 1999).

During the RI for Burial Sites 4-A through 4-E, conducted from 1988 through 1991, numerous soil borings and several test pits were sampled (JMM, 1989, 1990, and 1991b). Relatively low concentrations of several CAHs, SVOCs, pesticides/PCBs, dioxins/furans, trace metals, and petroleum hydrocarbons were detected in the three shallow soil borings and two test pits located within the 4-A Burn Pits (Figure 2.3). Higher contaminant concentrations were detected in the 4-E Oil/Holding Burn Pit, as determined from the six soil borings and one test pit located within the source material. PCE, TCE, *cis*-1,2-DCE, VC, and petroleum-related VOCs were detected. TCE and DCE detected at maximum concentrations of 29 mg/kg and 82 mg/kg, respectively, at a depth of 8 feet bgs. Ethylbenzene was detected at 23 mg/kg. SVOCs, pesticides, trace metals, dioxins/furans, and petroleum hydrocarbons also were detected at Site 4-E. In the only deep soil sample collected within the Site 4-E source area near the basal clay (at 20 feet bgs), TCE and VC were both detected at a concentration of 0.04 mg/kg.

2.4.1.2 Groundwater

CAHs, specifically *cis*-1,2-DCE and VC, are the primary chemical of concern (COCs) in groundwater at OU4. The ROD amendment for the hotspot also lists benzene and PCBs as groundwater COCs for the northern lobe plume (Montgomery Watson, 2000). During investigation of groundwater within the OU4 hotspot source area (i.e., the Oil Pit), PCE, TCE, *cis*-1,2-DCE, and VC were detected in groundwater samples collected at a depth of 12 feet bgs (3 feet below the water table) using direct-push methods. Milligrams-per-liter- (mg/L) range concentrations of *cis*-1,2-DCE and VC were detected in one shallow groundwater sample collected within the Oil Pit (Montgomery Watson, 1996). Dissolved *cis*-1,2-DCE and VC were predominant in the plume downgradient from the source. However, most concentrations of *cis*-1,2-DCE downgradient from the hotspot source were below the ROD-established cleanup level of 70 micrograms per liter ($\mu\text{g/L}$). Downgradient concentrations of VC ranged from 2 to 55 $\mu\text{g/L}$ (the cleanup goal for VC is 2 $\mu\text{g/L}$), but most commonly were between 5 $\mu\text{g/L}$ and 15 $\mu\text{g/L}$. The extent of this CAH contamination is shown on Figure 2.4. As shown in this figure, the northern lobe (hotspot) plume has extended slightly beyond the western Depot boundary.

The CAHs detected most extensively throughout the main (Burial Site) plume at OU4 during the RI/FS were *cis*-1,2-DCE and VC (JMM, 1991b). In addition to these two chemicals, the OU4 ROD identifies benzene, PCBs, and dioxins/furans (as 2,3,7,8-TCDD

equivalents) as groundwater COCs for the main plume (DLA, 1992b). Concentrations of *cis*-1,2-DCE and VC in samples collected in April 1991 (before groundwater extraction was implemented) at the source area and within the plume are shown on Figures 2.16 and 2.17. Source-area concentrations of *cis*-1,2-DCE in shallow wells JMM-52 and JMM-53 screened across the water table were 60,000 µg/L and 25,000 µg/L, respectively (Figure 2.16). Previous Phase II RI sampling conducted in July 1990 detected 84 mg/L of *cis*-1,2-DCE at well JMM-52 (JMM, 1990). *cis*-1,2-DCE also was detected at concentration of 390 µg/L in monitoring well JMM-54. This well is screened at the base of the shallow aquifer from 14 to 19 feet bgs, corresponding to the location and interval where TCE and VC were detected in saturated soil.

The magnitude of VC concentrations near the source area suggest that VC may have been a source compound (rather than strictly a TCE degradation daughter product). VC concentrations that exceed the federal maximum contaminant level (MCL) (and ROD cleanup goal) of 2 µg/L extended approximately 2,500 feet downgradient from the Burial Sites in April 1991 (Figure 2.17). Where detected, concentrations of TCE were generally below the ROD-established cleanup level 5 µg/L (DLA, 1992b). A TCE concentration of 17 µg/L was detected at well JMM-56 in 1991. In 1981, TCE was detected at nearby well AEHA-5 (Figure 2.11) at 23 µg/L (JMM, 1991b). During the RI, TCE was not detected in AEHA-5.

During sampling conducted in April 1991, high-boiling-point petroleum hydrocarbons were present at wells JMM-52 and JMM-53. The highest concentration was 43 mg/L, detected at JMM-53 (JMM, 1991b). The concentration of total organic carbon (TOC), an indicator of gross carbon in JMM-52, was 75 mg/L, and TOC concentrations greater than 20 mg/L were present within the source area. A TOC concentration of 8.1 mg/L was detected approximately 1,000 downgradient from the source at JMM-9. Interestingly, TOC was present at 22 mg/L within the deeper well, JMM-54. This suggests there may be gross carbon (i.e., natural and anthropogenic) at depth not identified or detected in the other analyses.

2.4.2 Operable Unit 1

Soil and groundwater contamination have been documented at OU1. Previous investigations at the suspected OU1 source areas (Figure 2.5) indicated that the contaminants associated with soil were detected only at Burial Site 3-A (OU3) and the Plain City Canal. At Burial Site 3-A, CAHs, PCBs, SVOCs, and pesticides were detected. Within the backfilled Plain City Canal, PCBs, dioxins/furans, pesticides, and metals were detected.

The contaminants associated with groundwater at the Plain City Canal are chlorinated ethenes, though no VOCs were detected in Canal soils. The contaminants associated with groundwater in the vicinity of Burial Site 3-A include chlorinated ethenes and ethanes. No SVOCs and pesticides were detected in groundwater. Apparently, TPH were not targeted for analysis in either soil or groundwater. In the OU1 RI/FS report, TOC was reported to have been analyzed in samples from USAEHA wells in 1984; however, these results were not presented in the report (JMM, 1991a). No chemical warfare agents were detected in groundwater samples collected from areas suspected of containing these substances.

Figure 2.16 Operable Unit 4 – April 1991 Isoconcentration Map for *cis*-1,2-DCE

Figure 2.17 Operable Unit 4 – April 1991 Isoconcentration Map for Vinyl Chloride

2.4.2.1 Soil

Remedial actions to remove contaminated soil and debris with the backfilled Plain City Canal to cleanup levels established in the ROD (DLA, 1992a) were completed in August 1994 (DDHU, 1998a). A reported 8,951 tons of contaminated soil and debris were removed from the canal site and Burial Site 3-A and disposed of off-Depot. The depths to which the contaminated materials were excavated have not been verified, but it is likely that this material was excavated to the depth of the shallow groundwater.

During the phased-RI investigations conducted from 1988 to 1991 and culminating in the RI/FS (JMM, 1991a), numerous soil borings and some test pits at OU1 were sampled. At Burial Site 3-A, low levels of TCE and 1,1,2,2-tetrachloroethane (PCA), PCBs, two uncommon SVOCs, and the pesticides DDE and *beta*-BHC were detected. Within the backfilled Plain City Canal, low levels of PCBs, dioxins/furans, metals, and the pesticides DDD, DDE, and DDT were detected. Phthalates (SVOCs) detected were considered laboratory contaminants. The fact that VOCs were not detected in soil and debris within the backfilled Plain City Canal is anomalous, because these materials are thought to be the source of the chlorinated ethenes detected in associated groundwater. Soil samples within the Canal were collected primarily within the top 5 feet of the soil column, though some soil samples were collected at various depths below the water table to the depth of the basal clay. Only one soil sample collected at 16 feet bgs in the area between Burial Sites 3-A and 3-C contained contamination (5 µg/kg *cis*-1,2-DCE).

2.4.2.2 Groundwater

CAHs, specifically *cis*-1,2-DCE and VC, are the primary COCs in groundwater at OU1. The OU1 ROD also lists TCE as a groundwater COC (DLA, 1992a). The most widespread VOC detected in groundwater during RI sampling was *cis*-1,2-DCE (JMM, 1991a). However, pre-groundwater-extraction concentrations of *cis*-1,2-DCE and VC were generally quite low (< 10 µg/L). Concentrations of these compounds detected in April 1991 are shown on Figure 2.18. Dissolved contaminant concentrations have been shown to fluctuate seasonally at OU1. Concentrations generally are lower when water levels are high (summer) and higher when water levels are lower (winter).

The highest VOC concentration detected in groundwater was 26 µg/L of *cis*-1,2-DCE at well JMM-19. This well is located along the Plain City Canal source area (Figure 2.18). The ROD-established cleanup goal for *cis*-1,2-DCE in groundwater at OU1 is 70 µg/L (DLA, 1992a). The highest concentration of VC was 10 µg/L in wells AEHA-9 and ESE-13, located downgradient from well JMM-47, which also is located along the Plain City Canal source area. VC is the only groundwater COC detected at concentrations that exceeded its ROD-established cleanup level of 2 µg/L (DLA, 1992a). The average concentration of VC in the plume indicated on Figure 2.18 was estimated to be 6 µg/L (JMM, 1991a).

Additionally, low concentrations of TCE, 1,1-DCE, 1,1,1-trichloroethane (TCA), and 1,1-dichloroethane (DCA) were detected during the April 1991 sampling or in previous sampling rounds. TCE was detected at a concentration of 1.6 µg/L at well JMM-19 during the July 1990 sampling event, but has not been detected since the inception of groundwater ETI. The ROD cleanup goal for TCE is 5 µg/L (DLA, 1992a).

Figure 2.18 Operable Unit 1 – VOCs Detected in Shallow Groundwater

Based on the 1991 distribution of contamination shown on Figure 2.18, no obvious source of CAH contamination in groundwater was evident, nor was there a clear trend of decreasing concentrations along the plume flowpath or centerline. This apparent lack of decreasing concentrations probably resulted from the orientation of the Plain City Canal source area along the direction of groundwater flow, and the presence of multiple, small sources in the vicinity of Burial Sites 3-A and 3-C. The conspicuous detection of TCE and chlorinated ethanes in soil and groundwater in the vicinity of Burial Sites 3-A and 3-C, and similar concentrations of *cis*-1,2-DCE and VC in this area relative to the Plain City Canal source area, seems to indicate that sources other than the backfilled Plain City Canal are present. Concentrations of *cis*-1,2-DCE and VC were also detected in well JMM-22, which is screened just above the basal clay. Currently, concentrations of COCs at JMM-22 are similar to the pre-extraction levels, whereas concentrations in the other shallow site wells have decreased since the ETI system began operation.

2.5 REMEDIAL ACTION OBJECTIVES FOR GROUNDWATER

Parallel-track FSs were completed for OU1 and OU4 in conjunction with completion of the phased RIs in 1991 (JMM, 1991a and 1991b), and in accordance with CERCLA guidance (USEPA, 1985b). An array of remedial alternatives were evaluated, using the criteria of compliance with Applicable or Relevant and Appropriate Requirements (ARARs); long-term effectiveness and permanence; short-term effectiveness; reduction of toxicity; mobility; or volume of contamination; implementability; cost; and community and regulatory acceptance. The preferred remedial alternative for both OUs identified during the FSs consisted of soil excavation and off-Depot disposal, and groundwater extraction, removal of VOCs from extracted groundwater by air stripping, and reinjection of the treated groundwater into the shallow aquifer via injection wells.

Parallel-track RODs (DLA, 1992a and 1992b) were issued for both OUs, in which RAOs were established and implementation of the selected remedies was mandated under CERCLA (see Section 4). The RODs identified removal and off-Depot disposal of contaminated soil as the remedy for Burial Site source soils, and specified groundwater ETI as the remedy for the associated groundwater contaminant plumes underlying the burial areas. ARARs were considered and final soil and groundwater remediation criteria were established through negotiations among the US Army, the Utah Department of Environmental Quality (UDEQ) and, and USEPA Region VIII. An ESD for the OU4 ROD was issued for the OU4 hotspot and associated groundwater contamination (Montgomery Watson, 1999). Because some contaminated soil beneath the buildings at the OU4 hotspot was left in place, an amendment to the ROD also was required (Montgomery Watson, 2000). Based on the ESD and amendment, a separate groundwater remediation system consisting of an extraction trench with *ex-situ* chemical oxidation treatment of extracted groundwater, and discharge of treated water to the sanitary sewer system, was implemented. The extraction trench is located at the western Depot boundary (Figure 2.4).

The soil removal actions have been completed at OUs 1 and 4, and ROD-specified soil remediation criteria have been achieved (except in the areas underlying buildings at the OU4 hotspot, where the remedy has been modified to allow these soils to remain *in situ*). A small, recently identified secondary soil source of chlorinated solvent contamination at OU1 is scheduled for removal in the near future (Smith, 1999, personal communication).

Therefore, soil remedies and soil remediation criteria are not evaluated in this RPO report. Groundwater extraction and treatment are underway at OUs 1 and 4, and it is the ETI systems at these OUs that are the focus of the RPO evaluation. Descriptions of the OU 1 and 4 groundwater ETI systems are presented in Section 2.6.

The general RAO for soil and groundwater associated with OU1 and OU4 was identified as "*protection of human health and the environment*" (DLA, 1992a and 1992b; Montgomery Watson, 2000). The OU1 ROD identifies TCE, *cis*-1,2-DCE, and VC as the COCs requiring remediation in groundwater (DLA, 1992a); the OU4 ROD identifies benzene, *cis*-1,2-DCE, VC, PCBs, and (at the main plume only) dioxins and furans as the groundwater COCs (DLA, 1992b; Montgomery Watson, 2000). The RODs state that "*there are no current significant risks to human health and the environment from exposure to soil or groundwater at OU4, nor are any significant risks likely to develop in the future as long as the Depot remains in existence.*" The remediation criteria established for groundwater COCs are intended to be protective of hypothetical future residents extracting groundwater for potable use. The specific RAOs identified in the RODs for OU1 and OU4 are as follow:

- Prevent exposure to contaminated soil that poses an excess cancer risk of no greater than 1×10^{-4} with a target of 1×10^{-4} under a future residential exposure scenario (Risk Objective).
- Reduce COC concentrations in shallow groundwater below the federal MCLs (Cleanup Objective).
- Reduce the *cis*-1,2-DCE and VC concentrations in treated groundwater effluent to MCLs (70 $\mu\text{g/L}$ and 2 $\mu\text{g/L}$, respectively) (Discharge Objective).
- Eliminate or reduce the potential for further migration of the existing CAH plumes and achieve remediation to MCLs within the areas of attainment (defined as the area at both OUs containing VC above its MCL of 2 $\mu\text{g/L}$) (Containment Objective).
- Restore groundwater to MCLs within an estimated 5-year time frame (Performance Objective).

As described in the RODs, remediation of groundwater in the shallow aquifer will be considered complete when contaminant concentrations are maintained, with active groundwater extraction, below MCLs for a period of 1 year, whereupon the pump-and-treat (P&T) systems can be turned off (DLA, 1992a and 1992b). In addition, performance and compliance monitoring programs are required to evaluate the effectiveness of the selected remedy with respect to the following:

- Horizontal and vertical extent of the plume;
- Contaminant concentration gradients;
- Rate and direction of contaminant migration;

- Changes in contaminant concentrations or distribution over time;
- Containment of the plume; and
- Concentrations of contaminants in treatment system influent and effluent.

2.6 DESCRIPTION OF CURRENT REMEDIATION SYSTEMS

2.6.1 OU4 Burial-Site Plume Groundwater ETI System

The groundwater ETI system currently operating at the main plume at OU4 (i.e., the plume sourced at Burial Sites 4-A through 4-E (Figures 2.3, 2.16, and 2.17) consists of 31 groundwater extraction wells; a treatment system influent equalization tank; chemical (sodium hypochlorite and sodium hexametaphosphate) pre-treatment addition to control iron fouling and iron bacteria; twin packed-bed air-stripping towers; an effluent equalization tank; twin bag filters for iron-precipitate removal; and reinjection of the treated water to the shallow aquifer through 25 injection wells. Emissions from the two stripping towers are discharged directly to the atmosphere. In addition to the primary components listed above, the existing treatment system includes the following equipment:

- Transfer pumps,
- Blowers,
- Treated water injection pumps,
- Associated piping,
- Electrical power, and
- System controls and ancillary equipment.

The system is designed to remediate groundwater contaminated with VOCs, primarily VC, *cis*-1,2-DCE, and benzene. The third-quarter 1999 average extraction and treatment rate was approximately 100 gallons per minute (gpm); the mean influent concentrations of VC and *cis*-1,2 DCE were approximately 30 and 100 µg/L, respectively; and their respective concentrations in the treatment system effluent are < 0.5 µg/L (OHM, 1999).

As stated in the OU4 ROD (DLA, 1992b), the estimated time required to achieve the remediation goals associated with OU4 groundwater was 5 years. However, the present worth of the system was calculated on a basis of 10 years active system operation followed by 2 years of post-remediation monitoring. Based on these criteria, the present worth of capital and OM&M costs was projected to be \$3,022,000 (DLA, 1992b).

2.6.2 OU4 Northern Lobe Groundwater Treatment System

The groundwater extraction, treatment, and discharge system currently operating in the northern lobe of the OU4 groundwater plume (i.e., the plume sourced at the OU4

hotspot, Figure 2.4) consists of a 300-foot-long groundwater extraction trench, treatment using hydrogen peroxide and ozone addition in two (in series) reaction vessels, and discharge of treated effluent to the Central Weber Sewer Improvement District (CWSID) sanitary sewer system. In addition to the components listed above, the existing treatment system includes the following equipment:

- Extraction trench sump and treatment building sump pumps,
- Ozone generator,
- Ozone destructor,
- Hydrogen peroxide storage tanks and metering pumps,
- Associated piping,
- Electrical power, and
- System control and ancillary equipment.

The hotspot groundwater system is designed to remediate groundwater contaminated with VOCs, primarily VC and *cis*-1,2-DCE. The third-quarter 1999 average extraction and treatment rate was approximately 10 gpm; the mean influent concentrations of VC and *cis*-1,2 DCE were approximately 3.0 and 4.0 µg/L, respectively; and their respective concentrations in the treatment system effluent were < 0.5 µg/L (OHM, 1999).

As stated in the OU4 ROD Amendment (Montgomery Watson, 2000), the estimated time required to achieve the remediation goals associated with the OU4 northern lobe groundwater plume was 10 years. Based on this estimate, the present worth of capital and OM&M costs was projected to be \$1,104,000 (Montgomery Watson, 2000).

2.6.3 OU1 Groundwater Treatment System

The groundwater ETI system currently operating at OU1 consists of 16 groundwater extraction wells; an influent equalization tank; chemical (sodium hypochlorite and sodium hexametaphosphate) pre-treatment to control iron fouling and iron bacteria; twin packed-bed air stripping towers; an effluent equalization tank; twin bag filters for iron precipitate removal; and reinjection of the treated water to the shallow aquifer through 16 injection wells. In addition to the components listed above, the existing treatment system includes the following equipment:

- Transfer pumps,
- Blowers,
- Treated-water injection pumps,
- Associated piping,
- Electrical power, and
- System control and ancillary equipment.

The system is designed to remediate groundwater contaminated with VOCs, primarily VC, *cis*-1,2-DCE and benzene. The fourth-year (April 1999) average extraction and treatment rate was approximately 100 gpm; the mean influent concentrations of VC and *cis*-1,2 DCE were approximately 1.5 and 3 µg/L, respectively; and their respective concentrations in the treatment system effluent were < 0.5 µg/L (Klienfelder, 1999).

As stated in the ROD (DLA, 1992a), the estimated time required to achieve the remediation goals associated with OU1 groundwater was 5 years, with 2 additional years of post-remediation monitoring. Based on these criteria, the present worth of capital and OM&M costs was projected to be \$1,155,000 (DLA, 1992a).

2.7 CURRENT MONITORING PROGRAM DESCRIPTION

2.7.1 Monitoring Program at OU4

Since 1981, the groundwater quality beneath OU4 has been monitored by the US Army and its consultants. From 1981 through April 1991, 32 groundwater monitoring wells were installed in the vicinity of OU4 (JMM, 1991b). The monitoring well locations are shown on Figure 2.19. Groundwater samples collected from these wells have been analyzed for one or more of the following constituents:

- VOCs;
- SVOCs;
- Pesticides/PCBs;
- Dioxins/Furans;
- TPH;
- Metals; and/or
- Major anions, cations, TOC, and TDS.

Sixteen of the existing monitoring wells at OU4 were selected as compliance monitoring wells for the main (Burial Site) dissolved contaminant plume. The objective of the compliance monitoring program is to determine if cleanup objectives are being met in the shallow aquifer during and following remediation (JMM, 1993b). Analytical results for samples from these wells are used to assess the effectiveness of the extraction system at containing the plume and removing CAH mass, and to document progress toward RAOs during long-term monitoring (LTM).

Compliance wells were selected to allow monitoring of conditions upgradient from (well JMM-44), downgradient from (JMM-30 and JMM-64), crossgradient from (JMM-14, JMM-15, JMM-33, and JMM-65), and within (JMM-8, JMM-9, JMM-46, JMM-52, JMM-56, and JMM-57) the main plume area (JMM, 1993b). The main plume was defined as the area where VC concentrations exceed the MCL of 2 µg/L, based on 1991 data from the RI/FS (JMM, 1991b). Monitoring wells JMM-41D, JMM-42D, and JMM-

Figure 2.19 OU4 Monitoring Well Locations

43D also were included in the program to allow monitoring of COC migration into the deep artesian aquifer underlying the shallow aquifer at the site. Wells selected for the compliance monitoring program were chosen based on location, previous analytical results, quality of well construction, screen depth, and relationship to proposed injection well locations.

Monitoring wells within the plume area were selected to monitor progress of the remediation system in removing contamination mass to meet groundwater remediation criteria. Wells located outside the 1991 VC plume extent were selected to monitor potential contaminant migration beyond the plume boundary. The upgradient monitoring well JMM-44 allows monitoring of background groundwater quality.

The original compliance monitoring schedule for the main OU4 plume called for (JMM, 1993b):

- An initial round of groundwater sampling prior to operation of the ETI system;
- Quarterly groundwater sampling during the first year of ETI system operation;
- Semiannual groundwater sampling after the first year, until each compliance monitoring well has attained COC concentrations below remediation criteria for 1 year.

When COC remediation criteria are met, the ETI system will be shut down, and groundwater sampling will continue on an annual basis until the next scheduled statutory 5-year review. If remediation criteria are not met, then the ETI system will continue to operate, and groundwater sampling will continue on a semiannual basis, until the remediation criteria are met.

Groundwater samples are analyzed for VOCs, including VC, *cis*-1,2-DCE, and benzene, using USEPA Method 502.2 or 524.2. Due to the limited areal extent of PCBs, PCB analyses are performed only on groundwater samples from wells JMM-8, JMM-44, JMM-52, and JMM-56. If dioxins and furans are detected in treatment plant influent water, then groundwater samples also will be analyzed for those compounds.

2.7.2 Monitoring Program at OU1

Since 1981, the groundwater quality beneath OU1 has been monitored by the US Army and its consultants. From 1981 through August 1990, 26 groundwater monitoring wells were installed in the vicinity of OU1 (JMM, 1991a). Three of the wells (ONC-1, ONC-2, and ONC-4) are located south of (upgradient from) OU1 on Ogden Nature Center property (Figure 2.20). Groundwater samples collected from these wells have been analyzed for one or more of the following constituents:

- VOCs;
- SVOCs;
- Thiodiglycol;
- Mustard/Lewisite;

Figure 2.20 OU1 Monitoring Well Location Map

- Pesticides/PCBs;
- Dioxins/furans;
- TPH;
- Metals; and/or
- Major anions, cations, pH, specific conductivity, TOC, and TDS

Fifteen of the existing monitoring wells at OU1 were selected as compliance monitoring wells (JMM, 1993a). Analytical results for samples from these wells are used to assess the effectiveness of the extraction system, and to document compliance with ROD remediation criteria during LTM.

Compliance monitoring wells were selected for areas upgradient from (JMM-20), downgradient from (JMM-17, JMM-29, JMM-63), crossgradient from (JMM-6, JMM-48, JMM-62), and within (JMM-3, JMM-19, JMM-22, JMM-47, JMM-59, JMM-60, AEHA-9, ESE-15) the plume area (JMM, 1993a). The OU1 plume is defined as the area where VC concentrations exceed the MCL of 2 µg/L, based on 1991 data from the RI/FS (JMM, 1992a). Wells selected for the compliance monitoring programs were chosen based on location, previous analytical results, quality of well construction, screen depth, and relationship to proposed injection well locations.

Per the OU1 groundwater monitoring plan (JMM, 1993a), the original compliance monitoring schedule included:

- An initial round of groundwater sampling prior to operation of the ETI system;
- Quarterly groundwater sampling during the first year of ETI system operation;
- Semiannual groundwater sampling after the first year, until each compliance monitoring well has attained COC concentrations below remediation criteria for 1 year.

When COC remediation criteria are met, the treatment system will be shut down, and groundwater sampling will continue on an annual basis until the next scheduled statutory 5-year review. If remediation criteria are not met, then the ETI system will continue to operate, and groundwater sampling will continue on a semiannual basis until remediation criteria are met. The analytical parameters for compliance monitoring include VC, TCE, and *cis*-1,2-DCE, and the groundwater remediation criteria are based upon the MCLs for these compounds. USEPA Methods 502.2 or 524.2 are used for laboratory analyses.

SECTION 3

SAMPLE COLLECTION AND NATURAL ATTENUATION EVALUATION

3.1 AVAILABLE DATA

Investigation activities have been conducted at DDHU OUs 1 and 4 since 1980 (USATHAMA, 1980). Groundwater samples have been collected and analyzed for VOCs, SVOCs, fuel constituents, metals, PCBs, and other inorganic constituents/parameters. Limited groundwater analytical results from 1986 through 2000 were provided by the Sacramento Corps of Engineers to Parsons ES in electronic format and additional results were tabulated from existing hardcopy data. These data have been incorporated into this RPO evaluation.

After reviewing the available information for DDHU OUs 1 and 4, it became apparent that additional data, primarily geochemical in nature, would be required to support the evaluation of alternative remediation strategies (including MNA) for groundwater at the site. Accordingly, the DDHU RPO workplan (Parsons ES, 2000) proposed a field program to collect the information necessary for further evaluation of groundwater geochemistry and extent of contamination at DDHU OUs 1 and 4. Groundwater samples were collected in July and August 2000 from a subset of the existing monitoring wells. The resulting data were integrated with existing information to refine the conceptual hydrogeologic model of the site (Section 4), to assist with interpretation of the physical setting (Section 5), and to evaluate the nature and extent of contaminants in the subsurface (Section 4).

The following subsections summarize the procedures for collecting site-specific data necessary for the RPO evaluation. Additional details regarding investigation activities are presented in the work plan (Parsons ES, 2000).

3.1.1 Monitoring Event of July and August 2000

During the period from July 25 through August 2, 2000, 27 wells at DDHU OU1 and 28 wells at DDHU OU4 were sampled by Parsons ES (Table 3.1). Field activities associated with collection and analyses of groundwater samples in support of the DDHU RPO investigation were conducted in accordance with the provisions of the site specific Quality Assurance Project Plan (Parsons ES, 1999). As specified in Section 5.2.2 of the workplan, fugitive water quality parameters, including electrical conductivity, turbidity, pH, temperature, dissolved oxygen (DO), and oxidation reduction potential (ORP or Eh) were measured at monitoring wells located along the centerline of the OU1 and OU4 plumes. All groundwater samples collected during the July - August 2000 monitoring event were analyzed for VOCs using USEPA Method SW8260B (Table 3.2).

TABLE 3.1
SAMPLING LOCATIONS AND ANALYSES
FOR
GROUNDWATER SAMPLES COLLECTED BY PARSONS ES
Monitoring Event of July-August 2000
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Sampling Location	Operable Unit(s)	Analyses											
		Field								Laboratory			
		Alkalinity (field acid titration kit)	Carbon Dioxide (Hach Method 1436-01)	Dissolved Oxygen (direct-reading meter)	Ferrous Iron (Fe II) (colorimetric, 1,10-phenanthroline)	Total Iron (colorimetric, ferric iron reduction)	Sulfide (colorimetric, methylene blue)	Nitrite-N (colorimetric, azo dye)	Nitrate (colorimetric cadmium reduction)	VOCs ^{3/} (Method SW8260)	Methane, Ethane, Ethene (Method M2720C)	Chloride, Nitrate, Sulfate (IC Method E300)	Total Organic Carbon (Method 415.1)
AEHA-9	OU 1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ESE-12R	OU 1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ESE-13	OU 1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ESE-15	OU 1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
JMM-1	OU 1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
JMM-1 DUP	OU 1									✓	✓	✓	✓
JMM-2	OU 1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
JMM-17	OU 1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
JMM-19	OU 1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
JMM-22	OU 1									✓	✓	✓	✓
JMM-27	OU 1	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
JMM-47	OU 1	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
JMM-51	OU 1	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
EW-1	OU 1									✓			
EW-2	OU 1									✓			
EW-3	OU 1									✓			
EW-4	OU1									✓			
EW-5	OU 1	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
EW-6	OU 1	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
EW-7	OU 1	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
EW-8	OU 1	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
EW-9	OU 1	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
EW-10	OU 1	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
EW-11	OU 1									✓			
EW-12	OU 1									✓			
EW-13	OU 1									✓			
EW-14	OU 1									✓			
EW-15	OU 1									✓			
AEHA-5	OU 4	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
ESE--6	OU 4	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
JMM-8	OU 4	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓

TABLE 3.1 (Continued)
SAMPLING LOCATIONS AND ANALYSES
FOR
GROUNDWATER SAMPLES COLLECTED BY PARSONS ES
Monitoring Event of July-August 2000
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Sampling Location	Operable Unit(s)	Analyses											
		Field								Laboratory			
		Alkalinity (field acid titration kit)	Carbon Dioxide (Hach Method 1436-01)	Dissolved Oxygen (direct-reading meter)	Ferrous Iron (Fe II) (colorimetric, 1,10-phenanthroline)	Total Iron (colorimetric, ferric iron reduction)	Sulfide (colorimetric, methylene blue)	Nitrite-N (colorimetric, azo dye)	Nitrate (colorimetric cadmium reduction)	VOCs ^{a/} (Method SW8260)	Methane, Ethane, Ethene (Method M2720C)	Chloride, Nitrate, Sulfate (IC Method E300)	Total Organic Carbon (Method 415.1)
JMM-9	OU 4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
JMM-34	OU 4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
JMM-35	OU 4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
JMM-44	OU 4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
JMM-44 DUP	OU 4									✓	✓	✓	✓
JMM-45	OU 4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
JMM-46	OU 4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
JMM-52R	OU 4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
JMM-54R	OU 4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
JMM-58	OU 4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
JMM-64	OU 4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
EW-1	OU 4									✓			
EW-2	OU 4									✓			
EW-3	OU 4									✓			
EW-4	OU 4									✓			
EW-5	OU 4									✓			
EW-6	OU 4									✓			
EW-7	OU 4									✓			
EW-9	OU 4									✓			
EW-10	OU 4									✓			
EW-11	OU 4									✓			
EW-12	OU 4									✓			
EW-13	OU 4									✓			
EW-14	OU 4									✓			
EW-15	OU 4									✓			
EW-16	OU 4									✓			

^{a/}VOCs - Volatile Organic Compounds analyzed by SW8260B

All wells were purged using a peristaltic pump until the wellhead parameters stabilized.

TABLE 3.2
CHLORINATED ALIPHATIC HYDROCARBONS IN GROUNDWATER
JULY-AUGUST, 2000
SITES OU1 AND OU4
DEFENSE DEPOT HILL, UTAH

OU1																
Monitoring Well ID	SAMPLE DATE	Benzene (mg/l) ^d	Toluene (mg/l)	Chloro-benzene (mg/l)	1,1-DCA ^d (mg/l)	1,1-DCE ^d (mg/l)	cis-1,2-DCE (mg/l)	trans-1,2-DCE (mg/l)	Ethyl-benzene (mg/l)	Methylene Chloride (mg/l)	TCE ^d (mg/l)	1,2,4-TMB ^d (mg/l)	Vinyl Chloride (mg/l)	Ethane (mg/l)	Ethene (mg/l)	Methane (mg/l)
OU1-AEHA-9	07/26/00	<0.5 ^d	<1.0	<0.5	<0.5	0.14	2.9	<0.6	<0.6	<0.6	<1.0	<1.3	2	<0.5	<0.5	58
OU1-ESE-12R	07/25/00	<0.5	<1.0	<0.5	<0.5	0.091	<1.0	<0.6	<0.6	<0.6	<1.0	<1.3	<1.0	<0.5	<0.5	23
OU1-ESE-13	07/26/00	<0.5	0.11	<0.5	<0.5	0.17	2.3	<0.6	<0.6	<0.6	<1.0	<1.3	0.76	<0.5	<0.5	9.5
OU1-ESE-15	07/25/00	<0.5	<1.0	<0.5	<0.5	0.32	0.5	<0.6	<0.6	0.25	0.37	<1.3	<1.0	<0.5	<0.5	0.22
OU1-EW-11	08/01/00	<0.5	<1.0	<0.5	<0.5	0.1	0.45	<0.6	<0.6	<0.6	0.59	<1.3	<1.0	NM ^e	NM	NM
OU1-EW-12	08/01/00	<0.5	<1.0	<0.5	<0.5	<1.0	0.32	<0.6	<0.6	<0.6	0.2	<1.3	<1.0	NM	NM	NM
OU1-EW-13	08/01/00	<0.5	<1.0	<0.5	0.11	0.15	0.58	<0.6	<0.6	<0.6	<1.0	<1.3	<1.0	NM	NM	NM
OU1-EW-15	08/01/00	<0.5	<1.0	<0.5	<0.5	<1.0	<1.0	<0.6	<0.6	<0.6	0.28	<1.3	<1.0	NM	NM	NM
OU1-EW-4	08/01/00	<0.5	<1.0	<0.5	0.16	0.12	5.6	0.36	<0.6	<0.6	0.76	<1.3	1	NM	NM	NM
OU1-JMM-1	07/25/00	<0.5	<1.0	<0.5	<0.5	0.23	1.3	<0.6	<0.6	0.24	0.27	<1.3	<1.0	<0.5	<0.5	0.21
OU1-JMM-1 Dup	07/25/00	<0.5	0.097	<0.5	<0.5	0.27	1.3	<0.6	<0.6	<0.6	0.25	<1.3	<1.0	<0.5	<0.5	0.2
OU1-JMM-17	07/25/00	<0.5	<1.0	<0.5	<0.5	0.3	<1.0	<0.6	<0.6	<0.6	0.18	<1.3	<1.0	<0.5	<0.5	3.1
OU1-JMM-19R	07/25/00	<0.5	<1.0	<0.5	<0.5	0.14	4.8	0.46	<0.6	<0.6	0.44	<1.3	0.75	<0.5	<0.5	6
OU1-JMM-2	07/25/00	<0.5	<1.0	<0.5	<0.5	0.21	3.7	0.11	<0.6	0.33	<1.0	<1.3	3.3	<0.5	0.12	67
OU1-JMM-22	07/25/00	<0.5	0.096	<0.5	<0.5	0.31	4.3	<0.6	<0.6	<0.6	<1.0	<1.3	3.6	<0.5	<0.5	2990
OU1-JMM-47R	07/25/00	<0.5	<1.0	<0.5	<0.5	<1.0	0.91	<0.6	<0.6	<0.6	0.094	<1.3	0.24	<0.5	<0.5	1.4
OU1-JMM-59	07/26/00	<0.5	<1.0	<0.5	<0.5	0.27	1.7	<0.6	<0.6	<0.6	0.5	<1.3	0.33	<0.5	<0.5	2.2

OU4																
Monitoring Well ID	SAMPLE DATE	Benzene (mg/l)	Toluene (mg/l)	Chloro-benzene (mg/l)	1,1-DCA (mg/l)	1,1-DCE (mg/l)	cis-1,2-DCE (mg/l)	trans-1,2-DCE (mg/l)	Ethyl-benzene (mg/l)	Methylene Chloride (mg/l)	TCE (mg/l)	1,2,4-TMB (mg/l)	Vinyl Chloride (mg/l)	Ethane (mg/l)	Ethene (mg/l)	Methane (mg/l)
OU4-AEHA5	07/27/00	0.23	<1.0	0.3	<0.5	0.33	1.1	<0.6	<0.6	0.22	0.11	<1.3	7.9	<0.5	0.53	NM
OU4-EW-01	08/02/00	0.51	0.24	<0.5	<0.5	<1.0	8.7	0.2	0.3	<0.6	0.098	0.15	1.9	NM	NM	NM
OU4-EW-02	08/02/00	11	4.2	<0.5	<0.5	<1.0	290	<0.6	30	6.5	1.2	1.3	12	NM	NM	NM
OU4-EW-03	08/02/00	2.4	0.74	<0.5	<0.5	<1.0	6.1	0.23	4.2	<0.6	0.31	1.1	8.3	NM	NM	NM
OU4-EW-04	08/02/00	<0.5	<1.0	<0.5	<0.5	<1.0	0.36	<0.6	<0.6	<0.6	0.19	<1.3	0.18	NM	NM	NM
OU4-EW-05	08/02/00	<0.5	<1.0	<0.5	<0.5	<1.0	0.59	<0.6	<0.6	0.24	0.09	<1.3	0.15	NM	NM	NM
OU4-EW-06	08/02/00	13	<1.0	<0.5	<0.5	<1.0	380	2.8	13	44	20	<1.3	97	NM	NM	NM
OU4-EW-07	08/02/00	3.2	<1.0	<0.5	<0.5	<1.0	73	0.39	<0.6	7.6	<1.0	<1.3	37	NM	NM	NM
OU4-EW-09	08/02/00	<0.5	0.1	<0.5	<0.5	<1.0	0.46	<0.6	<0.6	1.1	0.28	<1.3	<1.0	NM	NM	NM
OU4-EW-10	08/02/00	<0.5	<1.0	<0.5	<0.5	<1.0	1.8	0.093	<0.6	1.3	0.1	<1.3	0.12	NM	NM	NM

TABLE 3.2 continued
CHLORINATED ALIPHATIC HYDROCARBONS IN GROUNDWATER
JULY-AUGUST, 2000
SITES OU1 AND OU4
DEFENSE DEPOT HILL, UTAH

Monitoring Well ID	SAMPLE DATE	OU4 continued														
		Benzene (mg/l)	Toluene (mg/l)	Chloro-benzene (mg/l)	1,1-DCA (mg/l)	1,1-DCE (mg/l)	cis-1,2-DCE (mg/l)	trans-1,2-DCE (mg/l)	Ethyl-benzene (mg/l)	Methylene Chloride (mg/l)	TCE (mg/l)	1,2,4-TMB (mg/l)	Vinyl Chloride (mg/l)	Ethane (mg/l)	Ethene (mg/l)	Methane (mg/l)
OU4-EW-11	08/02/00	0.14	<1.0	<0.5	<0.5	<1.0	0.44	<0.6	<0.6	1.1	<1.0	<1.3	0.57	NM	NM	NM
OU4-EW-12	08/02/00	<0.5	<1.0	<0.5	<0.5	<1.0	<1.0	<0.6	<0.6	0.9	<1.0	<1.3	<1.0	NM	NM	NM
OU4-EW-13	08/02/00	<0.5	<1.0	<0.5	<0.5	<1.0	0.53	<0.6	<0.6	1.3	<1.0	<1.3	<1.0	NM	NM	NM
OU4-EW-14	08/02/00	0.31	0.1	0.51	<0.5	0.1	6.8	0.18	<0.6	1.4	0.33	<1.3	4.6	NM	NM	NM
OU4-EW-15	08/02/00	0.24	<1.0	0.35	<0.5	0.11	6.6	0.14	<0.6	<0.6	0.31	<1.3	2.3	NM	NM	NM
OU4-EW-16	08/02/00	0.12	<1.0	<0.5	<0.5	<1.0	4.8	0.16	<0.6	1.1	0.2	<1.3	0.91	NM	NM	NM
OU4-EW-17	08/02/00	<0.5	<1.0	<0.5	<0.5	<1.0	4.2	0.2	<0.6	1.2	0.12	<1.3	0.8	NM	NM	NM
OU4-EW-18	08/02/00	0.19	<1.0	0.13	<0.5	0.093	11	0.72	<0.6	1.1	0.22	<1.3	1.7	NM	NM	NM
OU4-EW-19	08/02/00	0.23	<1.0	0.49	<0.5	0.13	9.8	0.2	<0.6	0.98	0.42	<1.3	5.8	NM	NM	NM
OU4-EW-20	08/02/00	<0.5	<1.0	<0.5	<0.5	<1.0	<1.0	<0.6	<0.6	0.45	<1.0	<1.3	<1.0	NM	NM	NM
OU4-EW-21	08/02/00	0.13	<1.0	0.13	<0.5	<1.0	8.5	0.38	<0.6	0.25	<1.0	<1.3	2.5	NM	NM	NM
OU4-EW-22	08/02/00	0.093	<1.0	0.13	<0.5	0.099	3.6	0.26	<0.6	<0.6	0.19	<1.3	0.74	NM	NM	NM
OU4-EW-23	08/02/00	<0.5	0.11	<0.5	<0.5	<1.0	0.32	<0.6	<0.6	0.21	<1.0	<1.3	<1.0	NM	NM	NM
OU4-EW-24	08/02/00	<0.5	<1.0	<0.5	<0.5	<1.0	6	0.26	<0.6	<0.6	<1.0	<1.3	1.8	NM	NM	NM
OU4-EW-25	08/02/00	<0.5	<1.0	0.15	<0.5	<1.0	3.8	0.35	<0.6	0.23	0.25	<1.3	1.1	NM	NM	NM
OU4-EW-26	08/02/00	<0.5	<1.0	<0.5	<0.5	<1.0	<1.0	<0.6	<0.6	0.33	<1.0	<1.3	<1.0	NM	NM	NM
OU4-EW-27	08/02/00	0.19	<1.0	0.35	<0.5	<1.0	11	0.77	<0.6	0.37	0.41	<1.3	3.9	NM	NM	NM
OU4-EW-28	08/02/00	<0.5	<1.0	<0.5	<0.5	<1.0	0.67	<0.6	<0.6	0.25	0.11	<1.3	0.13	NM	NM	NM
OU4-EW-29	08/02/00	<0.5	0.13	<0.5	<0.5	<1.0	3.6	<0.6	<0.6	0.2	<1.0	<1.3	0.78	NM	NM	NM
OU4-EW-30	08/02/00	<0.5	<1.0	<0.5	<0.5	<1.0	4.8	0.28	<0.6	0.23	0.24	<1.3	0.76	NM	NM	NM
OU4-EW-31	08/02/00	<0.5	<1.0	<0.5	<0.5	<1.0	3.6	0.12	<0.6	0.46	<1.0	<1.3	0.89	NM	NM	NM
OU4-JMM-30	07/26/00	<0.5	<1.0	<0.5	<0.5	0.14	0.13	<0.6	<0.6	<0.6	<1.0	<1.3	<1.0	<0.5	<0.5	1.5
OU4-JMM-34	07/26/00	0.39	<1.0	0.47	<0.5	0.16	26	1.1	<0.6	<0.6	0.14	<1.3	10	<0.5	0.43	73
OU4-JMM45	07/27/00	14.1	0.36	0.44	<0.5	0.61	163	0.66	0.45	9.2	0.69	<1.3	370	2.6	14.4	810
OU4-JMM-46	07/26/00	0.18	<1.0	0.16	<0.5	0.17	15	0.62	<0.6	<0.6	0.21	<1.3	5.4	<0.5	0.2	32
OU4-JMM52R	07/27/00	2	1.2	<0.5	<0.5	<1.0	18	<0.6	2.4	4	4.3	<1.3	2.8	<0.5	<0.5	840
OU4-JMM58	07/27/00	0.16	<1.0	0.16	<0.5	0.18	4.3	<0.6	<0.6	<0.6	0.17	<1.3	3.9	<0.5	<0.5	0.66
OU4-JMM-64	07/26/00	<0.5	<1.0	0.12	<0.5	0.28	10	0.41	<0.6	<0.6	0.28	<1.3	2.3	<0.5	<0.5	68
OU4-JMM9	07/27/00	0.19	<1.0	0.37	<0.5	0.31	4	<0.6	<0.6	0.22	<1.0	<1.3	2.5	<0.5	0.12	27

^a (mg/l) = milligrams per liter

^b NM = not measured

^c <X = The analyte was analyzed for and is not present above the reporting limit.

^d DCA = Dichloroethane

^e DCE = Dichloroethene

^f TCE = Trichloroethene

^g 1,2,4-TMB = 1,2,4-Trimethylbenzene

^h all chemicals except for ethane, ethene, and methane were analyzed using method SW8260. Ethane, ethene, and methane were analyzed using method M2720C.

At a limited number of monitoring wells Parsons ES also collected groundwater samples for analysis of geochemical parameters, including alkalinity, total organic carbon TOC, carbon dioxide, methane, ethane, ethene, ferrous iron, and the common anions nitrate, sulfate, and sulfide (Table 3.3). Methods of sample collection and chemical analyses of water samples are described in detail in Appendix B of the site specific QAPP (Parsons ES, 1999) and Section 5 of the workplan.

Sampling locations and analytical methods were selected to provide the additional information necessary for the DDHU RPO evaluation. Groundwater samples were collected and analyzed for geochemical parameters to provide a point-in-time view of the spatial distribution of these parameters in the groundwater system at DDHU OUs 1 and 4, and to provide insight into the geochemical processes currently active in the subsurface. This information, in combination with spatial and temporal data regarding the concentrations of VOCs in groundwater, was used in screening-level evaluation of remedial alternatives, including MNA.

3.1.2 Groundwater Sampling Procedures

Groundwater sampling generally was conducted in accordance with procedures specified in the workplan (Parsons ES, 2000). Fixed-base analyses for VOCs, sulfate, nitrate, chloride, TOC, methane, ethane, and ethene were performed by Severn Trent Services of Denver, Colorado.

3.2 OCCURRENCE AND MOVEMENT OF VOCS

In general, the concentrations and distribution of VOCs in groundwater collected during the July-August 2000 sampling event at OUs 1 and 4 (Figures 3.1 and 3.2) were similar to previous events (Figures 2.16, 2.17, and 2.18). *Cis*-1,2-DCE has historically been the contaminant detected at the greatest frequency, highest concentrations, and broadest distribution OUs 1 and 4. Low concentrations of VC also have been detected relatively frequently. Other VOCs, including TCE and the DCE isomers (*trans*-1,2-DCE and 1,1-DCE) also have been detected occasionally, though at much lower concentrations than *cis*-1,2-DCE and VC.

3.3 NATURAL ATTENUATION EVALUATION

The biodegradation of solvent constituents and the potential for future migration and persistence of dissolved chlorinated aliphatic hydrocarbons (CAHs) are assessed in this section to support evaluation of the groundwater pump-and-treat system and the long-term monitoring (LTM) plan at DDHU OUs 1 and 4. As used here, the term “remediation by natural attenuation” (RNA) refers to a remediation strategy for contaminants in the subsurface that relies on naturally occurring physical, chemical, and biological mechanisms to limit the possibility of exposure of potential receptors to concentrations of contaminants that exceed regulatory levels.

Mechanisms for RNA of CAHs include biodegradation, dispersion, dilution from recharge, sorption, and volatilization. Of these processes, biodegradation is the only mechanism working to transform contaminants into innocuous byproducts. Intrinsic bioremediation occurs when indigenous microorganisms work to bring about a reduction

TABLE 3.3
GROUNDWATER GEOCHEMICAL DATA JULY-AUGUST 2000
REMEDIAL PROCESS OPTIMAZATION, OU1 AND OU4
DEFENSE DEPOT HILL, UTAH

OU1

Well ID	DATE SAMPLED	Temp (°C) ^{a/}	Conductivity (µS/cm) ^{b/}	pH	Redox Potential (mV) ^{c/}	Dissolved Oxygen (mg/l) ^{d/}	Ferrous Iron (mg/l)	Total Iron (mg/l)	Sulfate (Lab) (mg/l)	Sulfide (mg/l)	Nitrite N (mg/l)	Nitrate (mg/l)	Nitrate (Lab) (mg/l)	Chloride (Lab) (mg/l)	Alkalinity (mg/l)	Carbon Dioxide (mg/l)	TOC (Lab) (mg/l)
AEHA-9	07/26/00	15	0.75	7.3	-6	0.18	ND ^{f/}	0.35	28.9	ND	ND	ND	<0.5	NM	282	20	1.8
ESE-12	07/24/00	15.5	0.8	7.62	18	5.8	0	0.05	11.7	ND	0	0	0	60.9	273	40	1.9
ESE-13	07/26/00	14.7	0.132	7.38	99	0.2	0	ND	24.1	ND	0	NM ^{e/}	0	48.1	284	30	1.2
ESE-15	07/25/00	14.7	0.14	7.3	127	0.36	0	0	22.7	ND	0	0	0.11	55	268	25	1.9
JMM-1	07/25/00	18.4	0.123	7.33	-28	1.5	0	0.2	25.5	ND	0	0	0.15	47.2	279	15	1.1
JMM-1 Dup ^{g/}	07/25/00	NM	NM	NM	NM	NM	NM	NM	25.6	NM	NM	NM	0.15	47.6	NM	NM	1.4
JMM-17	07/25/00	16.7	0.82	7.38	86	0.7	0	0.4	8.6	ND	0	0	0	10.8	196	15	2.8
JMM-19	07/24/00	17.2	0.47	7.3	-93	0.8	0.05	1.15	20.2	ND	0	0	0.15	50.5	256	50	0.91
JMM-2	07/25/00	14.6	0.164	7.08	-51	1.09	0	0	24.7	ND	0	0	0	90.5	297	20	2.7
JMM-22	07/25/00	14.4	0.16	7.4	-200	0.5	0	0.15	18.2	ND	0	0	0	93.6	312	30	2.7
JMM-47	07/24/00	15.9	0.56	7.1	-60	0.9	0.4	0.75	11.4	ND	0	0	0.19	49.9	269	40	1.6
JMM-51	07/26/00	16.4	0.84	7.28	-12	0.29	0	0.05	27.1	ND	0	NM	0	88	316	25	1.9

OU4

Well ID	DATE SAMPLED	Temp (C)	Conductivity (µS/cm)	pH	Redox Potential (mV)	Dissolved Oxygen (mg/l)	Ferrous Iron (mg/l)	Total Iron (mg/l)	Sulfate (Lab) (mg/l)	Sulfide (mg/l)	Nitrite N (mg/l)	Nitrate (mg/l)	Nitrate (Lab) (mg/l)	Chloride (Lab) (mg/l)	Alkalinity (mg/l)	Carbon Dioxide (mg/l)	TOC (Lab) (mg/l)
AEHA-5	07/27/00	14.8	0.9	7.34	-83	0.16	0.05	0.75	85.9	0	0	NM	<0.5	NM	450	40	2.8
ESE-6	07/26/00	15.5	0.86	7.13	-81	0.22	0.7	2	NM	0	0	NM	NM	NM	332	25	NM
EW-10	07/31/00	18.1	0.22	7.4	23	7	0	0	NM	0	0	NM	NM	NM	256	10	NM
EW-5	07/31/00	15.2	0.45	7.3	60	2.7	0	0	NM	0	0	NM	NM	NM	254	15	NM
EW-6	07/31/00	16.3	0.7	7.32	0.22	4.6	0	0.5	NM	0	0	NM	NM	NM	284	15	NM
EW-7	07/31/00	16.6	0.71	7.4	-18	3	0.05	0.95	NM	0	0	NM	NM	NM	300	15	NM
EW-8	07/31/00	16.8	0.59	7.3	-10	4.1	0	0	NM	0	0	NM	NM	NM	284	10	NM
EW-9	07/31/00	17	0.38	7.3	10	4.2	0	0	NM	0	0	NM	NM	NM	240	10	NM
JMM-30	07/26/00	NM	NM	NM	NM	NM	NM	NM	40	NM	NM	NM	0.13	69.9	NM	NM	1.8
JMM-34	07/26/00	14.7	1.5	7.13	-67	0.32	0.1	0.45	80.4	0	0	NM	0	201	470	30	2.7
JMM-35	07/28/00	14.3	1.47	7.2	-91	1.6	0	0	NM	0	0	NM	NM	NM	532	40	NM
JMM-44	07/28/00	14.8	1.49	7.15	-64	0.6	0.05	0.1	NM	0	0	NM	NM	NM	624	35	NM
JMM-45	07/27/00	16.9	1.46	7.1	-103	0.12	0.8	1.8	89.8	0	0	NM	0	226	560	40	4.8
JMM-46	07/26/00	14.8	1.45	7.22	-50	0.25	0.1	0.4	73.9	0	0	NM	0	201	402	20	1.3
JMM-52R	07/27/00	17.9	1.5	7.2	-192	0.07	0.5	0.75	110	0	0	NM	0	339	576	55	3.2
JMM-54R	07/28/00	17.2	1.3	7.34	-82	0.32	0.15	0.85	NM	0	0.02	NM	NM	NM	512	30	NM
JMM-58	07/27/00	15.9	0.69	7.52	150	0.33	0	0	49.9	0	0	NM	0	66.2	388	30	1.5
JMM-64	07/26/00	19.8	1.22	7.18	42	0.16	0.15	0.35	60.6	0	0	NM	0	152	360	30	2.2
JMM-8	07/28/00	15.3	1.25	7.24	-170	0.8	0.3	1.05	NM	0	0	NM	NM	NM	530	35	NM
JMM-9	07/27/00	13	0.61	7.42	24	0.13	0	0.6	43	0	0	NM	0	56.2	316	30	1.1

^{a/} C = degrees Centigrade.

^{b/} µS/cm = microsiemens per centimeter.

^{c/} mV = millivolts.

^{d/} mg/l = milligrams per liter.

^{e/} NM = not monitored

^{f/} ND = not detected

^{g/} Duplicate of previous sample

Figure 3.1 VOCs in Groundwater at OU1 July-August 2000

Figure 3.2 VOCs in Groundwater at OU4, July-August 2000

in the total mass of contamination in the subsurface without the addition of nutrients or Table 3.3 Groundwater Geochemical Data substrates. The major degradation processes that act upon CAHs are reviewed in detail in Appendix B.

This subsection summarizes and interprets site-specific data relevant to documenting the potential for natural attenuation processes to minimize the migration of dissolved VC, and to reduce the concentration, mass, and toxicity of VC through time. This assessment was used in the RPO evaluation to determine whether RNA may be a useful component in groundwater remediation at OUs 1 and 4.

3.3.1 OU1 Daughter Products

One of the most straightforward methods of evaluating the occurrence and specific biodegradation processes of CAHs is to examine the distribution of parent CAHs and their spatial and temporal relationship(s) to degradation products. At the same time, it is also useful to examine the spatial distribution of native organic carbon or other contaminants (e.g., fuel hydrocarbons) that may be acting as sources of electron donors.

Because reductive dehalogenation is the most commonly occurring biodegradation reaction, a typical plume pattern (e.g., Vogel, 1994) would have TCE concentrations highest near the chemical source area, with elevated DCE concentrations (consisting mostly of *cis*-1,2-DCE) in and just downgradient from (or surrounding) the source area. Vinyl chloride (VC) concentrations could be present throughout the CAH plume, with the highest VC concentrations likely to be found in areas that are neither strongly reducing nor oxidizing.

- DCE isomers have been detected at the greatest frequency, highest concentration, and broadest distribution at DDHU OU1. Low concentrations of VC also have been detected relatively frequently. Because DCE and VC are not source contaminants at DDHU OU1, this provides direct evidence that TCE has been reductively dehalogenated at the site.
- Ethane, ethene, carbon dioxide, and water are the final products in the series of reductive dehalogenation reactions involving chlorinated aliphatic hydrocarbons (Appendix B). Therefore, if TCE were completely degraded through its chain of daughter products, these compounds should appear. Groundwater samples collected during July-August, 2000 were analyzed for dissolved gases (Table 3.1). Ethane and ethene were not detected in any well above their respective quantitation limits of 0.5 µg/L with the exception of a singular detection of ethene at a concentration of 0.12 µg/L (at well JMM-2). The relative absence of TCE, combined with the persistence of *cis*-1,2-DCE and VC and absence of ethane or ethene, indicates that TCE degrades relatively rapidly to DCE and VC; while degradation of DCE and VC is likely to be occurring at a much slower rate.

3.3.2 OU1 Redox Couples in Biodegradation

Microorganisms can facilitate the biodegradation (oxidation) of carbon compounds only by using redox couples that have a higher oxidation/reduction potential (ORP) than the contaminants. The reduction of highly oxidized species results in an overall decrease

in the oxidizing potential of the groundwater. As shown on Figure 3.3, the reduction of oxygen and nitrate will reduce the oxidizing potential to levels at which ferric iron reduction can occur. As each chemical species that can be used to oxidize the contaminants is exhausted, the microorganisms are forced to use other available electron acceptors with lower oxidizing capacity. When sufficiently low (negative) ORP levels have been developed as a result of these redox reactions, sulfate reduction and methanogenesis can occur almost simultaneously (Stumm and Morgan, 1981). Figure 3.3 illustrates the sequence of microbially mediated redox processes based on the amount of free energy released for microbial use. In general, reactions yielding more energy tend to take precedence over processes that yield less energy (Stumm and Morgan, 1981).

ORP values measured in groundwater at the site in July-August 2000 ranged from -200 millivolts (mV) to 127 mV (Table 3.3). The lowest ORP value was measured at well JMM-22, completed near a suspected VOC source area in OU1 (Figure 3.1). The ORP value measured at “background” well ESE-12 also was low (18 mV; Table 3.3). However, this probably is not an indication of natural aquifer conditions. Rather, well ESE-12 may be downgradient from an area in which petroleum fuels are present in groundwater. Degradation of petroleum fuels would tend to lower the ORP values in downgradient wells. The highest value of ORP (127 mV) was measured at well ESE-15, near the western Base boundary, and north of all known areas of chemical disposal or fuel releases (Figure 3.1). Therefore, well ESE-15 was selected by Parsons ES to be representative of naturally occurring, or “background,” conditions in the absence of anthropogenic chemicals, and the relatively elevated ORP value at this well may be representative of “background” ORP. Most measured ORP values were in the range of about -93 to 99 mV (Table 3.3). Overall, groundwater beneath DDHU OU1 is not sufficiently reducing to support significant iron- or sulfate reduction and methanogenesis (Figure 3.1). However, methane was detected in every groundwater sample at low concentrations, with an exception at well JMM-2 where methane was detected at 2,990 µg/L (Table 3.3). Because the elevated concentration of methane detected at well JMM-2 corresponds with the lowest ORP observed, local areas likely exist that are sufficiently reducing to support methanogenesis.

3.3.3 OU1 Electron Acceptors

Biodegradation of natural and anthropogenic organic compounds brings about measurable changes in the chemistry of groundwater in the affected area. Concentrations of compounds used as electron acceptors (e.g., DO, nitrate, and sulfate) are depleted, and byproducts of electron acceptor reduction (e.g., ferrous iron, methane, and sulfide) are increased (Appendix A). By measuring these changes, it is possible to evaluate the relative importance of natural attenuation processes occurring at a site.

DO values measured in OU1 groundwater ranged from 0.18 to 5.8 milligrams per liter (mg/L), with the lowest DO concentration detected at well AEHA-9 (Table 3.3). Similar to ORP, this probably is not a good indication of naturally occurring conditions, but occurs because well AEHA-9 is downgradient from an area in which petroleum fuels are present in groundwater (IT Corporation, 1992). The concentration of DO at well ESE-12 was approximately 5.8 mg/L (Table 3.3). This well is upgradient from potential source areas in OU1. It, therefore, seems likely that a DO concentration of approximately 5.8 mg/L may be representative of “background” DO concentrations.

Figure 3.3 Sequence of Microbially Mediated Redox Process

The concentrations of DO in downgradient areas, with the exception of two wells, generally range from about 0.2 mg/L to 0.9 mg/L (Table 3.3). DO concentrations at these wells (JMM-1 and JMM-2) were 1.5 mg/L and 1.09 mg/L, respectively. It is believed that operation of the groundwater extraction well located in the vicinity of these two wells draws oxygenated groundwater into the plume area, and since degradation reactions do not proceed rapidly enough to quickly deplete the DO, slightly elevated concentrations are found in these wells. However, the overall disparity between plume and background DO concentrations suggests that oxygen has been consumed by biological processes.

After DO has been depleted in the subsurface, nitrate may be used as an electron acceptor for anaerobic biodegradation of organic carbon via denitrification. Nitrate concentrations below background in areas with high organic carbon concentrations and low DO are indicative of denitrification. Nitrate was detected in only four of eleven samples that were analyzed in July-August, 2000 (Table 3.3), and only trace concentrations of nitrate were detected at these wells. Nitrate was not detected in background wells. The distribution of nitrate in groundwater indicates that denitrification is not a significant process of biodegradation at OU1, most likely because nitrate is not present in significant concentrations.

Sulfate is reduced to sulfide during the oxidation of natural or anthropogenic carbon. In order to evaluate the potential for sulfate reduction, groundwater samples collected during the July-August 2000 monitoring event were analyzed for sulfate and sulfide (Table 3.1). Sulfate was detected in all groundwater samples, at concentrations ranging from 8.6 mg/L (in the sample from well JMM-17, the "background" well), to 28.9 mg/L in the sample from well AEHA-9. The concentrations of sulfate in groundwater within and downgradient from the plume generally ranged from about 18.2 to 28.9 mg/L (Table 3.3). The differences between possible background sulfate concentrations and concentrations within the CAH plume suggests that sulfate reduction is not a significant anaerobic biodegradation process at OU1. As a general rule, sulfide is an unstable sulfur species under oxidizing conditions, and can persist only under reducing conditions. The absence of sulfide in groundwater samples confirms that sulfate reduction is not prevalent at OU1 (Table 3.3).

3.3.4 OU1 Metabolic Byproducts

Geochemical data indicate that ferrous iron is not being produced in the CAH plume (Table 3.3). Therefore, this suggests that iron (III) hydroxide is not being reduced to iron (II) during biodegradation of native organic carbon or chlorinated solvents.

Although reductive dehalogenation may occur under nitrate- and sulfate-reducing conditions (Vogel *et al.*, 1987; Chapelle, 1996), the most rapid dehalogenation rates, affecting the widest ranges of CAHs, occur under methanogenic conditions (Bouwer, 1994). Methane was analyzed in groundwater samples (Table 3.1) to evaluate the potential for methanogenesis.

Methane was detected in every groundwater sample at concentrations ranging from 0.21 to 2990 μ L (Table 3.3). The anaerobic conditions present in groundwater and the concentrations and distribution of methane in groundwater indicate that methanogenesis is occurring in localized areas within the CAH plume at OU1.

3.3.5 OU1 Alkalinity and Carbon Dioxide Evolution

In aquifers that have carbonate minerals as part of the matrix, carbon dioxide forms carbonic acid, which dissolves these minerals and increases the alkalinity of the groundwater. An increase in alkalinity [measured as calcium carbonate (CaCO_3)] can be used to infer that organic carbon (native or anthropogenic) have been degraded through aerobic and/or anaerobic microbial respiration. If this area corresponds with elevated CAH concentrations, then the potential exists for CAHs to be utilized as an electron acceptor by reductive dehalogenation.

Total alkalinity (as calcium carbonate [CaCO_3]) also is a measure of the ability of groundwater to buffer changes in pH caused by the addition of biologically generated acids. Total alkalinity (as CaCO_3) in groundwater at DDHU OU1 ranged from 196 mg/L to 316 mg/L (Table 3.3). This range of alkalinity likely is sufficient to buffer potential changes in pH caused by biologically mediated reactions, and suggests that aerobic and/or anaerobic biodegradation processes should not cause detrimental shifts in groundwater pH. The neutral to slightly basic pH values measured in site groundwater support this observation. There are no apparent differences in the spatial distribution of alkalinity values, either suggesting that the degradation of dissolved CAH compounds is proceeding at rates too low to promote significant carbonic acid formation, or that the carbonate content of the alluvial units is low.

Carbon dioxide concentrations measured at DDHU OU1 range from 15 mg/L to 50 mg/L (Table 3.3). Concentrations in background wells range from 15 mg/L to 40 mg/L. Within the plume area, concentrations range from 15 mg/L to 50 mg/L. Carbon dioxide concentrations above background could result from both aerobic and anaerobic biodegradation processes as contaminants are ultimately converted to carbon dioxide and water. However, carbon dioxide concentrations within the extent of the chlorinated solvent plume are not elevated significantly above background concentrations.

3.3.6 Summary of CAH Biodegradation at OU1

The occurrence of *cis*-1,2-DCE and VC throughout the CAH is a direct indication that biotransformation of TCE via reductive dehalogenation has occurred and dehalogenation reactions are proceeding at OU1. However, the persistence of low concentrations of *cis*-1,2-DCE and VC suggests the rate of degradation of these compounds is slow relative to TCE. This conclusion is supported by the following observations:

- The prevalence of *cis*-1,2-DCE and VC are a direct indication that TCE has been reductively dehalogenated at OU1.
- Conditions in groundwater are generally anaerobic; oxygen concentrations are generally less than 1 mg/L, and ORP values range from -200 to 127 mV. Dehalogenation reactions preferentially proceed under anaerobic, reducing conditions, and are hindered by DO concentrations greater than about 1 mg/L (USEPA, 1998, and Appendix A). The observed range of ORP values is sufficient for nitrate and manganese reduction, but not for iron reduction sulfate reduction or methanogenesis. However, localized areas of methanogenic conditions were observed.

- Given the generally anaerobic, mildly reducing conditions at OU1, the potential for aerobic oxidation of *cis*-1,2-DCE and VC is low. However, decreasing trends in *cis*-1,2-DCE and VC (Section 4) suggests that while the rate may be slow relative to TCE, *cis*-1,2-DCE and VC continue to degrade anaerobically.

3.3.7 OU4 Daughter Products

One of the most straightforward methods of evaluating the occurrence and specific biodegradation processes of CAHs is to examine the distribution of parent CAHs and their spatial and temporal relationship(s) to degradation products. At the same time, it is also useful to examine the spatial distribution of native organic carbon or other contaminants (e.g., fuel hydrocarbons) that may be acting as sources of electron donors.

Because reductive dehalogenation is the most commonly occurring biodegradation reaction, a typical plume pattern (e.g., Vogel, 1994) would have TCE concentrations highest near the chemical source area, with elevated DCE concentrations (consisting mostly of *cis*-1,2-DCE) in and just downgradient from (or surrounding) the source area. Vinyl chloride (VC) concentrations could be present throughout the CAH plume, with the highest VC concentrations likely to be found in areas that are neither strongly reducing nor oxidizing.

- DCE isomers have been detected at the greatest frequency, highest concentration, and broadest distribution at DDHU OU4. Low concentrations of VC also have been detected relatively frequently. Because DCE and VC are not source contaminants at DDHU OU1, this provides direct evidence that TCE has been reductively dehalogenated at the site.
- Ethane, ethene, carbon dioxide, and water are the final products in the series of reductive dehalogenation reactions involving chlorinated aliphatic hydrocarbons (Appendix A). Therefore, if TCE were completely degraded through its chain of daughter products, these compounds should appear. Groundwater samples collected during July-August, 2000 were analyzed for dissolved gases (Table 3.1). Ethane was detected in one well (JMM-45) at a concentration of 0.26 μL and ethane was detected in five wells (AEHA-9, JMM-34, JMM-45, JMM-46, and JMM-9) at concentrations ranging from 0.12 $\mu\text{g/L}$ to 14.4 $\mu\text{g/L}$ (Table 3.3). The relative absence of TCE, combined with the persistence of *cis*-1,2-DCE and VC and the relative absence of ethane or ethene, indicates that TCE degrades relatively rapidly to DCE and VC; while degradation of DCE and VC is likely to be occurring at a much slower rate.

3.3.8 OU4 Redox Couples in Biodegradation

Microorganisms can facilitate the biodegradation (oxidation) of carbon compounds only by using redox couples that have a higher oxidation/reduction potential (ORP) than the contaminants. The reduction of highly oxidized species results in an overall decrease in the oxidizing potential of the groundwater. As shown on Figure 3.4, the reduction of oxygen and nitrate will reduce the oxidizing potential to levels at which ferric iron reduction can occur. As each chemical species that can be used to oxidize the contaminants is exhausted, the microorganisms are forced to use other available electron

Figure 3.4 Sequence of Microbially Mediated Redox Process

acceptors with lower oxidizing capacity. When sufficiently low (negative) ORP levels have been developed as a result of these redox reactions, sulfate reduction and methanogenesis can occur almost simultaneously (Stumm and Morgan, 1981). Figure 3.4 illustrates the sequence of microbially mediated redox processes based on the amount of free energy released for microbial use. In general, reactions yielding more energy tend to take precedence over processes that yield less energy (Stumm and Morgan, 1981).

ORP values measured in groundwater at the site in July-August 2000 ranged from -192 millivolts (mV) to 150 mV (Table 3.3). The lowest ORP value was measured at well JMM-52R, completed near a suspected VOC source area in OU1 (Figure 3.2). The ORP value measured at “background” well JMM-44 also was low (-64 mV; Table 3.3). The highest value of ORP (150 mV) was measured at well JMM-58, near the center of the CAH plume, downgradient from all known areas of chemical disposal or fuel releases, and in close proximity to extraction well 4EW-19 (Figure 3.2). Therefore, Parsons ES did not select this well as representative of naturally occurring or “background” conditions. To be representative of naturally occurring, or “background,” conditions in the absence of anthropogenic chemicals, and the relatively elevated ORP value at this well may be representative of “background” ORP. Most measured ORP values were in the range of about -103 to 42 mV (Table 3.3). Overall, groundwater beneath DDHU OU4 is not sufficiently reducing to support significant iron- or sulfate reduction and methanogenesis (Figure 3.4). However, methane was detected in every groundwater sample at low concentrations, with exceptions at wells JMM-45 and JMM-52R where methane was detected at 810 μ /L and 840 μ g/L, respectively (Table 3.3). Because the elevated concentrations of methane detected at wells JMM-45 and JMM-52R correspond with the lowest ORP values observed, local areas likely exist that are sufficiently reducing to support methanogenesis.

3.3.9 OU4 Electron Acceptors

Biodegradation of natural and anthropogenic organic compounds brings about measurable changes in the chemistry of groundwater in the affected area. Concentrations of compounds used as electron acceptors (e.g., DO, nitrate, and sulfate) are depleted, and byproducts of electron acceptor reduction (e.g., ferrous iron, methane, and sulfide) are increased (Appendix A). By measuring these changes, it is possible to evaluate the relative importance of natural attenuation processes occurring at a site.

DO values measured in OU4 groundwater ranged from 0.07 to 1.6 milligrams per liter (mg/L), with the lowest DO concentration detected at well JMM-52R (Table 3.3). Similar to ORP, this probably is not a good indication of naturally occurring conditions, but occurs because well JMM-52R is downgradient from a contaminant source area. The concentration of DO at well JMM-35 was approximately 1.6 mg/L (Table 3.3). This well is upgradient from potential source areas in OU4. It, therefore, seems likely that a DO concentration of approximately 1.6 mg/L may be representative of “background” DO concentrations.

The concentrations of DO in downgradient areas, with the exception of the extraction wells, generally range from about 0.07 mg/L to 0.8 mg/L (Table 3.3). DO concentrations at the extraction wells (EW-5, EW-6, EW-7, EW-8, EW-9 and EW-10) ranged from 2.7 mg/L to 7 mg/L. It is believed that operation of the groundwater extraction wells draws

oxygenated groundwater into the plume area, and since degradation reactions do not proceed rapidly enough to quickly deplete the DO, slightly elevated concentrations are found in these wells. However, the overall disparity between plume and background DO concentrations suggests that oxygen has been consumed by biological processes.

After DO has been depleted in the subsurface, nitrate may be used as an electron acceptor for anaerobic biodegradation of organic carbon via denitrification. Nitrate concentrations below background in areas with high organic carbon concentrations and low DO are indicative of denitrification. Nitrate was detected in only one of nine samples that were analyzed in July-August, 2000 (Table 3.3), and only at a trace concentration. Nitrate was not detected in background wells. The distribution of nitrate in groundwater indicates that denitrification is not a significant process of biodegradation at OU4, most likely because nitrate is not present in significant concentrations.

Sulfate is reduced to sulfide during the oxidation of natural or anthropogenic carbon. In order to evaluate the potential for sulfate reduction, groundwater samples collected during the July-August 2000 monitoring event were analyzed for sulfate and sulfide (Table 3.1). Sulfate was detected in all groundwater samples, at concentrations ranging from 40 mg/L (in the sample from well JMM-30, the “background” well), to 110 mg/L in the sample from well JMM-52R. The concentrations of sulfate in groundwater within and downgradient from the plume generally ranged from about 43 to 90 mg/L (Table 3.3). The differences between possible background sulfate concentrations and concentrations within the CAH plume suggests that sulfate reduction is not a significant anaerobic biodegradation process at OU4. As a general rule, sulfide is an unstable sulfur species under oxidizing conditions, and can persist only under reducing conditions. The absence of sulfide in groundwater samples confirms that sulfate reduction is not prevalent at OU4 (Table 3.3).

3.3.10 OU4 Metabolic Byproducts

Geochemical data indicate that ferrous iron is not being produced in the CAH plume (Table 3.3). Therefore, this suggests that iron (III) hydroxide is not being reduced to iron (II) during biodegradation of native organic carbon or chlorinated solvents.

Although reductive dehalogenation may occur under nitrate- and sulfate-reducing conditions (Vogel *et al.*, 1987; Chapelle, 1996), the most rapid dehalogenation rates, affecting the widest ranges of CAHs, occur under methanogenic conditions (Bouwer, 1994). Methane was analyzed in groundwater samples (Table 3.1) to evaluate the potential for methanogenesis.

Methane was detected in every groundwater sample at concentrations ranging from 0.66 to 840 µg/L (Table 3.3). The anaerobic conditions present in groundwater and the concentrations and distribution of methane in groundwater indicate that methanogenesis is occurring in localized areas within the CAH plume at OU4.

3.3.11 OU4 Alkalinity and Carbon Dioxide Evolution

In aquifers that have carbonate minerals as part of the matrix, carbon dioxide forms carbonic acid, which dissolves these minerals and increases the alkalinity of the

groundwater. An increase in alkalinity [measured as calcium carbonate (CaCO_3)] can be used to infer that organic carbon (native or anthropogenic) have been degraded through aerobic and/or anaerobic microbial respiration. If this area corresponds with elevated CAH concentrations, then the potential exists for CAHs to be utilized as an electron acceptor by reductive dehalogenation.

Total alkalinity (as calcium carbonate [CaCO_3]) also is a measure of the ability of groundwater to buffer changes in pH caused by the addition of biologically generated acids. Total alkalinity (as CaCO_3) in groundwater at DDHU OU1 ranged from 316 mg/L to 624 mg/L (Table 3.3). This range of alkalinity likely is sufficient to buffer potential changes in pH caused by biologically mediated reactions, and suggests that aerobic and/or anaerobic biodegradation processes should not cause detrimental shifts in groundwater pH. The neutral to slightly basic pH values measured in site groundwater support this observation. There are no apparent differences in the spatial distribution of alkalinity values, either suggesting that the degradation of dissolved CAH compounds is proceeding at rates too low to promote significant carbonic acid formation, or that the carbonate content of the alluvial units is low.

Carbon dioxide concentrations measured at DDHU OU4 range from 25 mg/L to 55 mg/L (Table 3.3). Concentrations in background wells range from 35 mg/L to 40 mg/L. Within the plume area, concentrations range from 30 mg/L to 55 mg/L. Carbon dioxide concentrations above background could result from both aerobic and anaerobic biodegradation processes as contaminants are ultimately converted to carbon dioxide and water. However, carbon dioxide concentrations within the extent of the chlorinated solvent plume are not elevated significantly above background concentrations.

3.3.12 Summary of CAH Biodegradation at OU4

The occurrence of *cis*-1,2-DCE and VC throughout the CAH is a direct indication that biotransformation of TCE via reductive dehalogenation has occurred and dehalogenation reactions are proceeding at OU4. However, the persistence of low concentrations of *cis*-1,2-DCE and VC suggests the rate of degradation of these compounds is slow relative to TCE. This conclusion is supported by the following observations:

- The prevalence of *cis*-1,2-DCE and VC are a direct indication that TCE has been reductively dehalogenated at OU4.
- Conditions in groundwater are generally anaerobic; oxygen concentrations are generally less than 1 mg/L, and ORP values range from -192 to 150 mV. Dehalogenation reactions preferentially proceed under anaerobic, reducing conditions, and are hindered by DO concentrations greater than about 1 mg/L (USEPA, 1998, and Appendix A). The observed range of ORP values is sufficient for nitrate and manganese reduction, but not for iron reduction sulfate reduction or methanogenesis. However, localized areas of methanogenic conditions were observed.
- Given the generally anaerobic, mildly reducing conditions at OU4, the potential for aerobic oxidation of *cis*-1,2-DCE and VC is low. However, decreasing trends in *cis*-1,2-DCE and VC (Section 4) suggests that while the rate may be slow relative to TCE, *cis*-1,2-DCE and VC continue to degrade anaerobically.

SECTION 4

REVIEW OF CONCEPTUAL SITE MODEL

The conceptual hydrogeologic model of a site describes the groundwater and surface-water systems at the site, the relationships among the systems, and their temporal evolution. The conceptual site model (CSM) provides the basis for understanding the occurrence and movement of water and contaminants at the site, and incorporates and organizes the geologic and hydrologic information into a framework that guides site investigations and subsequent remediation activities. Without an adequate conceptual understanding of the hydrogeologic framework and the relationships among the components of the hydrologic system, subsequent activities and levels of effort will not generate conclusions that can be used with any confidence. At a minimum, the hydrogeologic CSM should incorporate the following information:

- A description of the general regional and local geology, including lithology, stratigraphy, and structure;
- Identification of principal hydrogeologic units, including specific hydrogeologic intervals and discrete zones or areas of relatively higher or lower hydraulic conductivity;
- Values for the hydraulic properties of the various hydrogeologic units, including conductivity, specific yield and specific storage; and, if thicknesses of hydrostratigraphic units are known, their bulk properties of transmissivity and storativity;
- The elevations and configuration of the groundwater potentiometric surface(s);
- Surface drainage configurations, the sizes of streams, and gaining or losing reaches;
- Hydrologic boundaries, including streams, drainage divides, and hydrogeologic contacts with materials of lower or higher permeability;
- Source(s) of contaminants; and
- Direction(s) and rate(s) of contaminant migration.

The most current CSM of DDHU OUs 1 and 4 was developed by JMM (1991a and 1991b). The CSM was later refined at the OU4 area in the OU4 Hotspot Investigation and Alternatives Analysis Report (Montgomery Watson, 1996). This model is referred to herein as the “current” CSM, and is presumed to represent the basic framework within

which the current remediation systems were conceived, evaluated, and designed. Much of the information used to define the conceptual model can be found in Section 2 of this report. Examination and, if necessary, refinement of the conceptual hydrogeologic model, as previously interpreted and presented, is therefore a critical element of the RPO evaluation.

4.1 CURRENT CONCEPTUAL MODEL

The current CSMs for OU1 and OU4 (Figure 4.1 and 4.2) are based on the site history, hydrogeology, and nature and extent of contamination as discussed in Section 2. The vadose zone (extending from ground surface to a depth of about 8 feet bgs) and the saturated zone (extending from a depth of about 8 feet bgs to about 25 feet bgs) are the zones most likely to be affected by contaminants; therefore, the CSM focuses on these zones. The current CSM for DDHU OU1 and OU4 incorporates the following principal features:

- The vadose zone beneath DDHU consists of low-to moderate-permeability, interfingering clays, silts and fine sands. The shallow groundwater zone beneath DDHU consists of more permeable sands and gravels. A dark silt and clay aquitard underlies the saturated zone at an average depth of about 25 to 30 feet bgs.
- This basal clay is approximately 60 to 80 feet thick, and is uniform in areal extent beneath DDHU.
- Permeability of sediments to water and/or air is an important control on the rate of water percolation (and contaminant leaching). The average permeability (hydraulic conductivity) of the saturated shallow aquifer in the horizontal plane is approximately 33 ft/day or 1.17×10^{-2} cm/sec in the vicinity of OU1 (JMM, 1991a) and approximately 42 ft/day or 1.5×10^{-2} cm/sec in the vicinity of OU4 (JMM, 1991b).
- The depth to the water table beneath DDHU is approximately 8 feet bgs (JMM 1991a and 1991b). Due to seasonal variations, groundwater levels beneath OU1 and OU4 fluctuate as much as 3 to 5 feet (JMM, 1991a and 1991b). Groundwater levels are highest in the summer and lowest in the winter.
- At locations distal from groundwater EWs, horizontal hydraulic gradients in the groundwater system are generally of low magnitude (about 0.0023 ft/ft). See Figures 2.12 and 2.15 for current water table maps of OU1 and OU4. Groundwater flow velocities resulting from these gradients range from about 73 ft/yr at OU1 to 140 ft/yr at OU4 (JMM 1991a and 1991b). Horizontal hydraulic gradients generally increase with proximity to EWs as a consequence of drawdown induced by the EWs in the groundwater system surrounding the extraction system.
- *Cis*-1,2-DCE and vinyl chloride are the constituents of primary concern at DDHU OU1 and OU4. Historic site activities and disposal practices are the sources of contaminants in the vadose zone and in groundwater at OU 1 and OU4. Burial sites 3A and the Plain City Canal are the suspected sources of CAHs at OU1. Burial site 4E is the primary source of groundwater contamination at OU4, with

Figure 4.1 OU1 Conceptual Site Model

Figure 4.2 OU4 Conceptual Site Model

burial site 4A as a potential secondary source. The oil holding pit and three trenches in the vicinity of Buildings 15C and 16C were identified as additional sources of groundwater contamination at OU4 (OU4 Hot Spot) (Montgomery Watson, 1995). Soil remediation at OU4 was conducted in June, 1995 and consisted of soil removal in the source areas to a depth of approximately 8 ft bgs (depth of shallow groundwater). Source removal at the OU4 hot spot was conducted from October to November 1998 and involved the removal of approximately 4,775 tons of soil and debris to a depth of 7 ft bgs, which was 1 ft below water table at the time (IT Corp., 1999). Contaminated soil remains beneath the buildings in the hot spot area to maintain integrity of the building foundations. At OU1 soil remediation consisted of the removal of approximately 8,951 tons of soil and debris. Soil removal was completed by August 1994. Additional soil was removed from a west trending extension of the Plain City canal in 1999 (IT Corp., 1999).

- Contaminated surface soils (soils in the uppermost 8 feet of the soil column) at OU1 and OU4, and contaminated groundwater beneath OU1 and OU4, represent potential exposure pathways for exposure of susceptible populations. Hypothetical receptors that could potentially be exposed to contaminants at or near OU1 and OU4 include offsite residents, future onsite residents, onsite construction workers, and workers using contaminated groundwater.
- Removal of contaminated soils at OU1 and OU4, has effectively isolated contaminants in vadose-zone soils from potential direct human exposure (Section 2.1). Therefore, surface and near-surface soils at OU1 and OU4 do not represent a completed receptor exposure pathway (JMM 1992a and 1992b).
- The primary migration route and potential exposure pathway for COCs associated with OU1 and OU4 comprises VOCs dissolved in groundwater beneath the sites, and moving with advective groundwater flow to potential downgradient receptors. VOCs dissolved in groundwater are the only COCs considered in the OU1 and OU4 RODs (JMM 1992a and 1992b) and the amended ROD for the OU4 hot spot (Montgomery Watson, 2000).
- Although no known completed exposure pathways currently exist from the domestic use of groundwater, exposure of hypothetical current and future, on- and off-site residents is considered to be a potential future exposure pathway, and to represent viable exposure routes through ingestion, inhalation, and dermal exposure (JMM 1992a and 1992b). The primary objective of groundwater remediation at DDHU OU1 and OU4 is to prevent off-Base migration of contaminated groundwater, thereby preventing this exposure route from being completed. A secondary objective of groundwater remediation, as expressed in the RODs for OU1, OU4, and the OU4 hot spot (JMM 1992a, 1992b, Montgomery Watson 2000), is aggressive extraction and treatment of groundwater to remove contaminant mass. Therefore, groundwater extraction and treatment has been identified as the preferred remedial alternative for VOCs in groundwater at OU1 and OU4.

4.2 CHLORINATED SOLVENTS IN THE ENVIRONMENT

Chlorinated solvent constituents are the contaminants of primary concern in the groundwater at DDHU OU1 and OU4. Consideration of the physical and chemical properties of chlorinated solvents is critical in evaluating the migration, distribution, and fate of these chemicals in the environment; identifying and delineating source areas; and assessing the possible range in performance of various remedial alternatives (Nyer and Skladany, 1989). Once chlorinated solvents have been introduced to the subsurface, their characterization and removal are problematic. Where possible, cost-effective remediation strategies should focus on identifying and delineating those parts of the subsurface environment containing the greatest mass of introduced chemicals, or where chemicals are present at high concentrations. These areas represent potential chemical source areas, from which chemicals can leach into groundwater, migrate to surface-water bodies, or volatilize into soil vapor. These areas can function as long-term contaminant sources, contributing chemical mass to the environment for decades. Identification and reduction of chemical source areas is essential, particularly when natural attenuation processes are slow, and the cost of containing groundwater plumes is high.

4.2.1 Fate And Transport Of Chlorinated Solvents

4.2.1 Concentration Trends in Extracted Groundwater

The identified sources of contaminated soil and debris from the vadose zone at both OU1 (Burial site 3A and the Plain City Canal) and OU4 (Burial sites 4A through 4E, and OU4 hot spot) were excavated. The depth of excavation extended to about 1 foot below the water table, or a total of 8 feet bgs. It should be noted that some contaminated soils remain at the OU4 hot spot beneath existing buildings, in order to maintain foundation integrity. The most effective remediation strategy for DNAPL in the vadose zone has been applied at OU1 and OU4.

Figures 3.1 and 3.2 in Section 3 show the current concentrations of CAHs, including vinyl chloride, in the groundwater at both OU1 and OU4, respectively. Based upon the 2 µg/L contours for both OU1 and OU4, the amount of vinyl chloride that remains in the groundwater is approximately less than 0.1 pounds at OU1 and 3.5 pounds at OU4 (see Section 3). A comparison of the current vinyl chloride plume area for OU1 (Figure 3.1) with the area of attainment established by the ROD (JMM,1992a) (Figure 2.20) shows a significant reduction in the area of the vinyl chloride plume. The ROD estimated that cleanup goals (i.e. concentrations of vinyl chloride below 2 µg/L) would be achieved five years after commencement of remediation. The OU1 pump-and-treat system began operation in December 1994. Based upon the ROD estimate, groundwater cleanup goals should have been achieved by December 1999. Figure 3.1 indicates that vinyl chloride concentrations above 2 µg/L still persist in the groundwater as of July/August 2000. Based upon this trend of vinyl chloride concentrations in groundwater, revisions to the CSM at OU1 should assume that:

- The area of attainment to meet cleanup goals for vinyl chloride has decreased significantly in size; and

- A source for vinyl chloride in groundwater still persists within the current plume area.

At OU4 a comparison of the current vinyl chloride plume area (Figure 3.2) with the area of attainment established for the main plume area by the ROD (JMM,1992b) (Figure 2.19) shows that the main vinyl chloride plume has been contained by the pump-and-treat system, and concentrations of vinyl chloride within the plume area have decreased overall. However, there has not been a significant reduction in the size of the area of attainment. The ROD estimated that cleanup goals (i.e. concentrations of vinyl chloride below 2 µg/L) would be achieved five years after commencement of remediation. The OU4 pump-and-treat system for the main plume began operation in July 1995. Based upon the ROD estimate, groundwater cleanup goals should have been achieved by end of the year 2000. Figure 3.2 indicates that vinyl chloride concentrations above 2 µg/L still persist in the groundwater as of July/August 2000. Based upon this trend of vinyl chloride concentrations in groundwater, revisions to the CSM at OU4 should assume that:

- The area of attainment to meet cleanup goals for vinyl chloride has not decreased significantly in size; and
- A source for vinyl chloride in groundwater still persists within the current plume area.

4.3 REFINEMENT OF CONCEPTUAL SITE MODEL

Examination of the available information can be used to refine the CSM for DDHU OU1 and OU4, to address the issues noted above. The refined CSM can then be used as a framework within which to evaluate the existing remediation systems at OU1 and OU4, and predict the possible ranges in their future performance (Section 6). The revised CSM is based on the original conceptual model developed for OU1 and OU4 (JMM 1992a and 1992b), and on the preceding discussions, incorporates the refinements described as follows:

- Very little refinement of the hydrogeologic parameters of the CSM is necessary. Outside of the area of influence of the ETI systems, the configuration of the water table surface and the general trends of groundwater flow at each site have changed very little since before treatment began. Once the ETI systems are turned off, the shallow aquifer in the area of influence will easily return to pre-treatment conditions.
- Examination of the historic pattern of solvent disposal at OU1 and OU4, the results of past CAH mass removal, and historic trends in contaminant concentrations, suggests that chlorinated solvents were introduced to the subsurface through disposal in burial pits. At present the main sources of CAHs have been removed from the vadose zone, and any CAH source that remains, is most likely to be found at or below the water table in dissolved phase. Vinyl chloride concentrations persist in dissolved phase in the groundwater at both OU1 and OU4.
- The revised CSM for OU1 should assume that the area of the vinyl chloride plume has decreased significantly in size since the pre-treatment area of attainment was

established in 1992. The size of the current vinyl chloride plume will have a significant impact on the optimization of the current pump-and-treat system.

- The revised CSM for OU4 should assume that vinyl chloride concentrations within the plume have decreased since 1991, but the area of attainment has not decreased significantly in size. The current pump-and-treat system has contained the vinyl chloride plume, but have not reduced the size of the plume.

SECTION 5

EVALUATION OF REMEDIATION GOALS

A clear understanding of the goals and objectives of a remediation project is an essential step in the RPO process. An understanding of the original remediation goals is required to evaluate the merits of those goals in light of an evolving CSM and changes in regulatory approaches. This RPO evaluation provides an opportunity to review the RAOs and groundwater remediation criteria for OUs 1 and 4 at DDHU, and to promote additional interaction and communication with regulatory officials responsible for oversight of remediation activities. The objectives of this section are to:

- Summarize the key findings and decisions of documents previously prepared (e.g., RI/FS reports, risk assessments, and the final RODs) as they relate to the identification of COCs and determination of groundwater remediation criteria;
- Review the current regulatory framework; and
- Review the RAOs and groundwater remediation criteria selected for OUs 1 and 4 at DDHU.

5.1 KEY FINDINGS OF HISTORICAL DOCUMENTS

This subsection summarizes information presented in the following key documents, as it pertains to cleanup goals for contaminated media at OUs 1 and 4 DDHU:

- OUs 1 and 4 RI/FS reports (JMM, 1991a and 1991b);
- OUs 1 and 4 RODs (DLA, 1992a and 1992b); and
- OU4 ROD Amendment (Montgomery Watson, 2000).

5.1.1 Key Findings Related to Contaminants at OU1

Environmental investigations at OU1 were conducted from 1981 through 1991 (JM, 1989, 1990, and 1991a). Soil contamination at the backfilled Plain City Canal and Burial Site 3-A was identified as a primary source of VOC contamination in shallow groundwater. Groundwater analytical results for samples collected in 1990 and 1991 showed VC and TCE present at concentrations above their MCLs. VC and *cis*-1,2-DCE were the most widespread detected VOCs. The total areal extent of the groundwater containing VC at concentrations above its MCL of 2 µg/L was estimated to be 32 acres, and the total volume of water in this area was estimated to be 56 million gallons. Dioxin

and furan congeners also were detected in sediment-laden groundwater samples collected in 1990 from monitoring wells located in the Plain City Canal. However, during the April 1991 sampling round, these contaminants were not detected in sediment-free groundwater samples.

A baseline risk assessment (BRA) was conducted for OU1 following completion of the site characterization activities (US Army Corps of Engineers [USACE, 1991a). The BRA results indicated that there are no significant risks associated with current receptor exposures to OU1 groundwater. Construction worker exposures to soil and residential exposures to drinking water from the contaminated groundwater plume were evaluated under future land use conditions. The potential excess cancer risks to construction workers exposed to soil were determined to be at the low end of USEPA's target risk range of 1E-06 to 1E-04, while the potential risks to future residents exposed to contaminated groundwater were above the target risk range (USACE, 1991a).

Remediation criteria and selected remedies for soil and groundwater are defined in the ROD for OU1 (DLA, 1992a). Soil cleanup goals were established for arsenic, lead, zinc, PCBs, dioxins, furans, *cis*-1,2-DCE, TCE, and VC. The soil cleanup levels for arsenic, zinc, and the VOCs were risk-based concentrations developed assuming residential exposure scenarios. In September 1997, DDHU underwent closure as part of the 1995 BRAC Act, and the DDHU property will be transferred to the Ogden Local Redevelopment Authority under provisions of the BRAC (DDHU, 1998b). The development of risk-based soil cleanup levels based on residential exposures would be overly conservative if the DDHU property continues to be used for nonresidential (e.g., industrial) purposes in the future. Nonetheless, the selected remedy for soils established in the ROD (DLA, 1992a) involved excavation and removal of all contaminated soils at OU1 with disposal at an approved offsite facility. Soil removal actions were completed in August 1994 for sources contributing to OU1 groundwater contamination. Therefore, the RAOs and remediation criteria for soils at OU1 are not further evaluated.

Groundwater remediation criteria were established for TCE, *cis*-1,2-DCE, and VC in the OU1 ROD, and are listed in Table 5.1 (DLA, 1992a). Groundwater cleanup goals are based on drinking water MCLs, and the attainment area for OU1 groundwater cleanup was defined by the 2- μ g/L contour for VC. The selected remedy for groundwater at OU1 included groundwater extraction, treatment by air stripping for VOCs and by GAC adsorption for dioxins/furans, and reinjection into the shallow aquifer via injection wells. Per the ROD (DLA, 1992a), "the ability of pump and treat technology to achieve and maintain low contaminant levels may be limited, as evidenced by experience at other sites." The current OU1 groundwater ETI system was constructed in 1994, and began operation in December 1994. The design and operation of this system are discussed in Section 7. The RAOs and remediation criteria for OU1 groundwater are evaluated further in Sections 5.2 and 5.3.

5.1.2 Key Findings Related to Contaminants at OU4

Environmental investigations were conducted at OU4 from 1981 through 1991 for the main plume associated with Burial Sites 4-A through 4-E (JMM, 1989, 1990, and 1991b), and subsequently at the OU4 hotspot (Montgomery Watson, 1996). Soil contamination at Burial Site 4-E was identified as a primary source of groundwater contamination, and soil

TABLE 5.1
OU1 GROUNDWATER CLEANUP LEVELS
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Chemical of Concern	Cleanup Level (µg/L) ^{a/}
Trichloroethene	5
<i>cis</i> -1,2-Dichloroethene	70
Vinyl Chloride	2

^{a/} Cleanup level established in Record of Decision based on federal maximum contaminant level (DLA, 1992a); µg/L = micrograms per liter.

contamination at Burial Site 4-A was identified as a potential secondary source. Groundwater analytical results for samples collected at OU4 in 1990 and 1991 showed VOCs, SVOCs, PCBs, dioxins/furans, and metals to be present in groundwater. Vinyl chloride, *cis*-1,2-DCE, TCE, benzene, and PCBs were detected at concentrations above MCLs, while VC and *cis*-1,2-DCE were the most widespread contaminants. The total areal extent of groundwater in the main (Burial Site) plume containing VC at concentrations greater than 2 µg/L was estimated to be 50 acres, and the total volume of water in this area was estimated to be 65 million gallons. Dioxin and furan isomers were detected in sediment-laden groundwater samples collected in 1990. The detection of dioxins and furans was attributed to adsorption of these compounds to silt particles in the shallow aquifer and the turbidity of the groundwater samples.

A BRA was conducted for the main groundwater plume at OU4 following completion of the site characterization activities (USACE, 1991b). The BRA results indicated that there were no significant risks associated with current receptor exposures at the site. Construction worker exposures to soil and residential exposures to drinking water from the contaminated groundwater plume were evaluated under future land use conditions. The potential risks to construction workers exposed to soil were determined to be in the middle of USEPA's target risk range of 1E-06 to 1E-04, while the potential risks to residents exposed to contaminated groundwater were above the target risk range.

Remediation criteria and selected remedies for soil and groundwater affected by wastes from the Burial Sites were defined in the ROD for OU4 (DLA, 1992b). Soil remediation criteria were established for arsenic, lead, benzene, *cis*-1,2-DCE, PCBs, 2,3,7,8-TCDD-equivalents, and VC. Consistent with OU1, the soil cleanup levels for constituents other than lead, PCBs, and dioxins were based on residential risk-based concentrations. The selected remedy for OU4 soils included excavation and removal of all backfilled soil and debris in Burial Sites 4-A and 4-E. The selected remedy was designed to prevent direct receptor exposures to contaminated soil, and to eliminate a primary source of organic contamination in groundwater.

During the installation of the OU4 groundwater treatment system, VC was detected at concentrations above its MCL at proposed injection well locations previously believed to be free of subsurface contamination. Soil contamination at an oil holding pit and three

trenches located between Buildings 15C (359) and 16C (367) at OU4 was identified as a “hotspot” source contributing to the formations of an extension of the main OU4 groundwater plume (Figure 2.4). The plume extension is referred to as the northern lobe of the OU4 groundwater plume (Montgomery Watson, 1996). As a consequence of this discovery, the OU4 ROD was amended to address the hotspot (Montgomery Watson, 1999 and 2000).

A BRA was conducted for the hotspot, and was documented in the *Final OU4 Hotspot Exploration Trench Report* (Montgomery Watson, 1997a). Risk drivers were identified as lead in soil at trenches A and B, and petroleum hydrocarbons in the soils and groundwater. Per the OU4 ROD amendment (Montgomery Watson, 2000), the selected remedy for contaminated hotspot soil included excavation and off-site disposal of soils located between buildings, containment of soils located under buildings, and institutional controls prohibiting disturbance of the concrete floor and/or subsurface soils at the site. Source removal operations at the OU4 hotspot were conducted from October to November 1998. Approximately 3,000 pounds of ORC were placed in the open excavation at the water table in an attempt to promote biodegradation of the residual hydrocarbons left in place. Because the OU4 soil removal actions per the ROD and the ROD amendment are essentially complete, the RAOs and remediation criteria for soils at OU4 are not evaluated further in this report.

Groundwater remediation criteria were established for benzene, *cis*-1,2-DCE, VC, PCBs, and 2,3,7,8-TCDD-equivalents in the main plume in the OU4 ROD (DLA, 1992b). The hotspot ROD amendment also established remediation criteria for all of these COCs except dioxins for the northern lobe of the OU4 plume (Montgomery Watson, 2000). The remediation criteria for the OU4 COCs, listed in Table 5.2, are based on drinking water MCLs, and the attainment area for OU4 groundwater cleanup is defined by the 2- $\mu\text{g/L}$ contour for VC. The selected remedy for the main groundwater plume at OU4 included groundwater extraction, treatment by air stripping for VOCs and by GAC adsorption for dioxins, and reinjection into the shallow aquifer (DLA, 1992b). The remedy for the hotspot plume consists of extraction of groundwater from a 300-foot-long extraction trench, treatment by chemical oxidation, and discharge of treated water to the sanitary sewer. Groundwater discharge treatment criteria were established for benzene, total DCE, *cis*-1,2-DCE, PCE, TCE, and vinyl chloride to achieve a total toxic organics limit of 100 $\mu\text{g/L}$ under the Central Weber Sewer Improvements District industrial discharge permit.

The OU4 groundwater ETI system for the main plume was installed in July 1995, and northern lobe trench/treatment/discharge system was completed in April 1999. The design and operation of these systems are discussed in Section 5. The RAOs and remediation criteria for OU4 groundwater are further evaluated in Section 4.3.

5.2 CURRENT REGULATORY FRAMEWORK

DDHU was placed on the NPL in 1987 (JMM, 1989). The remedial alternatives specified in the RODs for OU1 (DLA, 1992a) and OU4 (DLA, 1992b; Montgomery Watson, 2000) were selected in accordance with CERCLA as amended by SARA of 1986, and with the National Oil and Hazardous Substances Pollution Contingency Plan (NCP). Utah state regulatory guidance also was considered when determining remedial

TABLE 5.2
OU4 GROUNDWATER CLEANUP LEVELS
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Chemical of Concern	Cleanup Level ($\mu\text{g/L}$) ^{a/}
Benzene	5
<i>cis</i> -1,2-Dichloroethene	70
Vinyl chloride	2
PCBs	0.5
2,3,7,8-TCDD equivalents ^{b/}	0.00003

^{a/} Cleanup level established in Record of Decision based on federal maximum contaminant level (DLA, 1992b; Montgomery Watson, 2000); $\mu\text{g/L}$ = micrograms per liter.

^{b/} Dioxins/furans are chemicals of concern in the main OU4 plume, but not in the northern lobe sourced at the hotspot.

goals for DDHU. State and federal guidelines relevant to establishing groundwater cleanup goals for OUs 1 and 4 at DDHU are reviewed in the following subsections.

5.2.1 State Guidelines

Utah state requirements regarding the establishment of groundwater remediation levels are provided in UDEQ Division of Solid and Hazardous Waste Proposed Hazardous Waste Rules. According to the Rules, Article R315-101 (*Cleanup Action and Risk-Based Closure Standards*) is applicable to any responsible party involved in management of a site contaminated with hazardous waste or hazardous constituents. Per R315-101, the remedial process may include the development of a site management plan, which is supported by the results of a risk assessment. The risk assessment must be conducted using a residential exposure scenario if residential exposures occur at the site or are likely to occur in the future. However, if residential exposures are not applicable at the site, then “actual land use conditions” or “potential land use conditions based upon applicable zoning and future land use planning considerations” (whichever result in a more conservative risk estimate) should be evaluated in the risk assessment report.

In September 1997, DDHU underwent closure as part of the 1995 BRAC Act, and the DDHU property will be transferred to the Ogden Local Redevelopment Authority under provisions of the BRAC (DDHU, 1998b). The establishment of groundwater cleanup goals based on MCLs at DDHU under Article R315-101 would be overly conservative if the DDHU property continues to be used for nonresidential (e.g., industrial) purposes in the future because MCLs are developed based on the protection of residents exposed to water used for domestic, potable consumption. It should be noted that Article R325-101 allows for non-residential land use considerations when determining corrective action.

If a non-residential scenario is to be used as the basis for cleanup goals, the site management plan must contain appropriate corrective action procedures based on the results of the risk assessment (R315-101-6). For sites where 1) excess cancer risks are less than 1E-04 for non-residential (e.g., industrial) scenarios, but greater than 1E-06 for residential scenarios, and 2) the hazard index is less than one for both residential and non-residential scenarios, it is stated in Article R315-101-6 that: *“the site management plan may contain, but is not required to contain, procedures for corrective action. The site management plan shall contain appropriate management activities e.g., monitoring, deed notations, site security, or post-closure care, as determined on a case-by-case basis in accordance with criteria identified in R315-101-(b)(4).”*

Article R315-101-6 is potentially significant to DDHU because it provides an opportunity to apply management activities or institutional controls to address potential exposures to groundwater at the site. Per R315-101-1(b)(4), appropriate corrective action or management activities at a site, should be considered based on the following criteria:

- “The impact or potential impact of the contamination on human health;
- The impact or potential impact of the contamination on the environment;
- The technologies available for use in clean-up; and
- Economic considerations and cost-effectiveness of cleanup options.”

Utah’s non-degradation policy for groundwater is applicable when assessing the potential impact of site contamination on the environment. According to Article R315-101-3, *“When closing or managing a contaminated site, the responsible party shall not allow levels of contamination in groundwater, surface water, soils, and air to increase beyond the existing levels of contamination at a site when site management commences.”* This rule suggests that certain water bodies may be designated for beneficial uses other than public drinking water supply (i.e., the highest beneficial use). Examples for applying technological or economic factors in determining appropriate correct actions at a site are not included in Article R315-101-3.

5.2.2 Federal Guidelines

For sites where established cleanup goals may not be achievable, USEPA’s (1993) technical-impracticability (TI) waiver protocol includes provisions for an exception to the application of MCLs as ARARs. ARARs may be waived by USEPA for any six of the reasons specified in the NCP (under CERCLA §121[d][4]), including TI from an engineering perspective. The TI evaluation generally should include the following components, based on site-specific information and analyses (USEPA, 1993):

1. Specific ARARs or matrix-specific cleanup standards for which TI determinations are sought.
2. Spatial area over which the TI waiver will apply.

3. A CSM that describes site geology, hydrology, and groundwater contamination sources, transport, and fate.
4. An evaluation of the restoration potential of the site, including data and analyses that support any assertion that attainment of ARARs or matrix cleanup standards is technically impractical from an engineering perspective, including as a minimum:
5. A demonstration that contaminant sources have been identified and have been or will be removed and contained to the extent possible;
6. An analysis of the performance of any ongoing or completed remedial action;
7. Predictive analysis of the time frames to attain required cleanup levels using available technologies; and
8. A demonstration that no other remedial technologies (conventional or innovative) could reliably, logically, or feasibly attain the cleanup levels at the site within a reasonable timeframe.
9. Estimate of cost of the existing or proposed remedy options, including construction and OM&M costs.
10. Any additional information or analyses that USEPA deems necessary for the TI evaluation.

If a TI decision is made, USEPA (1993) requires that an alternative cleanup strategy be developed. As part of this alternate strategy, site-specific cleanup goals may be developed for the affected media using a risk-based corrective action (RBCA) approach. The application of the RBCA process at DDHU is discussed further in Section 5.3.

5.3 EVALUATION OF DDHU GROUNDWATER RAOS AND CLEANUP GOALS

The RPO process provides for re-evaluation of the aquifer cleanup goals at DDHU based on the progress toward achieving those goals, and the expectation that the goals will be met within a reasonable remedial time and cost framework. This evaluation is important because cleanup goals serve as a basis for determining if remedial actions (such as groundwater ETI systems) are effective and when specific remedial actions may be discontinued. The appropriateness of the cleanup goals developed for groundwater at DDHU, and an example of alternative groundwater cleanup goals based on the RBCA process are discussed in the following sections.

5.3.1 Appropriateness of Groundwater Cleanup Levels

The existing cleanup goals for groundwater at OU1 and OU4 at DDHU were established based on the assumptions that all groundwater beneath and downgradient from the facility represent sources of drinking water (i.e., the highest beneficial use would be for drinking water under a residential scenario). However, shallow

groundwater at DDHU currently is not used, and is not likely to be used in the future, as a potable water supply. As discussed in Section 5.2, Utah regulations allow the use of institutional controls under non-residential/non-drinking-water scenarios. Thus, use of drinking water MCLs as groundwater cleanup levels at DDHU may be overly conservative.

Based on a review of current state and federal guidelines, current and anticipated future land use conditions at DDHU, and the technical infeasibility of achieving the established groundwater cleanup goals at DDHU, it is recommended that DLA consider applying for exceptions to the use of MCLs as cleanup goals for groundwater at DDHU. If a non-residential land use scenario and/or a TI decision is made at DDHU, USEPA (1993) requires that an alternative cleanup strategy be developed. The RBCA process provides one method for determining alternate site-specific cleanup goals. The RBCA process uses a tiered approach, which integrates site assessment and response actions with human health and ecological risk assessment, to evaluate the necessity for remedial action, and to tailor corrective actions to site-specific conditions and risks. The development of a risk-based cleanup goal for VC in groundwater at DDHU is presented as an example in Section 5.3.2.

5.3.2 Development of RBCA-Based Groundwater Cleanup Levels

This section develops a risk-based cleanup goal for VC in groundwater at DDHU to illustrate the RBCA process and demonstrate how these goals compare to ARARs established in the RODs for OU1 and OU4 (DLA, 1992a and 1992b). The risk-based cleanup goal developed for VC and the established cleanup goal for VC (i.e., the MCL) are compared in Table 5.3. The risk-based goal was developed for a generic industrial land-use scenario at DDHU. The risk-based goal was established based on the following exposure assumptions:

**TABLE 5.3
ALTERNATE RISK-BASED CLEANUP GOAL
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH**

Groundwater COC	Alternate Risk-Based Cleanup Goal ($\mu\text{g/L}$)	OU1 and OU4 ROD Cleanup Goal ^{a/} ($\mu\text{g/L}$)
VC	68.3	2

^{a/} Sources: DLA (1992a and 1992b); Montgomery Watson (2000).

- An onsite well will be used to supply water for onsite landscape irrigation purposes only (no consumption);
- Groundskeepers may be exposed through dermal contact to contaminants in extracted groundwater that is used for landscape irrigation. (Ingestion exposures were not evaluated in this example calculation because the COCs at DDHU are

VOCs, which have a relatively low propensity to bioaccumulate. In addition, inhalation exposures were not evaluated due to the dissipation of VOCs into ambient air);

- Based on assumed worker attire, the hands, forearms, and lower legs would be the body parts dermally exposed;
- A groundskeeper would irrigate an average of once per week for 50 weeks per year. The watering frequency in the warmer months may be 2 times a week, but in the winter this would be significantly less, averaging to approximately once a week for a given year; and
- The risk-based cleanup goal is based on a 1 in 1,000,000 (i.e., $1E-06$) excess cancer risk.

Details of the exposure assumptions, models, and input parameters are presented in Appendix B.

It should be noted that the risk-based cleanup goal presented in Table 5.3 is generic for industrial settings, and does not necessarily represent actual or expected exposure conditions at OUs 1 and 4. Site-specific risk-based cleanup goals for DDHU COCs should be developed after requesting regulatory approval to proceed with a risk-based approach. The example VC risk-based cleanup goal presented in Table 5.3 is based on USEPA conservative default parameters and assumptions for the industrial exposure scenario.

SECTION 6

EVALUATION OF REMEDIAL SYSTEMS

The remedial action objectives (RAOs) for groundwater at OUs 1 and 4 were presented in Section 2.5; and the current extraction, treatment, and injection (ETI) systems operating at these OUs were described in Section 2.6. The current groundwater monitoring programs at OUs 1 and 4 were reviewed in Section 2.7. The focus of Section 6 is the evaluation of the performance of the ETI systems and the effectiveness of the long term monitoring (LTM) program at tracking remedial progress. Based on this evaluation, short-term recommendations to reduce operation, monitoring, and maintenance (OM&M) costs are developed, and longer-term opportunities for revisiting remedial decisions, refining remediation goals, and enhancing system performance are identified (Section 7).

6.1 GROUNDWATER REMEDIAL ACTION OBJECTIVES FOR OU1 AND OU4

The importance of understanding the remedial action objectives for OUs 1 and 4 at DDHU was discussed in Section 5, and the RAOs established for the OUs in the RODs (DLA, 1992a and 1992b; Montgomery Watson, 2000) were reviewed. Because the effectiveness of the current remediation systems is directly related to their ability to achieve remedial action objectives, attainment of RAOs can be used as a measure of each system's performance. Although the RODs state that there is no current risk to receptors from exposures to OU1 or OU4 groundwater, specific RAOs were identified to ensure compliance with applicable or relevant and appropriate requirements (ARARs) (i.e., MCLs) under a potential future residential land-use scenario, and to restore the groundwater to its highest beneficial use (Section 5). These specific objectives, introduced in Section 2.5 and summarized in Table 6.1, potentially represent the performance criteria for OU1 and OU4 ETI system evaluations. The *Risk, Cleanup, Containment*, and *Performance Objectives* listed in the table generally apply to groundwater remaining in the subsurface. The *Discharge Objective* applies to effluent from the above-ground treatment system.

The RAOs establish the cleanup standards for groundwater at both OU1 and OU4. The RODs specify that remediation of groundwater in the shallow aquifers will be considered to be complete when contaminant concentrations are maintained, with active groundwater extraction, below MCLs for a period of one year. In this event, the treatment systems can be shut down. Following shutdown of the systems, monitoring of groundwater at OUs 1 and 4 must continue until the next statutory 5-year review. If MCLs are exceeded within this period of time, extraction and treatment of groundwater will resume.

TABLE 6.1
REMEDIAL ACTION OBJECTIVES AND PERFORMANCE CRITERIA
REMEDIAL PROCESS OPTIMIZATION
OPERABLE UNITS 1 AND 4
DEFENSE DEPOT HILL, UTAH

Remedial Action Objective	Corresponding Performance Criterion	Rationale
<p>Risk Objective: Prevent future receptor exposures to contaminated groundwater that poses a risk of greater than 1×10^{-4} with a target risk level of 1×10^{-6}</p>	None	Groundwater extraction and treatment alone cannot prevent exposure to contaminant already in groundwater. Institutional controls, currently in place, prevent exposure to groundwater
<p>Cleanup Objective: Reduce the COC concentrations in groundwater beneath the OUs to levels below federal MCLs</p>	Remove sufficient contaminant mass from the subsurface so that the maximum COC concentrations at any point within the OUs are below federal MCLs.	Groundwater in the OUs is considered to be a potential future potable water source. In the absence of site-specific risk-based cleanup goals, federal MCLs are presumed to be protective of human health and the environment (i.e., the highest beneficial use of the shallow groundwater).
<p>Discharge Objective: Reduce the contaminant concentrations in the treated groundwater effluent to MCLs</p>	Remove contaminants from extracted groundwater so that the treated effluent is below federal MCLs	Treated groundwater is reinjected into the shallow aquifer. Contaminant concentrations in treated effluent must be below MCLs to eliminate potential further degradation of groundwater.
<p>Containment Objective: Eliminate or reduce the potential for further migration of the existing CAH plumes and achieve remediation to MCLs within the <i>area of attainment</i> (defined as the areas at both OUs containing dissolved vinyl chloride above its MCL of 2 µg/L)</p>	None	Data analysis and modeling indicate the plumes are stable (e.g., not expanding) under current extraction system operation.
<p>Performance Objective: Restore groundwater to MCLs within an estimated 5-year time frame</p>	Remove sufficient contaminant mass so that all COC concentrations in groundwater at the OUs is below MCLs within 5 years	Five years was the time frame estimated in the RODs for achieving groundwater cleanup goals.

RAOs are used to establish performance criteria that can be viewed as measurable milestones on the road to achieving site cleanup and closure. These criteria are developed using the results of modeling, calculations, estimates or extrapolations made during the initial design stages, and are used to estimate remediation timelines and anticipated progress. Performance criteria should be selected and stated so that they can be evaluated using data routinely collected at a site, and should be reviewed annually (at a minimum), to assess system effectiveness/efficiency (i.e., an RPO Phase I review).

Several of the RAOs are not directly applicable as criteria of system performance. The RAO based on the *Risk Objective* is not a suitable criterion because groundwater extraction and treatment alone can not prevent exposure to site contaminants, and therefore, no system performance criteria can be established using the *Risk Objective*. Additionally, no performance criteria have been established in the OU1 and OU4 RODs regarding the *Containment Objective* for the OU1 or OU4 plumes. However, containment will be discussed in detail in later sections in terms of capture zone analyses and optimization of the extraction well fields. The RPO evaluation of the ETI systems will therefore focus on the *Cleanup, Discharge, and Performance Objectives* (Table 6.1). The performance criteria associated with the applicable RAOs, and the rationale for their selection, are provided in Table 6.1.

6.2 EVALUATION OF OU1 REMEDIAL SYSTEM

6.2.1 Summary of OU1 Groundwater ETI System Operations

The current groundwater extraction system at OU1 consists of 16 extraction wells, all screened from just below the groundwater table to the top of the underlying clay layer. The completion intervals of the extraction wells typically extend from approximately 10 to 25 feet below ground surface (bgs). The design groundwater extraction rate for each well was in the range of 5 to 10 gallons per minute (gpm); and the total extraction rate for the entire well field was on the order of 100 gpm. Recent production rates for all extraction wells at OU1 are listed in Table 6.2. The groundwater extraction system was installed to capture the dissolved VOC plume and to remove VC and *cis*-1,2-DCE mass from groundwater. Sixteen injection wells were installed around the perimeter of the VC area of attainment (as defined by the 2 µg/L isoconcentration contour), and were intended to function as a hydraulic barrier to prevent further migration of contaminated groundwater to previously uncontaminated areas.

6.2.2 Effectiveness of Current Extraction System at OU1

In general, two primary remediation objectives are associated with conventional groundwater extraction (“pump-and-treat”) systems (NRC, 1993): removal of contaminant mass from the subsurface, and establishing or maintaining hydraulic control to restrict or prevent continued migration of dissolved contaminants. For most groundwater extraction systems, controlling contaminant migration is the primary objective, while contaminant mass removal is a secondary benefit.

The effectiveness of a remediation system is judged by how well it achieves its objectives. A system is considered optimized if it is effectively achieving its objectives at the lowest possible total cost and/or in the shortest period of time. The effectiveness of

TABLE 6.2
RECENT PRODUCTION HISTORY OF GROUNDWATER EXTRACTION WELLS
OPERABLE UNIT 1
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Extraction Well	Design Production Rate (gpm) ^{a/}	Actual Production Discharge Rate (Date)					Approximate <i>cis</i> -1,2 DCE and VC Concentrations in Extraction Well Discharge (µg/L) ^{b,c/}			Current <i>cis</i> -1,2 DCE Removal Rate (lbs/year) ^{d, e/}	Current VC Removal Rate (lbs/year) ^{d, e/}
		8/11/99	11/3/99	2/2/00	5/3/00	8/9/00	<i>cis</i> -1,2 DCE	VC	Date		
		(gpm)	(gpm)	(gpm)	(gpm)	(gpm)					
EW-1	No Data	8.8	6.8	3.1	3.6	4.8	1.6	< 1.0 (0.47)	1-Aug-00	0.038	0.011
EW-2	No Data	5.9	3.9	11.4	8.3	6.8	<1.0 (0.65)	< 1.0 (ND)	1-Aug-00	0.021	0.003
EW-3	No Data	9.0	6.4	8.7	5.8	8.5	3.4	< 1.0 (0.23)	1-Aug-00	0.115	0.008
EW-4	No Data	3.2	3.0	5.0	3.4	3.1	5.6	1.0	1-Aug-00	0.087	0.016
EW-5	No Data	12.1	9.3	11.2	11.7	14.4	<1.0 (0.37)	< 1.0 (ND)	31-Jul-00	0.019	0.005
EW-6	No Data	9.5	6.5	7.7	8.6	8.7	2.6	< 1.0 (0.74)	31-Jul-00	0.094	0.027
EW-7	No Data	6.8	4.9	6.1	7.2	6.3	3.2	1.0	31-Jul-00	0.088	0.027
EW-8	No Data	7.5	5.3	8.0	7.8	7.8	<1.0 (0.98)	< 1.0 (0.18)	31-Jul-00	0.031	0.006
EW-9	No Data	8.1	6.1	7.6	6.9	5.3	1.5	< 1.0 (0.14)	31-Jul-00	0.045	0.004
EW-10	No Data	3.4	4.3	6.3	6.3	1.7	<1.0 (0.96)	< 1.0 (0.12)	31-Jul-00	0.019	0.002
EW-11	No Data	3.3	2.4	3.6	3.2	4.1	<1.0 (0.45)	< 1.0 (ND)	1-Aug-00	0.007	0.001
EW-12	No Data	7.0	6.0	2.5	8.3	7.0	<1.0 (0.32)	< 1.0 (ND)	1-Aug-00	0.009	0.003
EW-13	No Data	7.3	5.6	7.6	6.3	4.7	<1.0 (0.58)	< 1.0 (ND)	1-Aug-00	0.016	0.003
EW-14	No Data	6.5	2.6	4.0	2.7	4.7	1.6	< 1.0 (0.25)	1-Aug-00	0.029	0.004
EW-15	No Data	7.4	7.0	8.2	5.1	6.7	< 1.0 (ND)	< 1.0 (ND)	1-Aug-00	0.003	0.003
EW-16	No Data	8.1	7.4	6.7	6.7	3.9	2.1	< 1.0 (0.78)	1-Aug-00	0.060	0.022
Total Mass Removed per Ye										0.679	0.146

^{a/} gpm = gallons per minute.

^{b/} µg/L = micrograms per liter.

^{c/} Concentrations in parathesis are laboratory estimated concentrations below the MDL. ND indicates that the concentration was below the detection

^{d/} lbs/yr = pounds per year.

^{e/} If the concentration was below the MDL, removal rates were calculated using laboratory-estimated concentrations. In cases where the concentration removal rates were calculated using an assumed concentration of 0.1 µg/L.

the complete OU1 extraction system and of its individual extraction wells was first evaluated in terms of the performance objective of mass removal. Although incremental improvements in the effectiveness and efficiency of a groundwater extraction system may be achieved through changes in well placement or extraction depth intervals, the opportunities to optimize the current extraction system are restricted by the physics of the system, the nature and distribution of COCs in groundwater, and the potential presence of TCE/DCE source mass (e.g., at Burial Sites 3A and 3C), which could result in continued generation of VC in groundwater through reductive dechlorination of its parent compounds (TCE and *cis*-1,2-DCE).

6.2.2.1 Mass Removal

The estimate provided in the ROD for OU1 in 1992 indicated that a period of approximately 5 years would be required to achieve the groundwater RAOs within the area of attainment (Figure 6.1) at OU1 (DLA, 1992a). A volume of approximately 260 million gallons of groundwater (equal to five pore volumes) was projected to be extracted and treated during that time.

The rate of removal of contaminant mass can be estimated using

$$\text{MASS REMOVAL RATE} = \text{GROUNDWATER EXTRACTION RATE} \times \text{CONTAMINANT CONCENTRATION}$$

with appropriate adjustment of units (e.g., conversion of gallons per minute to liters per year). Using historic concentrations influent to the OU1 treatment plant and the actual volume of groundwater treated to that time (224 million gallons), the total mass of VC removed from the subsurface at OU1 by the groundwater extraction system, as of mid-July 1999, was estimated to be approximately 2.9 pounds (Parsons ES, 2000) – an average removal rate of about 0.6 pounds of VC per year, through the 5-year operational history of the groundwater extraction and treatment system. This removal of VC mass has been accompanied by a decrease in the size of the area of attainment (as defined by the 2 µg/L isoconcentration contour) (compare isoconcentration contours for 1993 and 2000; Figure 6.1), although it is not clear that the decrease in the extent of the VC plume is solely a result of active groundwater extraction, or whether much of the decrease may be a consequence of attenuation processes (degradation, volatilization, dispersion).

The recent production history of all operating extraction wells at OU1 is presented in Table 6.2, together with the concentrations of *cis*-1,2-DCE and VC detected in the discharge effluent of individual wells during the monitoring event of July and August 2000 (Section 3.1). Based on current extraction rates and contaminant concentrations, the groundwater extraction and treatment system is estimated to be removing *cis*-1,2-DCE from the subsurface at OU1 at the rate of approximately 0.7 pound per year, and is removing VC at a rate of less than 0.2 pound per year. The rate of removal of contaminant mass has apparently declined significantly during the six-year period of system operation, from an average removal rate of 0.6 pounds of VC per year, to the current rate (0.2 pounds of VC per year).

Decreases in the rate of removal of contaminant mass from groundwater systems through time commonly occur with active groundwater extraction systems (NRC, 1994).

**Figure 6.1 Chlorinated Aliphatic Hydrocarbons (CAH) in Groundwater at OU1 –
1993 and 2000**

This is likely due to contaminant sorption/desorption phenomena -- contaminants in the subsurface tend to diffuse into inaccessible soil pore spaces and become very strongly sorbed, particularly to fine-grained soil particles. As water moves through saturated soil, sorbed contaminants desorb only slowly from the soil into groundwater; and much of the contaminant mass remains sorbed to soil particles, as a consequence of equilibrium partitioning between groundwater and soil. In recognition of the problems associated with sorption of contaminants to soil and the slow rates of desorption/dissolution reactions, USEPA (1992) issued a directive regarding groundwater remediation at Superfund sites, which stated that groundwater pump-and-treat systems usually cannot remediate dissolved contaminant concentrations to levels below typical site remediation goals for groundwater. The National Research Council (NRC, 1994) further stated that:

1. Groundwater extraction is ineffective for restoring groundwater quality to drinking-water standards, primarily as a result of the decreasing rates of contaminant desorption from within soil particles into groundwater.
2. Most aquifers are heterogeneous and have low-permeability zones where contaminants become immobilized. Groundwater pumping causes preferential flow of groundwater in zones of high permeability, resulting in the trapping of even highly soluble contaminants in low-permeability zones.

As a direct consequence of these limitations, groundwater extraction systems are generally ineffective at removing contaminant mass from the subsurface.

Although *cis*-1,2-DCE has historically been detected in groundwater samples from several wells within OU1, the detected concentrations have never exceeded the MCL for *cis*-1,2-DCE (70 µg/L). Therefore, application of the *Cleanup Objective* (Objective No. 2 in Table 6.1) as a performance criterion in the evaluation of the groundwater ETI system at OU1 must focus on removal of VC mass. A mass of approximately 2.8 pounds of VC was initially estimated to be present in groundwater at OU1, prior to the installation and operation of the groundwater extraction system (DLA, 1992a). However, no equilibrium sampling (e.g., groundwater sampling following temporary shut-down of the extraction system to allow the groundwater system to achieve chemical equilibrium) has been conducted since operation of the extraction system began in December 1994. Therefore, no realistic estimate can be made of the mass of VC remaining in OU1 groundwater.

Rather than attempting to estimate the total mass of VC remaining in groundwater at OU1, and comparing the total remaining VC mass with current mass-removal rates, Parsons used an alternative approach to develop estimates of the total length of time required to attain the MCL for VC in groundwater (2 µg/L) at all points within the area of attainment at OU1. Plots were generated to show the concentrations of VC in groundwater samples from individual monitoring wells through time (Figure 6.2). The temporal trends in concentrations of VC in the groundwater samples from monitoring wells AEHA-9, JMM-19, JMM-47, JMM-59, JMM-60, and JMM-62 appear to indicate that VC concentrations in groundwater in the vicinity of each of these wells have been decreasing through time. The temporal concentration data for these wells were fitted with first-order equations, and the first-order curves were projected through time until they intersected the cleanup goal for VC in groundwater (the MCL for VC of 2 µg/L).

Figure 6.2 Temporal Trends and Projected Cleanup Times for Vinyl Chloride in Groundwater at OU1

Assuming that the concentrations of VC in groundwater samples from these wells continue to decrease through time, and the trends of decreasing concentrations continue to approximate first-order processes, this procedure can provide an estimate of the length of time required to achieve cleanup goals in groundwater at each monitoring location. Cleanup goals for groundwater have already been attained at most locations in OU1 (Figures 6.1 and 6.2). Cleanup goals have not been achieved at monitoring wells AEHA-9, JMM-2 (not shown on Figure 6.2) or JMM-22. The projected date at which the VC cleanup goal will be achieved at well AEHA-9 is approximately the third quarter of 2003. However, no trend in concentrations is apparent in the data for well JMM-22, and it is not possible to use this method to project the time required to achieve cleanup goals in groundwater at this location.

Application of this procedure assumes that no additional contaminant mass is being/will be introduced to the groundwater system at OU1. However, it seems likely that during the entire period of operation of the ETI system, VC has been generated continuously, though at a slow rate, via degradation of *cis*-1,2-DCE through reductive dechlorination. A mass of approximately 6 pounds of *cis*-1,2-DCE – about three times the initial VC mass -- was initially estimated to be present in groundwater at OU1, prior to the installation and operation of the groundwater extraction system (DLA, 1992a); and the concentrations of *cis*-1,2-DCE detected during the July-August 2000 monitoring event in groundwater samples from monitoring wells (Table 3.2) and in OU1 extraction-well effluent samples (Table 6.2) were generally several times greater than the detected VC concentrations. Therefore, a source of mass for generation of VC through reductive dechlorination processes is available. In addition, the OU1 plume is moderately anaerobic (i.e., DO levels are typically below 0.5 mg/L) and reducing (the ORP at most sampling locations is negative), indicating that conditions are suitable for the occurrence of reductive dechlorination of TCE and DCE (Section 3.3), which will eventually generate the VC daughter product (USEPA, 1999). This suggests that even though minor amounts of contaminant mass (less than 0.2 pound of VC per year) are being removed from the subsurface by the groundwater extraction and treatment system, VC will continue to be present in groundwater within the attainment area as long as parent compounds (TCE and DCE isomers) remain. Furthermore, slow desorption of VC and parent compounds from soils in the groundwater zone also represents a potential long-term, continuing source of contaminants in groundwater. Therefore, although application of the trend-projection technique described above can be used to predict that RAOs will be achieved for groundwater at OU1 no earlier than about the third quarter of 2003 (3 years from the present), it seems likely that a somewhat longer (though unknown) period of time will actually be required. This observation is reinforced by the lack of apparent temporal trend in VC concentrations in groundwater samples from well JMM-22 (Figure 6.2).

As is clear from the above discussion, the groundwater extraction system at OU1 has not been effective in removing VC mass from the subsurface. The effectiveness of individual extraction wells can also be evaluated by examining the rates of removal of contaminant mass. The recent production histories for the 16 extraction wells are presented in Table 6.2, and the approximate removal rates for *cis*-1,2-DCE and VC are presented in Figures 6.3 and 6.4. The approximate removal rates were calculated based on effluent sampling conducted at the extraction wells in July and August 2000, and the

Figure 6.3 Removal of *cis*-1,2-DCE Mass During 2000

Figure 6.4 Removal of VC Mass During 2000

average production rate of each extraction well over the past year. Examination of rates of production of *cis*-1,2-DCE and VC indicates that significant removal of contaminant mass is not occurring at any extraction well; and all wells are regarded as ineffective (Table 6.3). Only three wells (EW-6, EW-7 and EW-16) are producing more than 0.02 pound of VC per year. Wells EW-1 and EW-4 are removing an estimated 0.011 and 0.016 pound of VC per year, respectively. The remaining 11 extraction wells, all having production rates less than 0.01 pound of VC per year, are removing virtually no VC mass. Therefore, the extraction and treatment system at OU1 is not an effective means of removing the little remaining VC mass from groundwater.

It is likely that very little contaminant mass was present in groundwater at OU1, prior to installation and operation of the groundwater extraction and treatment system. Since 1994, the system has probably removed less than 3 pounds of VC from the subsurface. Examination of the results of the most recent groundwater monitoring event (July-August 2000) indicates that the concentrations of VC remaining in groundwater are currently at or near the 2 µg/L MCL for VC throughout OU1. The low concentrations of *cis*-1,2-DCE and VC detected in groundwater samples from monitoring wells, and in extraction-well effluent, indicate that very little contaminant mass remains in the subsurface at OU1. Although reductive dechlorination of TCE and *cis*-1,2-DCE will continue to produce low concentrations of VC in groundwater at OU1, the slow rate of VC generation suggests that significant expansion of the VC plume accompanied by migration of VC at detectable concentrations to downgradient receptors, will probably not occur.

Inspection of the locations of groundwater extraction wells at OU1 relative to the dissolved VC plume indicates that none of the extraction wells is located within that part of the plume containing the highest concentrations of VC (near monitoring wells JMM-2 and JMM-22, having VC concentrations of 3.3 µg/L and 3.6 µg/L, respectively). Some very limited increase in the rate of mass removal at OU1 could possibly be realized by extracting groundwater only from the area near monitoring wells JMM-2 and JMM-22. Extraction wells operating throughout most of the VC area of attainment are not contributing significantly to removal of VC mass, and are producing water having non-detectable (or very low) concentrations of contaminants (Tables 3.2 and 6.2). Although water produced from these wells is essentially “clean”, it is nevertheless being extracted, treated and discharged to the injection wells.

6.2.2.2 Plume Containment

Comparison of the historic extent of VC in groundwater with the current extent of the VC plume (Figure 6.1) indicates that the extent of VC in groundwater at OU1 has decreased substantially since 1992/1993. Examination of the current distribution of VC in groundwater (Figure 6.1) indicates that VC is present in groundwater, at concentrations that exceed the MCL for VC, only in a restricted part of OU1 near monitoring wells JMM-2 and JMM-22; and the concentrations of VC remaining in groundwater are currently near or below the 2 µg/L MCL for VC throughout the rest of OU1. Therefore, continued operation of the groundwater extraction and treatment system at OU1, in its current configuration or at current extraction rates, is probably unnecessary; and the rates of groundwater extraction can probably be reduced.

TABLE 6.3
RELATIVE EFFECTIVENESS OF INDIVIDUAL OU1 EXTRACTION WELLS
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DISTRIBUTION DEPOT HILL, UTAH

Extraction Well	Approximate Removal Rate of Vinyl Chloride (lbs/yr)	Relative Effectiveness		
		Effective ^{a/}	Marginal ^{b/}	Poor ^{c/}
EW-1	0.011			✓
EW-2	0.003			✓
EW-3	0.008			✓
EW-4	0.016			✓
EW-5	0.005			✓
EW-6	0.027			✓
EW-7	0.027			✓
EW-8	0.006			✓
EW-9	0.004			✓
EW-10	0.002			✓
EW-11	0.001			✓
EW-12	0.003			✓
EW-13	0.003			✓
EW-14	0.004			✓
EW-15	0.003			✓
EW-16	0.022			✓

^{a/} Individual well that removes VC at a rate of 1 pound per year (lb/yr) or greater.

^{b/} Individual well that removes VC at a rate between 0.1 and 1 lb/yr.

^{c/} Individual well that removes VC at a rate less than 0.1 lb/yr.

The characteristics of plume migration can be evaluated by examining changes in the areal distribution of COCs through time, or by examining changes in the concentrations of COCs through time at individual well locations within or downgradient from a plume. Vinyl chloride is the primary COC in groundwater at OU1. The effectiveness of the complete OU1 groundwater extraction system in containing the dissolved VC plume can be evaluated by assessing changes in VC concentrations through time at downgradient monitoring wells. As described in Section 6.2.2.1, temporal trends in VC concentrations were reviewed for groundwater monitoring wells within and near the area of attainment at OU1. In general, VC concentrations in groundwater samples either exhibit no trend, or exhibit temporal trends of decreasing concentrations. In addition to the reduction in the size of the VC plume, the concentrations of COCs in groundwater at locations downgradient from the VC area of attainment are near or below detection limits, suggesting that migration of VC at detectable concentrations to downgradient receptors, will probably not occur. Therefore, although it is not clear that the observed decreases in VC concentrations are solely a result of active groundwater extraction, or whether much of the decrease may be a consequence of attenuation processes, the current groundwater extraction system, in conjunction with attenuation processes, is effectively containing the plume, and is limiting or preventing continued migration of VC in groundwater.

The effectiveness of individual extraction wells can also be examined. An individual EW is regarded as effective in limiting VOC migration if all of the following conditions are met:

- The well is located on a groundwater flowpath downgradient from areas within which VOCs are present in groundwater at concentrations that are higher than in areas downgradient from the well;
- The “capture zone” of the well (i.e., the area within which VOCs will be drawn toward the well as a consequence of pumping, rather than past the well with ambient groundwater flow) is adequate to intercept migrating VOCs; and
- VOC concentrations in groundwater downgradient from the well decrease or remain stable through time.

The radius of capture of each extraction well, and the capture zone of the complete extraction system, were evaluated using the QuickFlowTM analytical groundwater flow model (Geraghty & Miller, Inc., 1991). QuickFlowTM is an interactive analytical model that simulates two-dimensional groundwater flow, under steady-state or transient conditions. The model may be used to delineate capture zones, and is capable of simulating the hydraulic effects of extraction and/or injection wells over a groundwater flow field having a uniform hydraulic gradient and direction of groundwater flow.

Analytical techniques for evaluating the capture zones of groundwater extraction wells are relatively simplistic, and do not account for aquifer heterogeneities or spatial changes in hydraulic gradient. Nevertheless, an assessment of this type provides a means of evaluating the relative effectiveness of an extraction system in limiting chemical migration. The radius of capture for a particular extraction well depends on the well pumping rate, the aquifer hydraulic conductivity, the natural (steady-state) groundwater

hydraulic gradient and flow direction in the vicinity of the well, and the saturated thickness of the aquifer.

Rates of groundwater extraction and injection were recorded during system evaluations in June 1998 and June 1999 (Kleinfelder, 2000). These were assumed to be representative of long-term rates of extraction/injection for the purpose of evaluating groundwater capture zones; and the averages of the two extraction/injection rates recorded for each well were used in QuickFlowTM simulations (Table 6.4). The groundwater flow direction and hydraulic gradient at OU1 were estimated from potentiometric-surface maps generated during the RI/FS (Montgomery, 1991), and from more recent maps (July 1998 and July 1999) generated for the project close-out report (Kleinfelder, 2000). The configuration of the water table (Figures 2.14 and 2.15) was found to be generally consistent through time, with a flow direction toward the northwest, and a gradient of 0.0022 ft/ft.

Analytical solutions (including QuickFlowTM) that are used to evaluate conditions in groundwater systems typically utilize the property of “transmissivity” (the product of hydraulic conductivity and saturated thickness) to characterize the hydraulics of the system. Site-specific values of hydraulic conductivity were estimated from the results of well-displacement (“slug”) testing of 21 wells in and near OU1, conducted during the RI/FS (Montgomery, 1991). The arithmetic average of the 21 hydraulic conductivity values (75.4 ft/day) was used as a representative hydraulic conductivity during initial simulations of the shallow water-bearing unit at OU1. Information from boring logs at OU1 and nearby OU4 indicated that the average saturated thickness of the shallow water-bearing unit is approximately 17 feet (Table 6.4). The average values of hydraulic conductivity and saturated thickness of the water-bearing unit at OU1 were used to generate an initial estimate of transmissivity (1,300 square feet per day [ft²/day]) for use in QuickFlowTM simulations.

An initial simulation was completed (Figure 6.5), using long-term average pumping rates, and the estimated average transmissivity of the shallow groundwater system at OU1 (1,300 ft²/day), to generate an estimate of the extent of the capture zone that might result from pumping the 16 extraction wells at OU1 during the 5-year period of historic system operation (from 1995 through 1999). The results of the initial simulation were then compared with historic conditions at OU1. A distinct depression in the water table, probably due to operation of the groundwater extraction system, is apparent in the configuration of the actual potentiometric surface at OU1 (Figure 2.15), based on water-level measurements collected while the extraction system was in full operation in July 2000. A comparison of the historic potentiometric surface (Figure 2.15) with the results of initial simulations (Figure 6.5) indicates that the historic depression in the water table was much larger than the depression that resulted from the model simulation. This suggested that use of different values of hydraulic parameters (e.g., transmissivity) might be appropriate, to better reproduce actual conditions in the groundwater system.

The value of transmissivity used in the QuickFlowTM model was varied within a limited range in an attempt to approximate site conditions. Potentiometric contours and capture zones were generated using a value of transmissivity somewhat lower than the estimated average transmissivity (510 ft²/day, corresponding to a hydraulic conductivity value of 30 ft/day), and using a value of transmissivity somewhat higher than the

TABLE 6.4
HISTORIC PRODUCTION RATES OF GROUNDWATER EXTRACTION/INJECTION WELLS
OPERABLE UNIT 1
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Extraction Well	Approximate Screened Interval (ft bgs) ^{a/}	Approximate Saturated Thickness (feet)	Design Production Rate (gpm) ^{b/}	Actual Production Discharge Rate (Date)		Average Extraction Rate (1998 - 1999) (gpm)
				6/98 (gpm)	6/99 (gpm)	
EW-1	10 - 25	17	No Data	3.3	7.3	5.3
EW-2	10 - 25	17	No Data	5.4	6.2	5.8
EW-3	10 - 25	17	No Data	4.3	9.8	7.1
EW-4	10 - 25	17	No Data	3.9	4.4	4.2
EW-5	10 - 25	17	No Data	1.6	12.4	7.0
EW-6	10 - 25	17	No Data	4.7	9.1	6.9
EW-7	10 - 25	17	No Data	0.0	7.0	3.5
EW-8	10 - 25	17	No Data	0.0	7.6	3.8
EW-9	10 - 25	17	No Data	0.0	8.1	4.0
EW-10	10 - 25	17	No Data	0.0	4.1	2.1
EW-11	10 - 25	17	No Data	1.7	3.6	2.6
EW-12	10 - 25	17	No Data	2.6	4.3	3.5
EW-13	10 - 25	17	No Data	0.0	5.2	2.6
EW-14	10 - 25	17	No Data	1.5	6.1	3.8
EW-15	10 - 25	17	No Data	2.3	7.5	4.9
EW-16	10 - 25	17	No Data	6.7	9.2	7.9

Injection Well	Approximate Screened Interval (ft bgs) ^{a/}	Approximate Saturated Thickness (feet)	Design Injection Rate (gpm) ^{b/}	Actual Injection Rate (Date)		Average Injection Rate (1998 - 1999) (gpm)
				6/98 (gpm)	6/99 (gpm)	
IW-1	10 - 25	17	No Data	4.6	6.3	5.5
IW-2	10 - 25	17	No Data	0.2	2.0	1.1
IW-3	10 - 25	17	No Data	0.5	4.8	2.6
IW-4	10 - 25	17	No Data	3.3	0.0	1.7
IW-5	10 - 25	17	No Data	1.2	5.7	3.4
IW-6	10 - 25	17	No Data	0.1	2.2	1.1
IW-7	10 - 25	17	No Data	3.0	6.7	4.8
IW-8	10 - 25	17	No Data	4.4	10.3	7.3
IW-9	10 - 25	17	No Data	3.4	8.7	6.1
IW-10	10 - 25	17	No Data	1.0	1.0	1.0
IW-11	10 - 25	17	No Data	3.2	10.4	6.8
IW-12	10 - 25	17	No Data	3.6	11.0	7.3
IW-13	10 - 25	17	No Data	3.2	6.0	4.6
IW-14	10 - 25	17	No Data	1.3	9.8	5.5
IW-15	10 - 25	17	No Data	3.9	15.6	9.7
IW-16	10 - 25	17	No Data	0.0	1.5	0.8

^{a/} ft bgs = feet below ground surface.

^{b/} gpm = gallons per minute.

Figure 6.5 Capture-Zone Simulation (1,300 ft²/day Transmissivity)

estimated average transmissivity (1,700 ft²/day, corresponding to a hydraulic conductivity value of 100 ft/day). The results of these simulations (Figures 6.6 and 6.7, respectively) were then compared with the historic configuration of the actual groundwater potentiometric surface at OU1 (Figure 2.15).

The potentiometric surface and capture zone resulting from use of a transmissivity of 510 ft²/day (Figure 6.6) appeared to be the most representative of the three simulations, and best replicated actual conditions (Figure 2.15). The transmissivity value of 510 ft²/day therefore was considered representative of hydrogeologic conditions at OU1, and was used in subsequent simulations to evaluate alternative groundwater extraction systems having different configurations. The configuration of the extraction/injection wellfield was altered in subsequent QuickFlow™ simulations so that only the wells in the immediate vicinity of the VC plume remained in operation, in order to assess whether the effectiveness of hydraulic capture/containment of the VC plume at OU1 could be maintained with fewer extraction wells, and/or with different pumping rates. Two different wellfield configurations, using two and three wells, were examined. In simulations utilizing two extraction wells (Figure 6.8), most of the VC plume was contained within the capture zone, but minor amounts of groundwater containing VC in the eastern part of the plume were not captured by the extraction system. However, an alternative extraction system using three of the existing extraction wells (wells EW-5, EW-6, and EW-16), operating at extraction rates of 5.20 gallons per minute (gpm) at each well (Tables 6.4 and 6.5) appears to be effective in capturing the VC plume (Figure 6.9), and could be implemented at OU1. This alternative system would be most effective if treated groundwater were injected at downgradient locations (e.g., injection wells IW-1, IW-2, IW-3, IW-4, IW-5, and IW-6), thereby reducing the local hydraulic gradient and increasing the capture zone of the extraction wellfield. Operation of the three-well system at extraction rates of 5.20 gpm at each of the three wells would be sufficient to capture/contain the VC plume at OU1 (Figure 6.9; Table 6.5).

6.2.3 Evaluation of Effectiveness of Current Treatment System

Groundwater extracted from the subsurface at OU1 is treated by passing it through an air-stripping tower to remove VOCs prior to reinjecting the water to the groundwater system by means of 16 injection wells located around the perimeter of OU1 (as defined by the 2 µg/L VC isoconcentration contour that was current in 1992). The results of analyses of water samples collected from the influent and effluent lines of the treatment plant (Kleinfelder, Inc., 2000) indicate that concentrations of *cis*-1,2-DCE (less than 3.0 µg/L) and VC (less than 1 µg/L) in water influent to the treatment plant are currently below the plant discharge limits specified in the ROD (70 µg/L for *cis*-1,2-DCE and 2 µg/L for VC). The concentrations of both compounds in the treated effluent are below method detection limits.

Based on the non-detection of COCs in treatment-plant effluent, the OU1 treatment system is meeting the treatment performance criterion (*Discharge Objective* in Table 6.1). However, the highest concentration of *cis*-1,2-DCE detected in any groundwater sample collected from the 16 extraction wells that were sampled during the event of July and August, 2000, was 5.6 µg/L (compare with the MCL for *cis*-1,2-DCE of 70 µg/L). The highest VC concentration in any groundwater sample collected from the 16 extraction wells was 1.0 µg/L (compare with the MCL for VC of 2 µg/L). The low

Figure 6.6 Capture-Zone Simulation (510 ft²/day Transmissivity)

Figure 6.7 Capture-Zone Simulation (1,700 ft²/day Transmissivity)

Figure 6.8 Simulated Capture Zone – Two-Well Configuration

TABLE 6.5
OPTIMIZED GROUNDWATER EXTRACTION/INJECTION SYSTEM
OPERABLE UNIT 1
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Extraction Well	Approximate Screened Interval (ft bgs)^{a/}	Approximate Saturated Thickness (feet)	Design Production Rate (gpm)^{b/}	Historic Average Extraction Rate (1998 - 2000) (gpm)	Optimized Extraction Rate (gpm)
EW-5	10 - 25	17	No Data	7.0	5.2
EW-6	10 - 25	17	No Data	6.9	5.2
EW-16	10 - 25	17	No Data	7.9	5.2
Injection Well	Approximate Screened Interval (ft bgs)^{a/}	Approximate Saturated Thickness (feet)	Design Injection Rate (gpm)^{b/}	Historic Average Injection Rate (1998 - 2000) (gpm)	Optimized Injection Rate (gpm)
IW-1	10 - 25	17	No Data	5.5	5.5
IW-2	10 - 25	17	No Data	1.1	1.1
IW-3	10 - 25	17	No Data	2.6	2.6
IW-4	10 - 25	17	No Data	1.7	1.7
IW-5	10 - 25	17	No Data	3.4	3.4
IW-6	10 - 25	17	No Data	1.1	1.3

^{a/} ft bgs = feet below ground surface.

^{b/} gpm = gallons per minute.

Figure 6.9 Simulated Capture Zone – Three-Well Configuration

concentrations of *cis*-1,2-DCE and VC in extracted groundwater influent to the treatment plant indicate that treatment of groundwater extracted using the current extraction well configuration, operating at the current pumping rates, is not required. If the configuration of the groundwater extraction system were altered so as to remove groundwater in the vicinity of monitoring wells JMM-2 and JMM-22 only, treatment might be required to meet discharge criteria because the most recently detected concentrations of VC in groundwater samples from wells JMM-2 and JMM-22 were 3.3 and 3.6 µg/L respectively (Table 3.2). A short-term pumping test could be conducted by extracting groundwater directly from JMM-2 and JMM-22, to evaluate whether treatment plant operation would need to continue if the configuration of the extraction well system were optimized to extract groundwater only from the most contaminated part of the area of attainment (preceding section).

6.2.4 Evaluation of OU1 Groundwater Monitoring Program

Groundwater monitoring programs have two primary objectives (USEPA, 1993; Gibbons, 1994):

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

The relative success of any remediation system and its components (including the monitoring network) must be judged based on its ability to achieve the stated objectives of the system. Designing an effective groundwater monitoring program involves locating monitoring points and developing a site-specific strategy for groundwater sampling and analysis so as to maximize the amount of relevant information that can be obtained while minimizing incremental costs. Relevant information is that required to effectively address the temporal and spatial objectives of monitoring. The effectiveness of a monitoring network in achieving these two primary objectives can be evaluated quantitatively using statistical techniques. In addition, there may be other important considerations associated with a particular monitoring network that are most appropriately addressed through a qualitative hydrogeologic evaluation of the network. The qualitative evaluation may consider such factors as hydrostratigraphy, locations of potential receptors with respect to a dissolved plume, and the direction(s) and rate(s) of contaminant migration. The evaluation of a monitoring network is therefore conducted in stages to address each of the objectives and considerations of monitoring: a qualitative evaluation is first completed, followed in succession by temporal and spatial evaluations.

6.2.4.1 Qualitative Hydrogeologic Evaluation

An effective monitoring program will provide information regarding plume migration and changes in chemical concentrations through time at appropriate locations, enabling decision-makers to verify that contaminants are not endangering potential receptors, and that remediation is occurring at rates sufficient to achieve RAOs. The design of the monitoring program should therefore include consideration of existing receptor exposure

pathways, as well as exposure pathways arising from potential future use of the groundwater.

Performance monitoring wells located upgradient, within, and just downgradient from a plume provide a means of evaluating system effectiveness relative to performance criteria. Long-term monitoring (LTM) of these wells also provides information about migration of the plume and temporal trends in chemical concentrations. Contingency monitoring wells downgradient from the plume are used to ensure that the plume is not expanding past the remediation zone or containment system, and to trigger a contingency remedy if contaminants are detected. Primary factors to consider include at a minimum:

- Types of contaminants,
- Aquifer heterogeneity,
- Distance to potential receptor exposure points,
- Groundwater seepage velocity,
- Potential surface-water impacts, and
- The effects of the remediation system.

These factors will influence the locations and spacing of monitoring points and the sampling frequency. Typically, the greater the seepage velocity and the shorter the distance to receptor exposure points, the more frequently groundwater sampling should be conducted. One of the most important purposes of LTM is to confirm that the contaminant plume is behaving as predicted. Visual and statistical tests can be used to evaluate plume stability. If a groundwater remediation system is effective, then over the long term, groundwater monitoring data should demonstrate a clear and meaningful decreasing trend in concentrations at appropriate monitoring points.

Monitoring is conducted periodically at DDHU OU1 to provide information regarding chemical and hydraulic (gradient) conditions within and downgradient from the contaminant plume (Section 2.7.2). The groundwater monitoring program is intended to provide water-level and analytical data for use in ensuring compliance with requirements of the ROD (JMM, 1992a), and for evaluating the overall effectiveness of the extraction system. The components of the groundwater monitoring program include:

- **Compliance monitoring.** This component of the monitoring program is used to assess periodically the water quality of the shallow aquifer, in order to evaluate whether cleanup criteria are being/have been achieved and maintained.
- **Water-level monitoring.** This component of the monitoring program is used to evaluate whether the groundwater contaminant plume is hydraulically contained by the groundwater extraction system.
- **Treatment system performance monitoring.** The purpose of this component of the monitoring program is to assess performance of the treatment system and to

monitor the quality of the water exiting the treatment system for aquifer re-injection.

Currently, groundwater samples are collected for monitoring purposes, using conventional-purge sampling methods, from a total of 15 monitoring wells at OU1 (Table 6.6) (JMM, 1993a). Groundwater samples from all wells are analyzed for VOCs using USEPA Method SW8260B. In addition to collection of samples from monitoring wells, key components of the groundwater extraction system at OU1 are also monitored, enabling overall system performance to be evaluated periodically. Monitoring of the extraction and treatment system may include collection of groundwater samples from any of four sampling ports within the system during monthly monitoring events (Table 6.6), and analysis of those samples for VOCs.

The estimated annual costs associated with the current groundwater monitoring program, are summarized in Table 6.7. As a consequence of the absence of a discernible trend in VC concentrations in groundwater samples from wells JMM-2 and JMM-22 within the area of attainment at OU1 (Section 6.2.2.1), it is not possible to estimate the length of time that will be required to meet the *Cleanup Objective* specified in the ROD (Item 2 in Table 6.1). For the purpose of generating cost estimates, Parsons assumed that an additional 10-year period will be required to achieve the *Cleanup Objective*. Assuming that the current monitoring program is continued for an additional 10 years, the cumulative cost of the monitoring program (in constant 2000 dollars) is estimated to be approximately \$720,000 (Table 6.7).

The direction of groundwater movement beneath OU1 has historically been from southeast to northwest (Section 2.3.3). Therefore, in the absence of active groundwater extraction, migration of contaminants from sources in OU1 also would be generally toward the northwest, and contaminants dissolved in groundwater at OU1 would eventually migrate past the western boundary of DDHU. However, the area near wells JMM-2 and JMM-22, within which VC concentrations in groundwater remain above 2 µg/L, is restricted in extent. If migration of VC from this area were to continue in the absence of active extraction, the concentrations would probably be diluted to levels below the MCL for VC (2 µg/L) within a very short distance downgradient.

In either situation (no extraction, or active groundwater extraction and treatment) virtually all contaminant mass in groundwater at OU1 will remain on the facility. This suggests that although periodic monitoring of groundwater conditions should be continued to address the two objectives of monitoring listed above, the frequency of monitoring at most locations could be reduced from semiannual to annual monitoring (Table 6.6), with little loss of information and no increase in risk to potential receptors.

Examination of the list of groundwater monitoring wells included in the periodic monitoring program suggests that some sampling points may be redundant or unnecessary. For example, groundwater samples are collected from monitoring wells JMM-20 and JMM-48, located upgradient from the VOC plume in OU1 (Figure 2.11). TCE, *cis*-1,2-DCE, and VC have historically not been detected in groundwater samples from these wells. Other wells at locations upgradient or crossgradient from the VOC source areas at OU1 are also candidates for abandonment, because the direction of

TABLE 6.6
CURRENT GROUNDWATER MONITORING PROGRAM^{a/}
OPERABLE UNIT 1
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Monitoring Point	Operable Unit	Field Analyses					Laboratory Analyses
		Temperature ^{b/}	Dissolved Oxygen ^{b/}	pH ^{b/}	ORP ^{b,c/}	Specific Conductance ^{b/}	VOCs ^{d/} (Method SW8260B)
AEHA-9	OU1 Plume	✓	✓	✓	✓	✓	✓
ESE-15	OU1 Downgradient	✓	✓	✓	✓	✓	✓
JMM-3	OU1 Downgradient	✓	✓	✓	✓	✓	✓
JMM-6	OU1 Cross Gradient	✓	✓	✓	✓	✓	✓
JMM-17	OU1 Downgradient	✓	✓	✓	✓	✓	✓
JMM-19	OU1 Upgradient	✓	✓	✓	✓	✓	✓
JMM-20	OU1 Upgradient	✓	✓	✓	✓	✓	✓
JMM-22	OU1 Plume	✓	✓	✓	✓	✓	✓
JMM-29	OU1 Downgradient	✓	✓	✓	✓	✓	✓
JMM-47	OU1 Cross Gradient	✓	✓	✓	✓	✓	✓
JMM-48	OU1 Cross Gradient	✓	✓	✓	✓	✓	✓
JMM-59	OU1 Plume	✓	✓	✓	✓	✓	✓
JMM-60	OU1 Upgradient	✓	✓	✓	✓	✓	✓
JMM-62	OU1 Cross Gradient	✓	✓	✓	✓	✓	✓
JMM-63	OU1 Downgradient	✓	✓	✓	✓	✓	✓
Effluent Port	OU1 Treatment System	✓	✓	✓	✓	✓	✓

^{a/} "Current" groundwater sampling event -- July 2000.

^{b/} direct-reading meter.

^{c/} ORP = oxidation-reduction potential.

^{d/} VOCs = volatile organic compounds.

TABLE 6.7
ESTIMATED COSTS ASSOCIATED WITH CURRENT MONITORING PROGRAM^{a/}
OPERABLE UNIT 1
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

15 Wells Sampled Semiannually				
Cost type	Quantity	Units	Unit Cost	Cost
Labor for sample collection				
1 person at \$65/hr	80	hours	\$ 65.00	\$ 5,200.00
Labor for data validation and data management				
1 person at \$65/hr	30	hours	\$ 65.00	\$ 1,950.00
Reporting				
150 hours at \$80/hr	150	hours	\$ 80.00	\$ 12,000.00
Laboratory Analyses				
VOCs by Method 8260B (primary samples + QA/QC)	16	Samples	\$ 150.00	\$ 2,400.00
Other Direct Costs				
Equipment rental (PID, pH/Eh, O ₂ /CO ₂ , etc.)	5	days	\$ 400.00	\$ 2,000.00
Vehicle Rental (1 vehicle for 1 day)	5	days	\$ 55.00	\$ 275.00
Miscellaneous Field Supplies				\$ 50.00
SUBTOTAL SEMIANNUAL COST				\$ 23,875.00
Monthly Treatment Plant Effluent Sampling				
Cost type	Quantity	Units	Unit Cost	Cost
Labor for sample collection				
1 person at \$65/hr	4	hours	\$ 65.00	\$ 260.00
Labor for data validation and data management				
1 person at \$65/hr	2	hours	\$ 65.00	\$ 130.00
Reporting				
10 hours at \$80/hr	10	hours	\$ 80.00	\$ 800.00
Laboratory Analyses				
VOCs by Method 8260B (primary samples + QA/QC)	2	Samples	\$ 150.00	\$ 300.00
Other Direct Costs				
Equipment rental (PID, pH/Eh, O ₂ /CO ₂ , etc.)	1	day	\$ 400.00	\$ 400.00
Vehicle Rental (1 vehicle for 1 day)	1	day	\$ 55.00	\$ 55.00
Miscellaneous Field Supplies				\$ 50.00
SUBTOTAL MONTHLY COST				\$ 1,995.00
Total Annual Cost				\$ 71,690.00
Long Term Monitoring for 10 years:			Total OU1 Program Cost	\$716,900.00

^{a/} Estimated by Parsons ES based on current (third quarter 2000) sampling program (Table 6.6).

groundwater flow, under natural conditions or with active groundwater extraction, is such that migration of VOCs into these areas will not occur.

Multiple wells completed in the shallow water-bearing unit at similar locations also represent potentially redundant monitoring points. For example, well JMM-29 is completed in the northwestern part of the VOC plume, less than 200 feet north of well MW-54. Both wells are routinely monitored, although use of one well would probably provide sufficient information for the purposes of satisfying the two primary objectives of monitoring (above). Therefore, one of the two wells may be a candidate for abandonment.

Active groundwater EWs require additional consideration. Because an EW withdraws groundwater from some volume of the groundwater system surrounding the well, the concentration of a constituent in the effluent discharged from the well cannot be regarded as representative of conditions at the well location. Rather, the constituent concentration is an average value, representative of concentrations throughout the volume from which the well extracts groundwater. Therefore, the results of monitoring effluent from an EW should not generally be used as indicators of local chemical conditions. However, periodic monitoring of EW discharge can provide an indication of the rate of removal of chemical mass from the subsurface, and as such generates information of use in evaluating long-term performance of the extraction (and treatment) system. Therefore, periodic monitoring of EW discharge should continue in those wells within the extraction network that remain in active service. However, if an EW is removed from service (e.g., well EW-1 in OU1), it should no longer be used for monitoring.

The results of the qualitative evaluation of the complete monitoring network at OU 1 are presented in Table 6.8. Recommendations for retaining or abandoning each existing monitoring point in OU1 also are presented in Table 6.8, together with the rationale for the recommendations.

6.2.4.2 Temporal Statistical Evaluation

Temporal data (chemical concentrations measured at different points in time) can be examined visually (Figure 6.2), or with statistical tests, to evaluate plume stability. If removal of chemical mass is occurring in the subsurface as a consequence of attenuation processes or operation of the remediation system, mass removal will be apparent as a decrease in chemical concentrations through time at a particular sampling location, as a decrease in chemical concentrations with increasing distance from chemical source areas, and/or as a change in the suite of chemicals through time or with increasing migration distance.

Temporal chemical-concentration data can be evaluated by plotting contaminant concentrations through time for individual monitoring wells (Figure 6.2), or by plotting contaminant concentrations versus downgradient distance from the contaminant source for several wells along the groundwater flowpath, over several monitoring events. Plotting temporal concentration data is recommended for any analysis of plume stability evaluation (Wiedemeier and Haas, 1999); however, visual identification of trends in plotted data may be a subjective process, particularly (as is likely) if the concentration

TABLE 6.8
QUALITATIVE EVALUATION OF GROUNDWATER MONITORING NETWORK
OPERABLE UNIT 1
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Monitoring Point	Elevation ^{a/} Top of Screen (feet)	Elevation ^{a/} Bottom of Screen (feet)	Monitoring Zone ^{b/}	Abandon/Retain		Rationale for Well to be Retained or Abandoned
				Abandon	Retain	
AEHA-9	4245.31	4235.31	Unit 2		✓	Samples shallow water-bearing unit within VC area of attainment.
ESE-15	4244.77	4239.77	Unit 2	✓		Too far downgradient and no contaminants are found in nearby wells.
JMM-3	4242.22	4237.22	Unit 2		✓	Needed to monitor downgradient plume migration.
JMM-6	4226.44	4221.44	Unit 2	✓		Too far cross/downgradient and no contaminants are found in nearby wells.
JMM-17	4240.64	4235.64	Unit 2		✓	Needed to monitor downgradient plume migration.
JMM-19	4240.97	4235.97	Unit 2		✓	Samples shallow water-bearing unit within VC area of attainment.
JMM-20	4252.11	4247.11	Unit 2	✓		Well is too far upgradient from area of elevated VC concentrations.
JMM-22	4228.03	4223.03	Unit 2		✓	Samples shallow water-bearing unit within VC area of attainment.
JMM-29	4235.42	4230.42	Unit 2	✓		Too far downgradient and no contaminants are found in closer wells.
JMM-47	4243.94	4238.94	Unit 2		✓	Samples shallow water-bearing unit within VC area of attainment.
JMM-48	4246.34	4241.34	Unit 2	✓		Well is too far away and crossgradient from source.
JMM-59	4251.8	4246.8	Unit 2		✓	Samples shallow water-bearing unit within VC area of attainment.
JMM-60	4245.58	4240.58	Unit 2		✓	Samples shallow water-bearing unit within VC area of attainment.
JMM-62	4241.26	4236.26	Unit 2	✓		Too far cross/downgradient and no contaminants are found in nearby wells.
JMM-63	4239.92	4234.92	Unit 2	✓		Too far downgradient and no contaminants are found in nearby wells.

^{a/} Elevations referenced to mean sea level.

^{b/} "Unit 2" monitoring zone is uppermost (shallow) water-bearing unit at DDHU OU1.

data do not have a uniform trend, but are variable through time as in the case of JMM-22 at OU1 (Figure 6.2).

The possibility of arriving at incorrect conclusions regarding plume stability on the basis of visual examination of temporal concentration data can be reduced by examining temporal trends in chemical concentrations using various statistical procedures, including the Mann-Kendall regression analyses test for trends. The Mann-Kendall non-parametric test (Gibbons, 1994) is well suited for application to the evaluation of environmental data because the sample size can be small (as few as four data points), no assumptions are made regarding the underlying statistical distribution of the data, and the test can be adapted to account for seasonal variations in the data. The Mann-Kendall test statistic can be calculated at a specified level of confidence to evaluate whether a temporal trend is present in contaminant concentrations detected through time in samples from an individual well. If a trend is determined to be present, a non-parametric slope of the trend line (change per unit time) can also be estimated using the test procedure. A negative slope (indicating decreasing contaminant concentrations through time) or a positive slope (increasing concentrations through time) provides statistical confirmation of temporal trends that may have been identified visually (Figure 6.10).

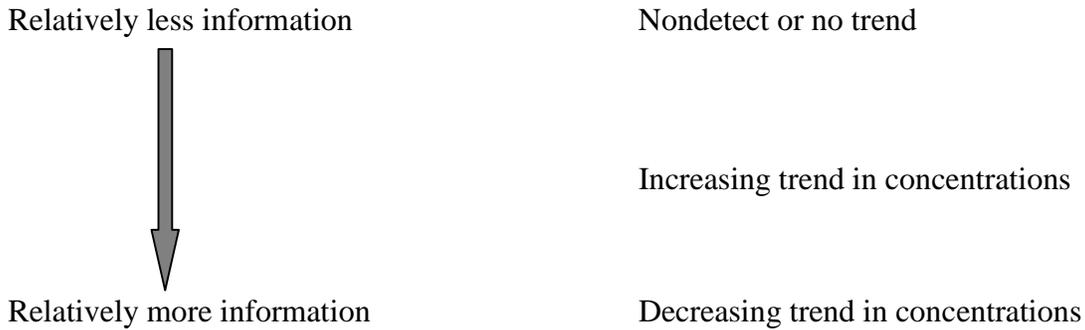
The amount and quality of information obtained from periodic monitoring at a particular monitoring well can be evaluated by considering the location of the well within (or outside of) the contaminant plume, the location of the well with respect to potential receptor exposure points, and the presence or absence of temporal trends in contaminant concentrations in samples collected from the well. The degree to which the amount and quality of information obtainable at a particular monitoring point serves the two primary objectives of monitoring (temporal and spatial objectives) must be considered in this evaluation. For example, the continued evaluation of a contaminant in groundwater at concentrations below the detection limit at a monitoring location provides no information about temporal trends in contaminant concentrations, or about the extent to which contaminant migration is occurring, unless the monitoring location lies along a groundwater flowpath between a contaminant source and a potential receptor exposure point. Therefore, a monitoring well having a history of contaminant concentrations below detection limits may be providing no useful information, depending on its location.

A trend of increasing contaminant concentrations in groundwater at a location between a contaminant source and a potential receptor exposure point may represent information critical in evaluating whether contaminants may migrate to the exposure point, thereby completing an exposure pathway. Identification of a trend of decreasing contaminant concentrations at the same location may be useful in evaluating decreases in the areal extent of a plume, but does not represent information that is critical to the protection of a potential receptor. Similarly, a trend of decreasing contaminant concentrations in groundwater near a contaminant source may represent important information regarding the progress of remediation near, and downgradient of the source, while identification of a trend of increasing contaminant concentrations at the same location does not provide as much useful information regarding contaminant conditions. In contrast, the absence of a temporal trend in contaminant concentrations at a particular location within, or downgradient of a plume, indicates that virtually no additional information can be obtained by continued monitoring of groundwater at that location, in that the results of continued monitoring through time are likely to fall within the historic range of

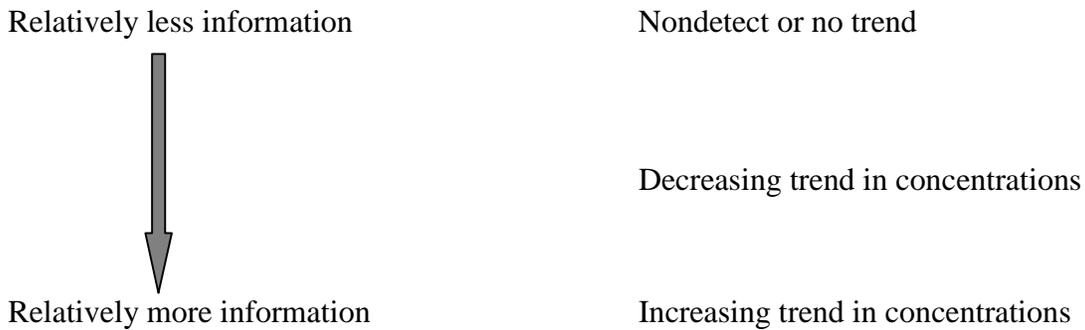
Figure 6.10 Conceptual Representation of Temporal Trends and Temporal Variations in Concentrations

concentrations that have already been detected. Continued monitoring at locations where no temporal trend in contaminant concentrations is present serves merely to confirm the results of previous monitoring activities at that location. The relative amounts of information generated by the results of temporal trend evaluation at monitoring points near, upgradient of, and downgradient from contaminant sources are presented schematically below:

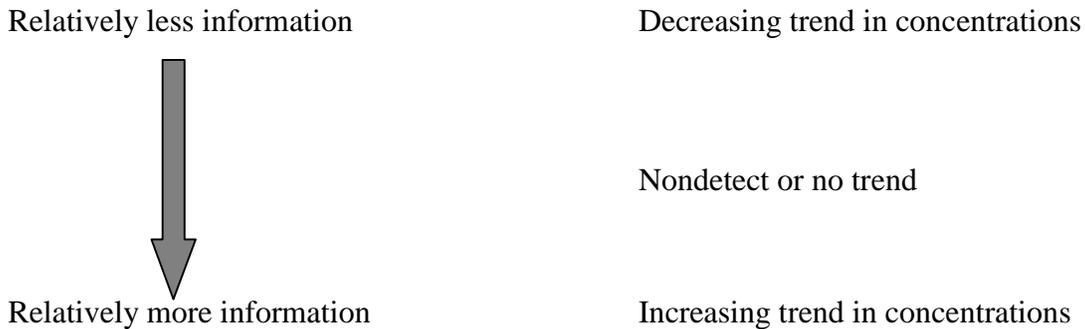
Monitoring Point Near Contaminant Source



Monitoring Point Upgradient from Contaminant Source



Monitoring Point Downgradient from Contaminant Source



Three VOCs (TCE, *cis*-1,2-DCE, and vinyl chloride) have been detected historically in groundwater samples from one or more monitoring wells at OU1, at concentrations that exceed the MCLs for the compounds, and at frequencies in excess of about 5 percent (Section 3.1). The monitoring results for each of the three VOCs detected in each well in

the current monitoring program were examined for trends using the Mann-Kendall test (Table 6.9). The objective of the evaluation was to identify those wells having increasing or decreasing concentration trends for each VOC, and to consider the quality of information represented by the existence or absence of concentration trends in terms of the location of each monitoring point.

The results of Mann-Kendall temporal trend analyses for the three VOCs (TCE, Figure 6.11, *cis*-1,2-DCE, Figure 6.12; and VC, Figure 6.13) enable areas of the VOC plume within which chemical concentrations are increasing, decreasing, or stable to be readily identified. Summary results of the temporal trend analyses are presented in Table 6.9. Color coding of the table entries denotes the presence/absence of temporal trends, and allows those monitoring points having nondetectable concentrations, decreasing or increasing concentrations, or no discernible trend in concentrations to be readily identified. In general, monitoring points at which chemical concentrations display no discernible temporal trend represent points generating the least amount of useful information. Depending on the location of the monitoring point, consistently nondetected concentrations of chemicals through time can also represent relatively little information. Monitoring points at which one or more of the three VOCs display increasing or decreasing temporal trends in concentrations represent points at which monitoring should probably continue.

6.2.4.3 Spatial Statistical Evaluation

Spatial statistical techniques can also be applied to the design and evaluation of monitoring programs to assess the relative value of data generated during monitoring, and to optimize monitoring networks. The spatial statistical evaluation of the monitoring networks at OU1 and OU4 was conducted using the MAROS software program (AFCEE, 1999), developed by Groundwater Services, Inc for AFCEE. The MAROS tool can be used to evaluate temporal data, but also provides a simple spatial statistical method, based on a weighted "area-of-influence" approach (implemented using Delauney triangulation), for optimizing the locations of monitoring points. Formal decision trees, and user-defined secondary lines of evidence (empirical or modeling results) are also provided, and can be used to evaluate monitoring data and make recommendations for future sampling frequency, monitoring locations, and density of the monitoring network. Users can then apply the results of an evaluation, completed using the MAROS tool, to establish practical and cost-effective compliance monitoring goals for a specific site. MAROS can also be utilized to identify the COCs at the site; determine whether temporal trends in groundwater COC concentration data are statistically significant; evaluate the relative importance of each well in the monitoring network; and identify those wells that are statistically most relevant to the current sampling program. Application of the MAROS tool to the site-specific evaluation of a monitoring network is completely dependent upon the amount and quality of the available data (e.g., data requirements for a temporal trend analysis include a minimum of four distinct sampling events).

Parsons used groundwater monitoring data, collected during the monitoring event of July 2000, to evaluate the spatial distribution of groundwater monitoring wells included in the current groundwater monitoring program. In application, the concentrations of TCE, *cis*-1,2-DCE, and VC detected in groundwater samples from each monitoring well were used in the Delaunay method (as implemented in the MAROS tool) to calculate a

TABLE 6.9
SUMMARY OF TEMPORAL STATISTICAL EVALUATION
OF
CURRENT GROUNDWATER MONITORING PROGRAM^{a/}
OPERABLE UNIT 1
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Monitoring Point	Trichloroethene	cis-1,2-Dichloroethene	Vinyl Chloride
AEHA-9	ND	-	-
ESE-15	ND	ND	ND
JMM-03	ND	ND	ND
JMM-06	ND	-	ND
JMM-17	ND	ND	ND
JMM-19	ND	ND	ND
JMM-20	-	ND	ND
JMM-22	ND	no trend	-
JMM-29	ND	-	no trend
JMM-47	ND	-	-
JMM-48	ND	S	ND
JMM-59	no trend	-	no trend
JMM-60	ND	-	-
JMM-62	ND	-	-
JMM-63	ND	-	ND

^{a/} "Current" groundwater sampling event -- July 2000.

ND	= Concentrations consistently below detection limits.
no trend	= No statistically significant temporal trend in concentration.
+	= Statistically significant increasing trend in concentration.
-	= Statistically significant decreasing trend in concentration.
< 4 meas	= Fewer than four measurements at the monitoring well.
	= No data available for the monitoring well.

Figure 6.11 Mann-Kendall Temporal Trend Analysis for Concentrations of TCE

Figure 6.12 Mann-Kendall Temporal Trend Analysis for Concentrations of *cis*-1,2-DCE

Figure 6.13 Mann-Kendall Temporal Trend Analysis for Concentrations of VC

unitless slope value at each monitoring point; and the slope values for each contaminant were summed to produce a representative slope factor for each monitoring well included in the current monitoring program. The unitless slope factor calculated for each monitoring well represents the relative worth of monitoring data associated with that well in relation to the entire monitoring well field, with higher values of slope factor indicating relatively greater worth; and each monitoring point in the network can be ranked according to the relative value of information generated by sampling at that point (Table 6.10). Wells having a summed slope factor less than about 0.84 are regarded as contributing relatively little information; wells having a slope factor between 0.85 and 1.84 contribute a moderate amount of information; and wells having a slope factor greater than 1.84 contribute the most information to the monitoring program. According to these evaluation criteria, the greatest amount of information (in the spatial sense) is obtained from monitoring wells AEHA-9, JMM-3, JMM-19, JMM-20, JMM-22, and JMM-47 in OU1 (Table 6.10).

6.2.4.4 Summary of Evaluation of OU1 Groundwater Monitoring Network

The existing groundwater monitoring network at OU1, consisting of 15 groundwater monitoring wells from which samples are periodically collected, was evaluated using qualitative hydrogeologic knowledge, temporal statistical techniques, and spatial statistics. At each stage in the evaluation, monitoring points that provided relatively greater amounts of information regarding the occurrence and distribution of VOCs in groundwater were identified, and were distinguished from those monitoring points that provided relatively lesser amounts of information. The results of the qualitative, temporal, and spatial evaluations are summarized in Table 6.11.

The results of evaluations were combined to generate a subset of the monitoring network that could potentially provide information sufficient to address the primary objectives of monitoring, at reduced cost. Wells not retained in the reduced monitoring network could be abandoned, with relatively little loss of information. The results of the evaluation were combined and summarized in accordance with the following algorithm:

1. The effluent of each active EW will be periodically sampled and analyzed. If an EW goes off-line or is otherwise removed from the system, monitoring at that well will cease.
2. Each well retained in the monitoring network on the basis of the qualitative hydrogeologic evaluation is retained in the reduced monitoring network.
3. Each well retained in the monitoring network on the basis of the temporal hydrogeologic evaluation is retained in the reduced monitoring network.
4. The six wells identified during the spatial evaluation of the monitoring network as generating the greatest amount of information for the program (wells AEHA-9, JMM-3, JMM-19, JMM-20, JMM-22, and JMM-47) are retained in any subset of the network that will be used for monitoring.

TABLE 6.10
SUMMARY OF SPATIAL EVALUATION OF CURRENT
GROUNDWATER MONITORING PROGRAM^{a/}
OPERABLE UNIT 1
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Monitoring Point	Operable Unit	Spatial Evaluation			
		TCE ^{c/}	<i>cis</i> -1,2-DCE ^{d/}	VC ^{e/}	Sum ^{f/}
AEHA-9	OU1 Plume	0.238	0.346	0.432	1.02
ESE-15	OU1 Downgradient	0	0.208	0	0.21
JMM-3	OU1 Downgradient	0.117	0.469	0.374	0.96
JMM-6	OU1 Cross Gradient	0.218	0.185	0.297	0.70
JMM-17	OU1 Downgradient	0	0.199	0	0.20
JMM-19	OU1 Upgradient	0.112	0.405	0.34	0.86
JMM-20	OU1 Upgradient	0.512	0.404	0.065	0.98
JMM-22	OU1 Plume	0.214	0.486	0.577	1.28
JMM-29	OU1 Downgradient	0	0.237	0	0.24
JMM-47	OU1 Cross Gradient	0.158	0.481	0.294	0.93
JMM-48	OU1 Cross Gradient	0	0.485	0.186	0.67
JMM-59	OU1 Plume	0.479	0.005	0.355	0.84
JMM-60	OU1 Upgradient	0.216	0.075	0.135	0.43
JMM-62	OU1 Cross Gradient	0	0.103	0.099	0.20
JMM-63	OU1 Downgradient	0	0.283	0	0.28

^{a/} "Current" groundwater sampling event -- July 2000.

^{b/} "Slope Factor" calculated for each constituent, at each monitoring point, using Delauney triangulation method (AFCEE, 1999).

^{c/} TCE = trichloroethene.

^{d/} *cis*-1,2-DCE = *cis*-1,2-dichloroethene.

^{e/} VC = vinyl chloride.

^{f/} "Sum" is the sum of the slope factors for all three constituents, calculated using Delauney triangulation method (AFCEE, 1999).

TABLE 6.11
SUMMARY OF EVALUATION OF CURRENT GROUNDWATER MONITORING PROGRAM^{a/}
OPERABLE UNIT 1
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Monitoring Point	Operable Unit	Qualitative Evaluation		Temporal Evaluation		Spatial Evaluation			Summary	
		Abandon/Retain?		Abandon/Retain?		Slope Factor			Abandon/Retain?	
		Abandon	Retain	Abandon	Retain	Low ^{b/}	Medium ^{c/}	High ^{d/}	Abandon	Retain
AEHA-9	OU1 Plume		✓	✓			✓			✓
ESE-15	OU1 Downgradient	✓			✓	✓				✓
JMM-3	OU1 Downgradient		✓	✓			✓			✓
JMM-6	OU1 Cross Gradient	✓		✓		✓			✓	
JMM-17	OU1 Downgradient		✓	✓		✓				✓
JMM-19	OU1 Upgradient		✓		✓		✓			✓
JMM-20	OU1 Upgradient	✓		✓			✓			✓
JMM-22	OU1 Plume		✓		✓		✓			✓
JMM-29	OU1 Downgradient	✓		✓		✓			✓	
JMM-47	OU1 Cross Gradient		✓	✓			✓			✓
JMM-48	OU1 Cross Gradient	✓		✓		✓			✓	
JMM-59	OU1 Plume		✓	✓		✓				✓
JMM-60	OU1 Upgradient		✓	✓		✓				✓
JMM-62	OU1 Cross Gradient	✓		✓		✓			✓	
JMM-63	OU1 Downgradient	✓		✓		✓			✓	

^{a/} "Current" groundwater sampling event -- July 2000.

^{b/} Low = slope factor sum of 0.0 to 0.84

^{c/} Medium = slope factor sum of 0.85 to 1.84

^{d/} High = slope factor sum of 1.85 to 3.85

5. Any well recommended for abandonment on the basis of the qualitative, temporal, and spatial evaluations can be removed from the network with virtually no loss of information.
6. Any well recommended for abandonment on the basis of the qualitative and temporal evaluations can be removed from the network with little loss of information, as long as that well has not been recommended for retention on the basis of the spatial evaluation.
7. Any well recommended for abandonment on the basis of one evaluation (e.g., qualitative hydrogeology) and for retention on the basis of another evaluation (e.g., temporal) is recommended for retention in the reduced network.
8. Only those wells recommended for abandonment on the basis of all three evaluations, or on the basis of the qualitative and temporal evaluations (with no recommendation resulting from the spatial evaluation) should be removed from the network.

The summary results of evaluations (Table 6.11) indicate that monitoring wells JMM-6, JMM-29, JMM-48, JMM-62, and JMM-63 could be removed from the monitoring network at OU1 with little loss of information. A reduced monitoring network, consisting of 10 monitoring wells, would be adequate to address the two primary objectives of monitoring. Furthermore, as a consequence of the northwesterly-directed hydraulic gradient in the groundwater system under ambient conditions, and the radially inward-directed gradient with active groundwater extraction, groundwater monitoring should be conducted no more frequently than biennially. Substantial additional savings could be realized if the conventional-purge VOC sampling method currently used at DDHU OU1 were replaced with diffusion-sampler technology (McClellan AFB/EM, 2000).

6.2.5 Cost Evaluation

The OU1 groundwater extraction system, consisting of 16 extraction wells, a single air stripping tower, and 16 injection wells, was constructed in 1994 and began operation in December 1994. In 1992, the present worth of capital and O&M costs from system installation through attainment of remediation goals was projected to be \$1,155,000 (JMM, 1992a). The actual capital cost for installation of the OU1 system was estimated to be \$340,000 (in 1994 dollars); and the annual O&M costs were estimated to be \$165,000 for 1999 (in 1999 dollars) (Parsons, 2000). The cumulative costs to date, calculated by accruing capital expenditures and annual O&M from 1994 to the present, are approximately \$1,330,000 (Table 6.12). To date, a total mass of about 3 pounds of VC has been removed from groundwater at OU1 (Section 6.2.2.1). Based on the cumulative total capital and O&M costs to date, the cost per pound to remove VC from groundwater at OU1 is approximately \$443,000.

In the ROD for OU1 (JMM, 1992a) the time required to achieve the RAOs was estimated to be approximately 5 years. Based on this estimate, VC removal should have been completed by the end of the year 1999. Trend analyses of available data indicate that the concentrations of VC throughout most of the OU1 attainment area may be

TABLE 6.12
SUMMARY OF CAPITAL, OPERATION, MAINTENANCE,
AND MONITORING COSTS
OPERABLE UNIT 1
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Item	Cost
Capital Costs ^{a/}	\$340,000
Estimated Annual OM&M Costs ^{b/}	\$165,000
Total Cost to Date ^{b/}	\$1,330,000
<hr/>	
Cost Per Pound of Vinyl Chloride Removed	
Mass of vinyl chloride removed to date (pounds)	~ 3
Cost ^{b/} per pound of vinyl chloride removed (to date)	\$443,000
Current rate of vinyl chloride mass removal (pounds per year)	0.2
Mass of vinyl chloride removed by end of year 2003 at current removal rate (pounds)	3.6
Cost ^{b/} per pound of vinyl chloride removed by end of year 2003	\$507,000

^{a/} 1994 dollars

^{b/} 1999 dollars.

reduced to below 2 µg/L by the end of the year 2003 under current operating conditions (Section 6.2.2; Figure 6.2). If the current rate of VC removal (less than 0.2 pound per year) is maintained through that period, then by the end of the year 2003, at total of less than 4 pounds of VC will have been removed from groundwater at OU1 (Figure 6.14). If the annual O&M costs remain constant, at about \$165,000 per year of operation (in constant 1999 dollars), and no additional capital expenditures accrue, the removal of 3.6 pounds of VC from OU1 groundwater will have been accomplished at a cost of more than \$500,000 per pound (in current [year 1999] dollars (Table 6.12; Figure 6.14).

6.2.6 Alternative Technology Evaluation

CAH in groundwater at DDHU OU1 are apparently attributable to contaminants originating at Burial Site 4A in the former Plain City Canal, and possibly to wastes disposed at Burial Sites 3A and 3C. As discussed in Section 2.4, the materials disposed in the canal apparently contained relatively low concentrations of solvents, and were deposited along the entire 1,600-foot segment of the canal that was used as a disposal site. Burial Sites 3A and 3C (Figure 2.5) may have contributed some CAH and fuel

hydrocarbons to the plume, but based on the low dissolved COC concentrations that since have emanated from the Burial Sites, the contribution of contaminant mass from these sites was apparently relatively minor.

Examination of groundwater monitoring data from July 1998, July 1999, and July and August 2000, indicates that the concentrations of *cis*-1,2-DCE have decreased to levels below the 70 µg/L MCL for *cis*-1,2-DCE at all monitoring points within the area of attainment at OU1. VC concentrations exceeded the 2-µg/L MCL for VC in groundwater samples from five wells in July 1998, in samples from two wells in July 1999, and in samples from three wells in July/August 2000. The highest concentrations of VC detected during the 1999 and 2000 monitoring events were 4.5 µg/L and 3.6 µg/L, respectively (both occurring in samples from monitoring well JMM-22). As a consequence of the low concentrations of CAH remaining in groundwater at OU1, active groundwater extraction technologies are, and will continue to be ineffective for purposes of groundwater remediation (Section 6.2.2). One or more alternative remedial technology(ies) may be better suited to complete the cleanup of OU1 groundwater to the VC MCL.

The primary factors affecting the identification and application of alternative remedial technologies at OU1 include the following:

- The concentrations of the primary COC (VC) in OU1 groundwater are less than 5 µg/L in the most contaminated part of the plume. Therefore, application of aggressive remedial measures such as excavation and disposal or *in situ* chemical oxidation is not warranted at OU1.
- The physico-chemical characteristics of VC (i.e., high volatility, moderate solubility, low degree of sorption to soil particles, and susceptibility to biodegradation through aerobic oxidation) indicate that this chemical will migrate readily with groundwater flow away from anaerobic source areas to more aerobic environments. After migrating to environments that are relatively more aerobic, VC in groundwater is likely to be mineralized (degrade to innocuous byproducts).
- The site hydrogeology at DDHU OU1 is characterized by moderate- to high-permeability sands and gravels in the uppermost (shallow) water-bearing unit. The water table within the shallow water-bearing unit is encountered at a depth of 8 to 10 feet bgs. The unit is 20 to 25 feet thick, is underlain by a ubiquitous low-permeability silty clay aquitard, and has a relatively flat groundwater gradient. These characteristics generally facilitate *in situ* technologies, in that contaminated groundwater is at relatively shallow depths, so that alternative electron donors (anthropogenic carbon source) or acceptors (e.g., atmospheric oxygen) are readily introduced into the groundwater system. Furthermore, as a consequence of the presence of the aquitard at relatively shallow depths, vertical migration of contaminants to deeper water-bearing zones is not a significant concern.

Figure 6.14 Cumulative Costs and VC Mass Removal for OU1 ETI System

- The exposure pathways analysis conducted in the BRA for OU1 (USACE, 1991a) indicated that there are no current significant risks to human health or the environment from exposure to contaminants in soil or groundwater at OU1. The ROD established groundwater remediation criteria to ensure protection of receptors under a potential future residential land use scenario; accordingly, potential future risks may be associated with extraction of shallow groundwater for potable use under a residential scenario (DLA, 1992a; Montgomery Watson, 2000). DDHU is currently under USACE jurisdiction, and is undergoing conversion for redevelopment as an industrial area. Institutional controls limiting access to, and future use of groundwater at OU1 are currently in place. Assuming that exposures under a future industrial use of the facility are similar to those under its past military supply-depot use, no potential future exposure pathways are likely to be completed (DLA, 1992a).

Alternative technologies considered for application at DDHU OU1 must be capable of addressing the RAOs established in the ROD (Table 6.1). In particular, candidate technologies must meet the requirements of the cleanup RAO, which requires reduction of COC concentrations in groundwater to levels below federal MCLs (e.g., 2 µg/L for VC). Technologies considered for *ex situ* treatment of extracted groundwater must meet the required discharge objectives (removal of COCs to concentrations below MCLs in treatment system effluent). The following technologies are considered potential candidates for remediation of OU1 groundwater:

- Reconfigured groundwater ETI system;
- Air sparging in that part of the area of attainment within which concentrations of VC remain above MCLs;
- Phytoremediation; and
- ETI shutdown and monitored rebound followed by monitored natural attenuation (MNA).

ETI Reconfiguration

The current groundwater extraction system, in conjunction with natural attenuation mechanisms, has removed most of the negligible mass of CAH that was initially present in groundwater at OU1, and has reduced the size of the VC area of attainment (Figures 6.1). In its current configuration, the extraction system is ineffective at removing the minimal mass of VC remaining at the site, due to the extremely low concentrations of VC remaining in groundwater, and because the extraction wells are not located in the most contaminated area of the plume. Reconfiguration of the extraction well layout, using the results of capture-zone modeling (Section 6.2.2.2) may increase the efficiency of mass removal, and will enhance the efficiency of the extraction system in controlling CAH migration.

Air Sparging

Air sparging could introduce dissolved oxygen into parts of the VC plume that are currently anaerobic, in order to enhance the potential for aerobic biodegradation of VC, and was considered to be a potential technology for remediating VC in groundwater at OU1. However, assuming that air sparging would be implemented only within the 2- $\mu\text{g/L}$ VC area of attainment, which currently covers an area of approximately 60,000 square feet, and using an assumed radius of influence for an air sparging well of 15 feet, approximately 85 sparging wells would be required to implement the technology. Also, while introduction of oxygen could enhance oxidation of VC, it could slow or halt degradation of remaining *cis*-1,2-DCE. Furthermore, the iron- and iron-bacteria-fouling problems plaguing the current groundwater ETI system would be compounded with direct air injection. For these reasons, air sparging is not a viable alternative technology for groundwater at OU1.

Phytoremediation

Phytoremediation may have some potential for application at OU1. However, little published information is available regarding the efficacy of phytoremediation for removal of VC from groundwater. Additionally, the saturated thickness of the water-bearing unit (25 feet) may preclude phytoremediation from withdrawing water out of the entire saturated thickness of the unit. Based on the lack of information and the aquifer thickness, phytoremediation was eliminated as a candidate technology for groundwater at OU1.

ETI Shutdown and Monitored Rebound/Monitored Natural Attenuation

The extremely low concentrations of VC (less than 5 $\mu\text{g/L}$) and *cis*-1,2-DCE (less than 20 $\mu\text{g/l}$) remaining in groundwater at OU1 suggest that complete shutdown of the existing ETI system may be a viable option. If the ETI system is shut down, groundwater conditions at OU1 will have to be monitored for a significant length of time (1 year at a minimum) to ensure that concentrations of VC and *cis*-1,2-DCE do not increase to unacceptable levels following system shutdown (“rebound”). The areal extent of contaminated groundwater at OU1 would also have to be monitored to ensure that CAH do not migrate to downgradient exposure points and threaten potential receptors. If the results of monitoring indicate that CAH in OU1 groundwater are not rebounding to unacceptable levels or migrating to previously-uncontaminated areas, monitored natural attenuation (MNA) may be a viable long term alternative for achieving closure of OU1 (as discussed in Section 3.2.4). The potential applicability of MNA as a long-term remedial option for groundwater at OU1 is based on the following observations:

1. The concentrations of VC in OU1 groundwater are less than 5 $\mu\text{g/L}$ at nearly all locations, and the concentrations of *cis*-1,2-DCE are well below the 70- $\mu\text{g/l}$ MCL for *cis*-1,2-DCE; and
2. No completed pathways exist for exposure of potential receptors to OU1 groundwater under current or planned future land uses.

The low residual DCE concentrations also indicate that little chemical mass is available to generate additional mass of VC (a daughter product of *cis*-1,2-DCE via the reductive dechlorination pathway), so that VC concentrations will continue to decline as a consequence of attenuation mechanisms (advection, dispersion, dilution, sorption and volatilization) after the ETI system has been shut down.

6.3 EVALUATION OF OU4 REMEDIAL SYSTEMS

6.3.1 Summary of OU4 Groundwater ETI System Operations

Two groundwater ETI systems are currently in operation at DDHU OU4 – the “main plume”, and the northern-lobe (or “hotspot”) system. The two systems are intended to control and remediate CAH plumes that originate at separate waste disposal sites, and thus operate independently.

6.3.1.1 OU4 Main-Plume ETI System

The main-plume groundwater extraction system at OU4 consists of 31 wells, all screened in the shallow water-bearing unit in the depth interval extending from just below the groundwater table to the top of the aquitard. Groundwater is typically encountered at depths of 6 to 9 feet bgs at OU4, and the underlying clay layer is encountered at depths of 20 to 25 feet bgs. The design groundwater extraction rate for each well was in the range of 3 to 6 gpm; and the total extraction rate for the entire well field was on the order of 125 gpm. Recent production rates for all extraction wells at OU4 are listed in Table 6.13. The extraction well system was designed to control plume migration and to remove TCE, *cis*-1,2-DCE and VC mass. Treated groundwater is re-injected to the shallow water-bearing unit via a system of 25 injection wells, installed around the perimeter of the VC area of attainment (as defined by the 2 µg/L isoconcentration contour; Figure 6.15). Discharge of treated groundwater using an injection system of this configuration was intended to form a hydraulic barrier to prevent further migration of contaminants to previously uncontaminated areas of the groundwater system.

6.3.1.2 OU4 Hot-Spot ETI System

The current groundwater extraction system at the OU4 “hot spot” consists of a single 300-foot-long interceptor trench installed downgradient of the northern lobe of the VC attainment area “hot spot” in OU4 (as defined by the 2 µg/L isoconcentration contour; Figure 6.15). The interceptor trench was designed to control the migration of the OU4 “hot spot” VC plume, and to remove *cis*-1,2-DCE and VC mass. Groundwater removed via the interceptor trench at OU4 “hot spot” is treated with a combined ozone/hydrogen peroxide injection system, prior to discharge to the Central Weber Sewer Improvement District (CWSID) sanitary sewer system (OHM, 2000).

TABLE 6.13
RECENT PRODUCTION HISTORY OF GROUNDWATER EXTRACTION WELLS/TRENCH
OPERABLE UNIT 4 (MAIN PLUME AND HOT SPOT)
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Extraction Well/Trench	Design Production Rate (gpm) ^{a/}	Actual Production Discharge Rate (Date)					Approximate <i>cis</i> -1,2 DCE and VC Concentrations in Extraction Well/Trench Discharge (µg/L) ^{b,c/}			Current <i>cis</i> -1,2 DCE Removal Rate (lbs/year) ^{d, e/}	Current VC Removal Rate (lbs/year) ^{d, e/}
		8/16/99 (gpm)	11/1/99 (gpm)	1/30/00 (gpm)	5/1/00 (gpm)	8/2/00 (gpm)	<i>cis</i> -1,2 DCE	VC	Date		
OUI Main Plume											
EW-1	No Data	1.4	1.4	0.7	0.8	0.8	8.7	1.9	1-Aug-00	0.039	0.009
EW-2	No Data	1.3	0.3	0.2	0.2	0.2	290	12	1-Aug-00	0.560	0.023
EW-3	No Data	1.6	1.6	1.2	1.3	1.1	6.1	8.3	1-Aug-00	0.036	0.050
EW-4	No Data	5.9	5.6	4.1	4.5	2.6	< 1.0 (0.36)	< 1.0 (0.18)	1-Aug-00	0.007	0.004
EW-5	No Data	2.5	3.2	0.6	1.2	1.5	< 1.0 (0.59)	< 1.0 (0.15)	1-Aug-00	0.005	0.001
EW-6	No Data	3.0	1.9	1.6	3.1	3.1	380	97	1-Aug-00	4.235	1.081
EW-7	No Data	8.9	9.3	8.9	4.1	5.3	73	37	1-Aug-00	2.338	1.185
EW-8	No Data	5.0	6.3	6.1	6.1	7.6	59.8 7	156 7	1-Aug-00	1.632	4.258
EW-9	No Data	3.4	3.6	5.0	3.2	1.0	< 1.0 (0.46)	< 1.0 (ND)	1-Aug-00	0.007	0.001
EW-10	No Data	0.6	0.4	0.0	0.2	0.1	1.8	< 1.0 (0.12)	1-Aug-00	0.002	0.000
EW-11	No Data	2.2	5.2	7.8	8.4	5.5	< 1.0 (0.44)	< 1.0 (0.57)	1-Aug-00	0.011	0.015
EW-12	No Data	4.4	3.9	5.2	6.0	0.0	< 1.0 (ND)	< 1.0 (ND)	1-Aug-00	0.002	0.002
EW-13	No Data	0.2	0.6	0.2	0.1	0.5	< 1.0 (0.53)	< 1.0 (ND)	1-Aug-00	0.001	0.000
EW-14	No Data	2.8	3.4	1.4	3.8	1.6	6.8	4.6	1-Aug-00	0.078	0.052
EW-15	No Data	2.4	3.0	2.2	3.9	2.2	6.6	2.3	1-Aug-00	0.079	0.028
EW-16	No Data	4.2	3.7	9.2	9.0	6.0	4.8	< 1.0 (0.91)	1-Aug-00	0.135	0.026
EW-17	No Data	4.4	3.1	8.1	4.8	5.5	4.2	< 1.0 (0.80)	1-Aug-00	0.095	0.018
EW-18	No Data	2.7	1.8	3.6	1.7	0.8	11	1.7	1-Aug-00	0.102	0.016
EW-19	No Data	6.1	5.3	4.5	3.2	1.5	9.8	5.8	1-Aug-00	0.177	0.105
EW-20	No Data	4.2	4.3	2.3	2.8	1.8	< 1.0 (ND)	< 1.0 (ND)	1-Aug-00	0.001	0.001
EW-21	No Data	2.7	5.6	5.5	5.1	4.2	8.5	2.5	1-Aug-00	0.172	0.051
EW-22	No Data	5.7	5.7	4.6	4.0	3.6	3.6	< 1.0 (0.74)	1-Aug-00	0.075	0.015
EW-23	No Data	2.7	1.9	3.4	4.2	2.6	< 1.0 (0.32)	< 1.0 (ND)	1-Aug-00	0.004	0.001
EW-24	No Data	1.9	1.4	1.1	2.1	2.0	6	1.8	1-Aug-00	0.045	0.013
EW-25	No Data	2.3	2.2	0.7	2.5	1.6	3.8	1.1	1-Aug-00	0.031	0.009
EW-26	No Data	3.7	3.8	2.1	2.8	3.2	< 1.0 (ND)	< 1.0 (ND)	1-Aug-00	0.001	0.001
EW-27	No Data	1.5	1.5	1.0	0.8	2.2	11	3.9	1-Aug-00	0.068	0.024
EW-28	No Data	1.7	2.0	1.7	0.8	2.1	< 1.0 (0.67)	< 1.0 (0.13)	1-Aug-00	0.005	0.001
EW-29	No Data	2.8	3.5	2.7	2.8	0.8	3.6	< 1.0 (0.78)	1-Aug-00	0.040	0.009
EW-30	No Data	3.8	4.3	4.4	5.6	4.2	4.8	< 1.0 (0.76)	1-Aug-00	0.094	0.015
EW-31	No Data	2.9	2.7	4.0	2.2	3.0	3.6	< 1.0 (0.89)	1-Aug-00	0.047	0.012
OUI "Hot Spot"											
Trench	No Data	11.1	11.1	11.1	11.1	11.1	3.6	< 1.0 (0.35)	13-Apr-00	0.175	0.017

Total Mass Removed per Year (lbs) -- Main Plume	10.125	7.025
Total Mass Removed per Year (lbs) -- "Hot Spot"	0.175	0.017

^{a/} gpm = gallons per minute.

^{b/} µg/L = micrograms per liter.

^{c/} Concentrations in parathesis are laboratory estimated concentrations below the MDL. ND indicates that the concentration was below the detection limit.

^{d/} lbs/yr = pounds per year.

^{e/} If the concentration was below the MDL, removal rates were calculated using laboratory-estimated concentrations. In cases where the concentration was below the practical quantitation limit, removal rates were calculated using an assumed concentration of 0.1 µg/L.

Figure 6.15 Chlorinated Aliphatic Hydrocarbons (CAH) in Groundwater at OU4 – 1993 and 2000

6.3.2 Effectiveness of Current Extraction Systems at OU4

6.3.2.1 OU4 Main Plume ETI System

Mass Removal

The effectiveness of the complete extraction systems at OU4, and of the individual wells in the systems, was first evaluated in terms of the performance objective of mass removal. The long-term effectiveness of the groundwater extraction systems at OU4 is potentially affected by the presence of PCE/TCE mass at one or more sources associated with Burial Sites 4A, 4B, 4C, 4D, or 4E, leading to continuing generation of *cis*-1,2-DCE and VC, and their dissolution into groundwater.

The estimate provided in the ROD for OU4 in 1992 indicated that a period of approximately 5 years (at a minimum) would be required to achieve the groundwater RAOs within the area of attainment (Figure 6.15) at OU4 (DLA, 1992b). A volume of approximately 330 million gallons of groundwater (equal to five pore volumes) was projected to be extracted and treated during that time.

Using historic concentrations influent to the OU4 treatment plant and the actual volume of groundwater treated to that time (229 million gallons), the total mass of *cis*-1,2-DCE and VC removed from the subsurface at OU4 by the groundwater extraction system, as of mid-July 1999, was estimated to be approximately 250 and 50 pounds, respectively (Parsons ES, 2000) – an average removal rate of about 50 pounds of *cis*-1,2-DCE and 10 pounds of VC per year, through the 5-year operational history of the groundwater extraction and treatment system. This removal of CAH mass has been accompanied by a slight decrease in the size of the area of attainment (as defined by the 2 µg/L isoconcentration contour) (compare isoconcentration contours for 1993 and 2000; Figure 6.15), some of which may be a consequence of attenuation processes (degradation, volatilization, dispersion), in addition to groundwater extraction.

The recent production history of all operating extraction wells in OU4 is presented in Table 6.13, together with the concentrations of *cis*-1,2-DCE and VC detected in the discharge effluent of individual wells during the monitoring event of July and August 2000 (Section 3.1). Based on current extraction rates and contaminant concentrations, the groundwater extraction and treatment system is estimated to be removing *cis*-1,2-DCE from the subsurface at OU4 at the rate of approximately 10 pounds per year, and is removing VC at a rate of about 7 pounds per year. The rate of removal of contaminant mass has apparently declined significantly during the five-year period of system operation, from an average removal rate of 50 pounds of *cis*-1,2-DCE and 10 pounds of VC per year, to the current rates.

Although *cis*-1,2-DCE has historically been detected in groundwater samples from several wells within OU1, the detected concentrations have exceeded the MCL for *cis*-1,2-DCE (70 µg/L) at only three wells (JMM-8, JMM-9, and JMM-45), in a restricted part of OU4, near the “hot spot”. Therefore, application of the *Cleanup Objective* (Objective No. 2 in Table 6.1) as a performance criterion in the evaluation of the groundwater ETI system at OU4 will focus primarily on removal of VC mass. A mass of approximately 120 pounds of *cis*-1,2-DCE and 50 pounds of VC was initially estimated

to be present in groundwater at OU4, prior to the installation and operation of the groundwater extraction system (DLA, 1992a). Since system startup in 1995, the groundwater extraction and treatment system has removed more CAH mass than was originally estimated to be present in the subsurface at OU4. This may be a consequence of the continued generation of *cis*-1,2-DCE and VC as daughter products of degradation of TCE in source areas (Burial Sites 4A, 4B, 4C, 4D, or 4E), or may be a result of the uncertainties associated with developing estimates of chemical mass in groundwater systems. No equilibrium sampling (e.g., groundwater sampling following temporary shut-down of the extraction system to allow the groundwater system to achieve chemical equilibrium) has been conducted since operation of the extraction system began in mid-1995. Therefore, no realistic estimate can be made of the mass of CAH remaining in OU4 groundwater.

Rather than attempting to estimate the total mass of CAH remaining in groundwater at OU4, and comparing the total remaining CAH mass with current mass-removal rates, Parsons used the alternative approach described for OU1 (Section 6.2.2.1) to develop estimates of the total length of time required to attain the MCL for VC in groundwater (2 µg/L) at all points within the area of attainment at OU4. Plots were generated to show the concentrations of VC in groundwater samples from individual monitoring wells through time (Figure 6.16). The temporal trends in concentrations of VC in the groundwater samples from monitoring wells JMM-9, JMM-46, JMM-56, JMM-57, and JMM-64 appear to indicate that VC concentrations in groundwater in the vicinity of each of these wells have been decreasing through time. The temporal concentration data for these wells were fitted with first-order equations, and the first-order curves were projected through time until they intersected the cleanup goal for VC in groundwater (the MCL for VC of 2 µg/L). Assuming that the concentrations of VC in groundwater samples from these wells continue to decrease through time, and the trends of decreasing concentrations continue to approximate first-order processes, this procedure can provide an estimate of the length of time required to achieve cleanup goals in groundwater at each monitoring location. Cleanup goals for groundwater have already been attained at many locations in OU4 (Figures 6.15 and 6.16). Cleanup goals have not been achieved at monitoring wells AEHA-5, JMM-9, JMM-34 (not shown on Figure 6.16), JMM-45 (not shown on Figure 6.16), JMM-46, JMM-52R (not shown on Figure 6.16), JMM-57, JMM-64, and several groundwater extraction wells. The projected date at which the VC cleanup goal will be achieved at well JMM-46 is approximately the third quarter of 2003. However, no trend in concentrations is apparent in the data for wells AEHA-5, JMM-8, and other wells in the vicinity of the OU4 source area (Figure 6.15), and it is not possible to use this method to project the time required to achieve cleanup goals in groundwater at this location.

Application of this procedure assumes that no additional contaminant mass is being/will be introduced to the groundwater system at OU4. However, it seems likely that during the entire period of operation of the ETI system, VC has been generated continuously, though at a slow rate, via degradation of TCE, which has in turn degraded to *cis*-1,2-DCE and thence to VC through reductive dechlorination. The concentrations of *cis*-1,2-DCE detected during the July-August 2000 monitoring event in groundwater samples from monitoring wells (Table 3.2) and in OU4 extraction-well effluent samples (Table 6.13) were generally several times greater than the detected VC concentrations.

Figure 6.16 Temporal Trends and Projected Cleanup Times for Vinyl Chloride in Groundwater at OU4

Therefore, a source of mass for generation of VC through reductive dechlorination processes is available. In addition, the OU4 plume is moderately anaerobic and reducing, indicating that conditions are suitable for the occurrence of reductive dechlorination of TCE and DCE (Section 3.3), which will eventually generate the VC daughter product (USEPA, 1999). This suggests that even though small amounts of contaminant mass are being removed from the subsurface by the groundwater extraction and treatment system, VC will continue to be present in groundwater within the attainment area as long as parent compounds (TCE and DCE isomers) remain. Limited evidence exists (Section 3.3) that the shallow water-bearing unit near the OU4 source area is becoming less reducing, which could eventually result in additional TCE/PCE flux from the source area, with resulting destabilization of the currently-stable main CAH plume in OU4. Furthermore, slow desorption of VC and parent compounds from soils in the groundwater zone also represents a potential long-term, continuing source of contaminants in groundwater. Therefore, although application of the trend-projection technique described above can be used to predict that RAOs will be achieved for groundwater at OU4 no earlier than about the third quarter of 2003 (3 years from the present), it seems likely that a somewhat longer (though unknown) period of time will actually be required. This observation is reinforced by the lack of apparent temporal trends in VC concentrations in groundwater samples from several wells (Figure 6.16).

The groundwater extraction system at the OU4 main plume therefore has not been effective in removing VC mass from the subsurface. The effectiveness of individual extraction wells can also be evaluated by examining the rates of removal of contaminant mass. The recent production histories for the 31 OU4 extraction wells are presented in Table 6.13, and the approximate removal rates for *cis*-1,2-DCE and VC are presented in Figures 6.17 and 6.18. The approximate CAH removal rates were calculated based on effluent sampling conducted at the extraction wells in July and August 2000, and the average production rate of each extraction well over the past year. Examination of rates of production of *cis*-1,2-DCE and VC indicates that significant removal of contaminant mass is occurring at only three wells (wells EW-6, EW-7, and EW-8); and that these three wells account for more than 80 percent of the removal of *cis*-1,2-DCE mass, and more than 90 percent of the removal of VC mass (Figures 6.17 and 6.18). The contaminant mass removal rates of five wells (wells EW-2, EW-16, EW-18, W-19 and EW-21) are between 0.1 and 1.0 lb./yr; these five wells are regarded as marginally effective (Table 6.14). The CAH mass-removal rates of the remaining 23 wells all are less than 0.1 lb./yr; and these wells are removing virtually no CAH mass (Figures 6.17 and 6.18). Therefore, the extraction and treatment system at the OU4 main plume generally is not an effective means of removing the little remaining CAH mass from groundwater (Table 6.14).

Inspection of the locations of groundwater extraction wells at OU4 relative to the dissolved VC plume indicates that those wells located nearest the main-plume source area in OU4 (e.g., wells EW-6, EW-7, and EW-8) produce the greatest amounts of CAH mass; and those wells located near the boundaries of the VC area of attainment (e.g., wells EW-25, EW-26, EW-27, and EW-28) produce virtually no contaminant mass (Figure 6.15 and Table 6.14). Some increase in the rate of mass removal at OU4 could possibly be realized by extracting groundwater only from the area near the OU4 source area, roughly bounded by extraction wells EW-3, EW-6, EW-7, and EW-9. Extraction wells operating

Figure 6.17 Removal of *cis*-1,2-DCE Mass During 2000

Figure 6.18 Removal of VC Mass During 2000

TABLE 6.14
RELATIVE EFFECTIVENESS OF
OU4 MAIN PLUME EXTRACTION WELLS AND OU4 HOTSPOT
INTERCEPTOR TRENCH
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DISTRIBUTION DEPOT HILL, UTAH

Extraction Well/Trench	Approximate Removal Rate of Vinyl Chloride (lbs/yr)	Relative Effectiveness		
		Effective ^{a/}	Marginal ^{b/}	Poor ^{c/}
EW-1	<0.01			✓
EW-2	0.023		✓	
EW-3	0.05			✓
EW-4	<0.01			✓
EW-5	<0.01			✓
EW-6	1.1	✓		
EW-7	1.2	✓		
EW-8	4.3	✓		
EW-9	<0.01			✓
EW-10	<0.01			✓
EW-11	0.015			✓
EW-12	<0.01			✓
EW-13	<0.01			✓
EW-14	0.05			✓
EW-15	0.028			✓
EW-16	0.026		✓	
EW-17	0.018			✓
EW-18	0.016		✓	
EW-19	0.11		✓	
EW-20	<0.01			✓

TABLE 6.14 (Continued)
RELATIVE EFFECTIVENESS OF
OU4 MAIN PLUME EXTRACTION WELLS AND OU4 HOTSPOT
INTERCEPTOR TRENCH
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DISTRIBUTION DEPOT HILL, UTAH

Extraction Well/Trench	Approximate Removal Rate of Vinyl Chloride (lbs/yr)	Relative Effectiveness		
		Effective ^{a/}	Marginal ^{b/}	Poor ^{c/}
EW-21	0.05		✓	
EW-22	0.015			✓
EW-23	<0.01			✓
EW-24	0.013			✓
EW-25	<0.01			✓
EW-26	<0.01			✓
EW-27	0.024			✓
EW-28	<0.01			✓
EW-29	<0.01			✓
EW-30	0.015			✓
EW-31	0.012			✓
Hot-Spot	0.017			✓

^{a/} Individual well that removes VC at a rate of 1 pound per year (lb/yr) or greater.

^{b/} Individual well that removes VC at a rate between 0.1 and 1 lb/yr.

^{c/} Individual well that removes VC at a rate less than 0.1 lb/yr.

throughout most of the remaining VC area of attainment are not contributing significantly to removal of CAH mass, and are producing water having non-detectable (or very low) concentrations of contaminants (Tables 3.2 and 6.13). Although water produced from these wells is essentially “clean”, it is nevertheless being extracted, treated and discharged to the injection wells.

Plume Containment

Comparison of the historic extent of VC in groundwater with the current extent of the VC plume (Figure 6.15) indicates that the extent of VC in groundwater at OU4 has

TABLE 6.15
STORIC PRODUCTION RATES OF GROUNDWATER EXTRACTION/INJECTION WELLS
OPERABLE UNIT 4
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Extraction Well	Approximate Screened Interval (ft bgs) ^{a/}	Approximate Saturated Thickness (feet)	Design Production Rate (gpm) ^{b/}	Actual Production Discharge Rate (Date)
				8/99 (gpm)
EW-1	10 - 20	13	No Data	2.6
EW-2	8.5 - 18.5	11	No Data	2.7
EW-3	10 - 20	13	No Data	1.2
EW-4	8 - 23	18	No Data	4.1
EW-5	10 - 20	14	No Data	1.7
EW-6	10 - 25	17	No Data	3.0
EW-7	12 - 22	16	No Data	9.1
EW-8	9 - 24	18	No Data	5.3
EW-9	10 - 25	18	No Data	2.4
EW-10	12 - 22	16	No Data	0.3
EW-11	8 - 23	18	No Data	3.7
EW-12	10 - 25	18	No Data	3.5
EW-13	12 - 22	16	No Data	0.4
EW-14	10 - 25	19	No Data	3.2
EW-15	10.5 - 25.5	19	No Data	3.9
EW-16	10 - 25	19	No Data	2.8
EW-17	7 - 26	19	No Data	4.9
EW-18	14 - 24	17	No Data	3.8
EW-19	11.5 - 26.5	18	No Data	1.6
EW-20	10 - 20	19	No Data	2.4
EW-21	16.5 - 26.5	18	No Data	1.5
EW-22	14 - 24	15	No Data	3.4
EW-23	12.5 - 27.5	18	No Data	2.1
EW-24	11 - 26	16	No Data	1.5
EW-25	10 - 25	16	No Data	1.5
EW-26	12.5 - 27.5	19	No Data	5.0
EW-27	12.5 - 27.5	19	No Data	1.8
EW-28	14 - 29	21	No Data	1.4
EW-29	12 - 22	12	No Data	4.7
EW-30	15.5 - 25.5	17	No Data	4.0
EW-31	15.5 - 30.5	21	No Data	2.6
IW-1	7-26	19	No Data	3.2
IW-4	7.5-20	14	No Data	3.2
IW-5	12.5-27.5	20.5	No Data	2.3
IW-6	9-31	24	No Data	2.7
IW-7	8.5-32	26	No Data	0.6
IW-8	7.5-30	24	No Data	3.0
IW-9	7.5-30	24.3	No Data	2.9
IW-10	9-30	22.5	No Data	3.3
IW-11	10-30	20	No Data	0.7
IW-12	9-30	21	No Data	5.8
IW-13	9.5-26.75	16.5	No Data	9.0
IW-14	7.5-33	14	No Data	10.5
IW-15	7.5-32.5	13	No Data	3.3
IW-16	8.5-27	18	No Data	4.7
IW-17	11.5-26	16	No Data	0.6
IW-18	11.5-26	16.5	No Data	8.9
IW-20	6.5-26	18	No Data	9.0

decreased since 1992/1993. Examination of the current distribution of VC in groundwater (Figure 6.15) indicates that the downgradient extent of VC in groundwater of the main OU4 plume, at concentrations that exceed the MCL for VC, has retracted toward the source area since the commencement of active groundwater extraction and treatment.

The effectiveness of the complete OU4 main-plume groundwater extraction system in containing the dissolved CAH plume can be evaluated by assessing changes in CAH concentrations through time at downgradient monitoring wells. As described earlier in Section 6.3.2.1 (“*Mass Removal*”), temporal trends in VC concentrations were reviewed for groundwater monitoring wells within and near the area of attainment at OU4. In general, VC concentrations in groundwater samples either exhibit no trend, or exhibit temporal trends of decreasing concentrations. In addition to the reduction in the size of the CAH plume, the concentrations of CAH in groundwater at locations downgradient from the VC area of attainment generally are near or below detection limits. Therefore, although it is not clear that the observed decreases in VC concentrations are solely a result of active groundwater extraction, or whether much of the decrease may be a consequence of attenuation processes, the current groundwater extraction system in the main plume at OU4, in conjunction with attenuation processes, is effectively containing the plume, and is limiting or preventing continued migration of VC in groundwater. Nevertheless, extraction wells operating throughout most of the area downgradient of the OU4 main-plume source area and are producing water having non-detectable (or very low) concentrations of contaminants (Tables 3.2 and 6.13). It therefore seems likely that continued operation of the groundwater extraction and treatment system at OU4, in its current configuration or at current extraction rates, is probably unnecessary; and the rates of groundwater extraction can probably be reduced.

As with the OU1 groundwater extraction system, the effectiveness of individual extraction wells at OU4 can also be examined. The radius of capture of each extraction well, and the capture zone of the complete extraction system, were evaluated using the QuickFlow™ analytical groundwater flow model (Geraghty & Miller, Inc., 1991). Rates of groundwater extraction and injection were recorded during a groundwater monitoring event in the third quarter of 1999 (Kleinfelder, 2000). These were assumed to be representative of long-term rates of extraction/injection of each well for the purpose of evaluating groundwater capture zones, and were used in QuickFlow™ simulations (Table 6.15). The groundwater flow direction and hydraulic gradient at OU4 were estimated from potentiometric-surface maps generated during the RI/FS (Montgomery, 1991), and from the results of three monitoring events in February, March, and April (OHM, 1999). The configuration of the water table (Figures 2.11 and 2.12) was found to be generally consistent through time, with a flow direction toward the southwest, and a gradient of 0.002 ft/ft.

Site-specific values of hydraulic conductivity were estimated from the results of well-displacement (“slug”) testing of 23 wells in OU4, conducted during the RI/FS (Montgomery, 1991). The arithmetic average of the 23 hydraulic conductivity values (30.9 ft/day) was used as a representative hydraulic conductivity during initial simulations of the groundwater system at OU4. Information from boring logs at OU4 indicated that the average saturated thickness of the shallow water-bearing unit is approximately 17 feet (Table 6.15). The average values of hydraulic conductivity and

saturated thickness of the water-bearing unit at OU5 were used to generate an initial estimate of transmissivity (525 ft²/day) for use in QuickFlow™ simulations.

An initial simulation was completed (Figure 6.19), using long-term average pumping rates, and the estimated average transmissivity of the shallow water-bearing unit at OU4 (525 ft²/day), to generate an estimate of the extent of the capture zone that might result from pumping the 31 extraction wells at OU4 during the approximate 5-year period of historic system operation (from 1995 through 1999). The results of the initial simulation were then compared with historic conditions at OU4. A distinct depression in the water table, probably due to operation of the groundwater extraction system, is apparent in the configuration of the actual potentiometric surface at OU4 (Figure 2.12), based on water-level measurements collected while the extraction system was in full operation in July 2000. A comparison of the historic potentiometric surface (Figure 2.12) with the results of initial simulations (Figure 6.19) indicates that the configuration of the historic depression in the water table conformed reasonably well with the depression that resulted from the model simulation. This suggested that use of the average values of hydraulic conductivity and saturated thickness to generate an estimate of the average value of transmissivity of the shallow water-bearing unit at IU4 was probably appropriate.

The value of transmissivity used in the QuickFlow™ model was varied within a limited range in an attempt to evaluate the sensitivity of the model to differing site conditions. Potentiometric contours and capture zones were generated using a value of transmissivity somewhat lower than the estimated average transmissivity (250 ft²/day, corresponding to a hydraulic conductivity value of 15 ft/day), and using a value of transmissivity somewhat higher than the estimated average transmissivity (850 ft²/day, corresponding to a hydraulic conductivity value of 50 ft/day). The results of these simulations (Figures 6.20 and 6.21, respectively) were then compared with the historic configuration of the actual groundwater potentiometric surface at OU4 (Figure 2.12).

The results of neither of the other two simulations replicated the actual groundwater potentiometric surface particularly well (Figures 6.20 and 6.21), while the potentiometric surface and capture zone resulting from use of a transmissivity of 525 ft²/day (Figure 6.19) appeared to be the most representative of the three simulations, and best replicated actual conditions (Figure 2.12). The transmissivity value of 525 ft²/day therefore was considered representative of hydrogeologic conditions at OU4, and was used in subsequent simulations to evaluate alternative groundwater extraction systems having different configurations. The configuration of the extraction/injection wellfield was altered in subsequent QuickFlow™ simulations so that active groundwater extraction was concentrated in those wells located along the axis of the main OU4 plume, in order to assess whether the effectiveness of hydraulic capture/containment of the main CAH plume at OU4 could be maintained with fewer extraction wells, and/or with different pumping rates.

In general, injection wells at locations upgradient of the OU4 main plume were removed from consideration, because injection of water in upgradient locations increases the local groundwater hydraulic gradient, thereby reducing the size of extraction-well capture zones. Groundwater extraction was concentrated in parts of the plume having the highest concentrations of CAH in groundwater, to maximize the removal of CAH

Figure 6.19 Capture-Zone Simulation (525 ft²/day Transmissivity)

Figure 6.20 Capture-Zone Simulation (250 ft²/day Transmissivity)

Figure 6.21 Capture-Zone Simulation (850 ft²/day Transmissivity)

mass, and reduce the possibility that dissolved CAH originating in those areas could migrate downgradient with moving groundwater.

A subset of the existing system, consisting of 16 extraction wells and 10 injection wells was evaluated, operating at historic pumping rates (Tables 6.15 and 6.16), appears to be effective in containing the main CAH plume (Figure 6.22), and could be implemented at OU4. While this is not the minimum number of wells necessary to achieve plume containment, it is considered to be a relatively effective configuration because in addition to containing the plume, groundwater extraction near CAH sources in OU4 will improve the rate of CAH mass removal. This alternative system would be most effective if treated groundwater were injected at downgradient locations, thereby reducing the local hydraulic gradient and increasing the capture zone of the extraction wellfield. Cessation of active operations at 14 of the existing extraction wells and 16 of the existing injection wells will generate annual O&M cost savings, as a result of reductions in labor, electrical power, and analytical costs associated with system O&M.

6.3.2.2 OU4 Hot Spot ETI System

Mass Removal

The estimate provided in the ROD amendment, addressing conditions at the OU4 “hot spot” in 1992 indicated that extraction and treatment of a volume of approximately 2.5 million gallons of groundwater would be required to achieve RAOs for groundwater at the OU4 “hot spot” (DLA, 1992b).

Using historic concentrations influent to the OU4 “hot spot” treatment system at startup (3 µg/L of VC and 3 µg/L of *cis*-1,2-DCE [OHM, 2000]), and the total volume of groundwater treated through December 1999 (1.1 million gallons), the total mass of *cis*-1,2-DCE and VC removed from the subsurface at the OU4 hotspot by the groundwater extraction trench, as of December 1999, was estimated to be approximately 0.195 and 0.146 pound, respectively (Parsons ES, 2000).

The recent production history of the OU4 “hot spot” extraction trench is presented in Table 6.13, together with the concentrations of *cis*-1,2-DCE and VC detected in the trench. Based on current extraction rates and contaminant concentrations, the groundwater extraction trench and treatment system is estimated to be removing *cis*-1,2-DCE from the subsurface at OU4 at the rate of approximately 0.18 pound per year, and is removing VC at a rate of about 0.02 pounds per year. These estimated rates of removal of CAH mass from the OU4 “hot spot” plume may be lower than actual rates, as a consequence of volatilization of VOCs during collection of groundwater in the interceptor trench.

No equilibrium sampling has been conducted since operation of the interceptor-trench system began in 1994. Therefore, no realistic estimate can be made of the mass of CAH remaining in OU4 groundwater in the vicinity of the “hot spot”. However, it is apparent that the interceptor trench at OU4 was only marginally effective at removing CAH mass from the OU4 “hot spot” groundwater plume at system startup, and is currently ineffective at removing *cis*-1,2-DCE and VC mass from OU4 “hot spot” groundwater. Because groundwater extraction via the interceptor trench at the OU4 “hot spot” appears

TABLE 6.16
OPTIMIZED GROUNDWATER EXTRACTION/INJECTION SYSTEM
OPERABLE UNIT 4
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Extraction Well	Approximate Screened Interval (ft bgs) ^{a/}	Approximate Saturated Thickness (feet)	Design Production Rate (gpm) ^{b/}	Actual Production Discharge Rate (Date)		Optimized Extraction Rate (gpm)
				8/99 (gpm)		
EW-1	10 - 20	13	No Data	2.6		2.6
EW-2	8.5 - 18.5	11	No Data	2.7		2.7
EW-3	10 - 20	13	No Data	1.2		1.2
EW-6	10 - 25	17	No Data	3.0		3.0
EW-7	12 - 22	16	No Data	9.1		9.1
EW-8	9 - 24	18	No Data	5.3		5.3
EW-11	8 - 23	18	No Data	3.7		3.7
EW-14	10 - 25	19	No Data	3.2		3.2
EW-15	10.5 - 25.5	19	No Data	3.9		3.9
EW-18	14 - 24	17	No Data	3.8		3.8
EW-19	11.5 - 26.5	18	No Data	1.6		1.6
EW-21	16.5 - 26.5	18	No Data	1.5		1.5
EW-22	14 - 24	15	No Data	3.4		3.4
EW-24	11 - 26	16	No Data	1.5		1.5
EW-25	10 - 25	16	No Data	1.5		1.5
EW-27	12.5 - 27.5	19	No Data	1.8		1.8
EW-29	12 - 22	12	No Data	4.7		4.7
EW-30	15.5 - 25.5	17	No Data	4.0		4.0
EW-31	15.5 - 30.5	21	No Data	2.6		2.6

Injection Well	Approximate Screened Interval (ft bgs) ^{a/}	Approximate Saturated Thickness (feet)	Design Injection Rate (gpm) ^{b/}	Actual Injection Rate (Date)		Optimized Injection Rate (gpm)
				6/98 (gpm)		
IW-13	9.5-26.75	16.5	No Data	9.0		9.0
IW-14	7.5-33	14	No Data	10.5		9.5
IW-15	7.5-32.5	13	No Data	3.3		3.3
IW-16	8.5-27	18	No Data	4.7		4.7
IW-17	11.5-26	16	No Data	0.6		0.6
IW-18	11.5-26	16.5	No Data	8.9		8.9
1W-20	6.5-26	18	No Data	9.0		9.0
4IW-21	4.5-17	9.5	No Data	0.8		0.8
4IW-22	7.5-20	12	No Data	1.0		1.0
4IW-23	7.5-24	18	No Data	3.0		3.0

^{a/} ft bgs = feet below ground surface.

^{b/} gpm = gallons per minute.

Figure 6.22 Simulated Capture Zone – Recommended Configuration

discharge effluent from the trench during a monitoring event in April 2000 (OHM, 2000). to be ineffective, its continued operation is probably not necessary to meet ROD objectives.

Plume Containment

The ROD amendment (Montgomery Watson, 2000), addressing conditions associated with the “hot spot” at OU4, does not include an RAO specifying a plume-containment objective for groundwater. However, a secondary benefit of the interceptor trench is that it appears to be containing the OU4 “hot spot” plume (Figure 6.15) within the boundaries of OU4 (Montgomery Watson, 2000).

6.3.3 Treatment System Evaluation

6.3.3.1 OU4 Main-Plume Treatment System

Groundwater extracted from the subsurface at OU4 is treated by passing it through one of two air-stripping tower to remove VOCs prior to reinjecting the water to the groundwater system by means of injection wells located around the perimeter of OU4 (as defined by the 2 µg/L VC isoconcentration contour that was current in 1992). The results of analyses of water samples collected from the influent and effluent lines of the treatment plant (Kleinfelder, Inc., 2000) indicate that concentration of *cis*-1,2-DCE (27.3 µg/L) in water influent to the treatment plant is currently below the plant discharge limits specified in the ROD (70 µg/L for *cis*-1,2-DCE), but that the concentration of VC (25.3 µg/L) in water influent to the treatment plant is currently above the plant discharge limits specified in the ROD (2 µg/L for VC). The concentrations of both compounds in the treated effluent are below method detection limits.

Because the concentrations of VC in water influent to the treatment system are above the discharge limit specified in the ROD, treatment of extracted groundwater is required to meet discharge criteria. The current main-plume treatment system appears to be operating efficiently; and the continued OM&M of the OU4 treatment plant is appropriate to meet ROD objectives.

6.3.3.2 OU4 Hot Spot Treatment System

Groundwater extracted from the interceptor trench at the OU4 “hot spot” is treated via ozone/hydrogen peroxide injection to remove *cis*-1,2-DCE and VC prior to discharge to the CWSID sanitary sewer system (OHM, 2000). Analysis of water samples collected from lines influent to the treatment system (OHM, 2000) indicate that the current concentration of *cis*-1,2-DCE in influent water is 3.6 µg/L, which is well below the 70 µg/L discharge limit for *cis*-1,2-DCE; and the current concentration of VC in influent water is 0.35 µg/L (estimated, based on data validation qualification), well below the 2 µg/L discharge limit for VC. The concentrations of both COCs in the treatment plant effluent are below method detection limits. Based on the very low influent concentrations of *cis*-1,2-DCE and VC, continued treatment of groundwater extracted from the interceptor trench is not required, at current rates of extraction. Because groundwater extracted from the interceptor trench at the OU4 “hot spot” does not appear

to require treatment prior to discharge, continued operation of the treatment system at the interceptor trench is not necessary to meet ROD objectives.

6.3.4 Evaluation of OU4 Groundwater Monitoring Program

The evaluation of the monitoring program at OU4 proceeded in general accordance with the procedures and algorithms used in the evaluation of the monitoring program at OU1. The evaluation was conducted in stages to address each of the objectives and considerations of monitoring: a qualitative evaluation was first completed, followed in succession by temporal and spatial evaluations.

6.3.4.1 Qualitative Hydrogeologic Evaluation

Monitoring is conducted periodically at DDHU OU4 to provide information regarding chemical and hydraulic (gradient) conditions within and downgradient from the contaminant plume (Section 2.7.2). The groundwater monitoring program is intended to provide water-level and analytical data for use in ensuring compliance with requirements of the ROD (JMM, 1992b; Montgomery Watson, 2000), and for evaluating the overall effectiveness of the extraction systems.

Currently, groundwater samples are collected for monitoring purposes, using conventional-purge sampling methods, from a total of 16 monitoring wells at OU4 (Table 6.17) (JMM, 1993b). Groundwater samples from all wells are analyzed for VOCs using USEPA Method SW8260B. In addition to collection of samples from monitoring wells, key components of the groundwater extraction system at OU4 are also monitored, enabling overall system performance to be evaluated periodically. Monitoring of the extraction and treatment system may include collection of groundwater samples from any of four sampling ports within the system during monthly monitoring events (Table 6.17), or from a sampling port at extraction well EW-4, and analysis of those samples for VOCs.

The estimated annual costs associated with the current groundwater monitoring program, are summarized in Table 6.18. As a consequence of the absence of a discernible trend in VC concentrations in groundwater samples from several wells (including wells AEHA-5, JMM-8, and other wells in the vicinity of the OU4 source area) within the area of attainment at OU4 (Section 6.3.2.1), it is not possible to estimate the length of time that will be required to meet the *Cleanup Objective* specified in the ROD (Item 2 in Table 6.1). For the purpose of generating cost estimates, Parsons assumed that an additional 10-year period will be required to achieve the *Cleanup Objective*. Assuming that the current monitoring program is continued for an additional 10 years, the cumulative cost of the monitoring program (in constant 2000 dollars) is estimated to be approximately \$770,000 (Table 6.18).

The direction of groundwater movement beneath OU4 has historically been from northeast to southwest (Section 2.3.3). Therefore, in the absence of active groundwater extraction, migration of contaminants from sources in OU4 also would be generally toward the southwest, and contaminants dissolved in groundwater at OU4 would eventually migrate past the western boundary of DDHU. Historical chemical data indicate that contaminants associated with the OU4 main plume and “hot spot” plume

TABLE 6.17
CURRENT GROUNDWATER MONITORING PROGRAM^{a/}
OPERABLE UNIT 4
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Monitoring Point	Operable Unit	Field Analyses					Laboratory Analyses
		Temperature ^{b/}	Dissolved Oxygen ^{b/}	pH ^{b/}	ORP ^{b,c/}	Specific Conductance ^{b/}	VOCs ^{d/} (Method SW8260B)
JMM-7R	OU4 Upgradient	✓	✓	✓	✓	✓	✓
JMM-8	OU4 Plume	✓	✓	✓	✓	✓	✓
JMM-9	OU4 Plume	✓	✓	✓	✓	✓	✓
JMM-14	OU4 Cross Gradient	✓	✓	✓	✓	✓	✓
JMM-15	OU4 Cross Gradient	✓	✓	✓	✓	✓	✓
JMM-30	OU4 Downgradient	✓	✓	✓	✓	✓	✓
JMM-33	OU4 Cross Gradient	✓	✓	✓	✓	✓	✓
JMM-41D	OU4 Downgradient	✓	✓	✓	✓	✓	✓
JMM-42D	OU4 Cross Gradient	✓	✓	✓	✓	✓	✓
JMM-43D	OU4 Cross Gradient	✓	✓	✓	✓	✓	✓
JMM-44	OU4 Upgradient	✓	✓	✓	✓	✓	✓
JMM-46	OU4 Plume	✓	✓	✓	✓	✓	✓
JMM-52R	OU4 Plume	✓	✓	✓	✓	✓	✓
JMM-56	OU4 Plume	✓	✓	✓	✓	✓	✓
JMM-57	OU4 Plume	✓	✓	✓	✓	✓	✓
JMM-64	OU4 Downgradient	✓	✓	✓	✓	✓	✓
JMM-65	OU4 Cross Gradient	✓	✓	✓	✓	✓	✓
EW-4	OU4 Extraction Well	✓	✓	✓	✓	✓	✓
Effluent Port	OU4 Treatment System	✓	✓	✓	✓	✓	✓

^{a/} "Current" groundwater sampling event -- July 2000.

^{b/} direct-reading meter.

^{c/} ORP = oxidation-reduction potential.

^{d/} VOCs = volatile organic compounds.

TABLE 6.18
ESTIMATED COSTS ASSOCIATED WITH CURRENT MONITORING PROGRAM^{a/}
OPERABLE UNIT 4
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DOPT HILL, UTAH

17 Wells Sampled Semiannually				
Cost type	Quantity	Units	Unit Cost	Cost
Labor for sample collection				
1 person at \$65/hr	84	hours	\$ 65.00	\$ 5,460.00
Labor for data validation and data management				
1 person at \$65/hr	32	hours	\$ 65.00	\$ 2,080.00
Reporting				
150 hours at \$80/hr	160	hours	\$ 80.00	\$ 12,800.00
Laboratory Analyses				
VOCs by Method 8260B (primary samples + QA/QC)	19	Samples	\$ 150.00	\$ 2,850.00
Other Direct Costs				
Equipment rental (PID, pH/Eh, O ₂ /CO ₂ , etc.)	5	days	\$ 400.00	\$ 2,000.00
Vehicle Rental (1 vehicle for 1 day)	5	days	\$ 55.00	\$ 275.00
Miscellaneous Field Supplies				\$ 50.00
SUBTOTAL SEMIANNUAL COST				\$ 25,515.00
Monthly Treatment Plant Effluent Sampling				
Cost type	Quantity	Units	Unit Cost	Cost
Labor for sample collection				
1 person at \$65/hr	4	hours	\$ 65.00	\$ 260.00
Labor for data validation and data management				
1 person at \$65/hr	2	hours	\$ 65.00	\$ 130.00
Reporting				
10 hours at \$80/hr	10	hours	\$ 80.00	\$ 800.00
Laboratory Analyses				
VOCs by Method 8260B (primary samples + QA/QC)	3	Samples	\$ 150.00	\$ 450.00
Other Direct Costs				
Equipment rental (PID, pH/Eh, O ₂ /CO ₂ , etc.)	1	day	\$ 400.00	\$ 400.00
Vehicle Rental (1 vehicle for 1 day)	1	day	\$ 55.00	\$ 55.00
Miscellaneous Field Supplies				\$ 50.00
SUBTOTAL MONTHLY COST				\$ 2,145.00
Total Annual Cost				\$ 76,770.00
Long Term Monitoring for 10 years:			Total OU4 Program Cost	\$767,700.00

^{a/} Estimated by Parsons ES based on current (third quarter 2000) sampling program (Table 6.17).

may have migrated off of the facility. The CAH plume is contained by the current extraction and treatment systems at OU4 and the OU4 “hot spot”. Although active generation of vinyl chloride through reductive dechlorination processes appears to be occurring, the plumes are stable, and are not increasing in areal extent (Sections 6.3.2.1 and 6.3.2.2). Under these conditions, the current monitoring system could be modified to reduce the frequency of groundwater monitoring at most locations from semi-annual to annual monitoring (Table 6.17), while continuing to meet the two objectives of monitoring (Section 6.2.4), with little loss of information and no increase in risk to potential receptors.

The results of the qualitative evaluation of the complete monitoring network at OU4 are presented in Table 6.19. Recommendations for retaining or abandoning each existing monitoring point in OU4 also are presented in Table 6.19, together with the rationale for the recommendations.

6.3.4.2 Temporal Statistical Evaluation

Three VOCs (TCE, *cis*-1,2-DCE, and vinyl chloride) have been detected historically in groundwater samples from one or more monitoring wells at OU4, at concentrations that exceed the MCLs for the compounds, and at frequencies in excess of about 5 percent (Section 3.1). The monitoring results for each of the three VOCs detected in each well in the current monitoring program were examined for trends using the Mann-Kendall test (Table 6.20). The objective of the evaluation was to identify those wells having increasing or decreasing concentration trends for each VOC, and to consider the quality of information represented by the existence or absence of concentration trends in terms of the location of each monitoring point.

The results of Mann-Kendall temporal trend analyses for the three VOCs (TCE, Figure 6.23, *cis*-1,2-DCE, Figure 6.24; and VC, Figure 6.25) enable areas of the VOC plume within which chemical concentrations are increasing, decreasing, or stable to be readily identified. Summary results of the temporal trend analyses are presented in Table 6.20. Color coding of the table entries denotes the presence/absence of temporal trends, and allows those monitoring points having nondetectable concentrations, decreasing or increasing concentrations, or no discernible trend in concentrations to be readily identified. In general, monitoring points at which chemical concentrations display no discernible temporal trend represent points generating the least amount of useful information. Depending on the location of the monitoring point, consistently nondetected concentrations of chemicals through time can also represent relatively little information. Monitoring points at which one or more of the three VOCs display increasing or decreasing temporal trends in concentrations represent points at which monitoring should probably continue.

6.3.4.3 Spatial Statistical Evaluation

Spatial statistical techniques can also be applied to the design and evaluation of monitoring programs to assess the relative value of data generated during monitoring, and to optimize monitoring networks. The spatial statistical evaluation of the monitoring networks at OU1 and OU4 was conducted using the MAROS software program (AFCEE, 1999).

TABLE 6.19
QUALITATIVE EVALUATION OF GROUNDWATER MONITORING NETWORK
OPERABLE UNIT 4
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Monitoring Point	Elevation ^{a/} Top of Screen (feet)	Elevation ^{a/} Bottom of Screen (feet)	Monitoring Zone ^{b/}	Abandon/Retain		Rationale for Well to be Retained or Abandoned
				Abandon	Retain	
JMM-7R	Unknown	Unknown ^{c/}	Unknown ^{c/}		✓	Samples shallow water-bearing unit within VC area of attainment.
JMM-8	4240.23	4235.23	Unit 2		✓	Samples shallow water-bearing unit within VC area of attainment.
JMM-9	4236.27	4231.27	Unit 2		✓	Samples shallow water-bearing unit within VC area of attainment.
JMM-14	4238.76	4233.76	Unit 2		✓	Samples shallow water-bearing unit within VC area of attainment.
JMM-15	4235.04	4230.04	Unit 2		✓	Samples shallow water-bearing unit within VC area of attainment.
JMM-30	4233.52	4228.52	Unit 2		✓	Samples shallow water-bearing unit within VC area of attainment.
JMM-33	4239.91	4234.91	Unit 2		✓	Samples shallow water-bearing unit within VC area of attainment.
JMM-41D	Unknown	Unknown	Unknown	✓		Too far downgradient and does not monitor shallow water-bearing unit.
JMM-42D	4138.04	4133.04	Unknown		✓	Monitors deeper unit beneath the plume in the shallow water-bearing unit.
JMM-43D	Unknown	Unknown	Unknown	✓		Too far downgradient and does not monitor shallow water-bearing unit.
JMM-44	4241.82	4236.82	Unit 2	✓		Samples shallow water-bearing unit within VC area of attainment.
JMM-46	4239.36	4234.36	Unit 2		✓	Samples shallow water-bearing unit within VC area of attainment.
JMM-52R	Unknown	Unknown	Unknown		✓	Samples shallow water-bearing unit within VC area of attainment.
JMM-56	4232.1	4227.1	Unit 2		✓	Samples shallow water-bearing unit within VC area of attainment.
JMM-57	4232.1	4227.1	Unit 2		✓	Samples shallow water-bearing unit within VC area of attainment.
JMM-64	Unknown	Unknown	Unknown		✓	Samples shallow water-bearing unit within VC area of attainment.
JMM-65	Unknown	Unknown	Unknown		✓	Samples shallow water-bearing unit within VC area of attainment.

^{a/} Elevations referenced to mean sea level.

^{b/} "Unit 2" monitoring zone is uppermost (shallow) water-bearing unit at DDHU OU4.

^{c/} "Unknown" indicates that information regarding well-completion intervals and monitoring zones is not available.

TABLE 6.20
SUMMARY OF TEMPORAL STATISTICAL EVALUATION
OF
CURRENT GROUNDWATER MONITORING PROGRAM^{a/}
OPERABLE UNIT 4
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Monitoring Point	Trichloroethene	cis-1,2-Dichloroethene	Vinyl Chloride
JMM-7R			
JMM-8		no trend	ND
JMM-9	-	-	-
JMM-14			ND
JMM-15		ND	ND
JMM-30		ND	ND
JMM-33		ND	ND
JMM-41D			
JMM-42D			
JMM-43D			
JMM-44		+	ND
JMM-46		ND	ND
JMM-52R			no trend
JMM-56	ND	-	no trend
JMM-57	ND	-	-
JMM-64		-	-
JMM-65		no trend	ND

^{a/} "Current" groundwater sampling event -- July 2000.

ND	= Concentrations consistently below detection limits.
no trend	= No statistically significant temporal trend in concentration.
+	= Statistically significant increasing trend in concentration.
-	= Statistically significant decreasing trend in concentration.
< 4 meas	= Fewer than four measurements at the monitoring well.
	= No data available for the monitoring well.

Figure 6.23 Mann-Kendall Temporal Trend Analysis for Concentrations of TCE

Figure 6.24 Mann-Kendall Temporal Trend Analysis for Concentrations of *cis*-1,2-DCE

Figure 6.25 Mann-Kendall Temporal Trend Analysis for Concentrations of VC

Parsons used groundwater monitoring data, collected during the monitoring event of July 2000, to evaluate the spatial distribution of groundwater monitoring wells included in the current groundwater monitoring program. In application, the concentrations of TCE, *cis*-1,2-DCE, and VC detected in groundwater samples from each monitoring well were used in the Delaunay method (as implemented in the MAROS tool) to calculate a unitless slope value at each monitoring point; and the slope values for each contaminant were summed to produce a representative slope factor for each monitoring well included in the current monitoring program. The unitless slope factor calculated for each monitoring well represents the relative worth of monitoring data associated with that well in relation to the entire monitoring well field, with higher values of slope factor indicating relatively greater worth; and each monitoring point in the network can be ranked according to the relative value of information generated by sampling at that point (Table 6.21). Wells having a summed slope factor less than about 0.84 are regarded as contributing relatively little information; wells having a slope factor between 0.85 and 1.84 contribute a moderate amount of information; and wells having a slope factor greater than 1.84 contribute the most information to the monitoring program. According to these evaluation criteria, the greatest amount of information (in the spatial sense) is obtained from monitoring wells JMM-8, JMM-30, JMM-33, JMM-44, JMM-64, and JMM-65 in OU4 (Table 6.21).

6.3.4.4 Summary of Evaluation of OU4 Groundwater Monitoring Network

The existing groundwater monitoring network at OU4, consisting of 17 groundwater monitoring wells from which samples are periodically collected, was evaluated using qualitative hydrogeologic knowledge, temporal statistical techniques, and spatial statistics. At each stage in the evaluation, monitoring points that provided relatively greater amounts of information regarding the occurrence and distribution of VOCs in groundwater were identified, and were distinguished from those monitoring points that provided relatively lesser amounts of information. The results of the qualitative, temporal, and spatial evaluations are summarized in Table 6.22.

The results of evaluations were combined to generate a subset of the monitoring network that could potentially provide information sufficient to address the primary objectives of monitoring, at reduced cost. Wells not retained in the reduced monitoring network could be abandoned, with relatively little loss of information. The results of the evaluation were combined and summarized in accordance with the decision structures and algorithms presented in Section 6.2.4.4.

The summary results of evaluations (Table 6.22) indicate that monitoring wells JMM-41D and JMM-43D possibly could be removed from the monitoring network at OU4 with comparatively little loss of information. A reduced monitoring network, consisting of 15 monitoring wells, probably would be adequate to address the two primary objectives of monitoring. Furthermore, as a consequence of the southwesterly-directed hydraulic gradient in the groundwater system under ambient conditions, and the radially inward-directed gradient with active groundwater extraction, groundwater monitoring should be conducted no more frequently than biennially. Substantial additional savings could be realized if the conventional-purge VOC sampling method currently used at DDHU OU4 were replaced with diffusion-sampler technology (McClellan AFB/EM, 2000).

TABLE 6.21
SUMMARY OF SPATIAL EVALUATION OF CURRENT GROUNDWATER MONITORING PROGRAM^{a/}
OPERABLE UNIT 4
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Monitoring Location	Operable Unit	Spatial Evaluation			
		TCE ^{c/}	Slope Factor ^{b/}		Sum ^{f/}
			<i>cis</i> -1,2-DCE ^{d/}	VC ^{e/}	
JMM-7R	OU4 Upgradient	0.040	0.295	0.323	0.66
JMM-8	OU4 Plume	0.710	1.005	1.073	2.79
JMM-9	OU4 Plume	0.181	0.241	0.359	0.78
JMM-14	OU4 Cross Gradient	0.000	0.988	0.561	1.55
JMM-15	OU4 Cross Gradient	0.073	0.175	1.024	1.27
JMM-30	OU4 Downgradient	0.204	1.098	0.850	2.15
JMM-33	OU4 Cross Gradient	0.003	1.380	0.968	2.35
JMM-41D	OU4 Downgradient	NA ^{g/}	NA	NA	NA
JMM-42D	OU4 Cross Gradient	NA	NA	NA	NA
JMM-43D	OU4 Cross Gradient	NA	NA	NA	NA
JMM-44	OU4 Upgradient	0.723	1.013	1.156	2.89
JMM-46	OU4 Plume	0.131	0.817	0.857	1.81
JMM-52R	OU4 Plume	NA	NA	NA	NA
JMM-56	OU4 Plume	0.232	0.524	0.632	1.39
JMM-57	OU4 Plume	0.003	0.559	0.238	0.80
JMM-64	OU4 Downgradient	0.576	1.046	0.932	2.55
JMM-65	OU4 Cross Gradient	0.153	1.297	1.063	2.51

^{a/} "Current" groundwater sampling event -- July 2000.

^{b/} "Slope Factor" calculated for each constituent, at each monitoring point, using Delauney triangulation method (AFCEE, 1999).

^{c/} TCE = trichloroethene.

^{d/} *cis*-1,2-DCE = *cis*-1,2-dichloroethene.

^{e/} VC = vinyl chloride.

^{f/} "Sum" is the sum of the slope factors for all three constituents, calculated using Delauney triangulation method (AFCEE, 1999).

^{g/} "ND" indicates that this analyte was not analyzed in the sample from this well, or that the Delauney triangulation method could not be applied.

TABLE 6.22
SUMMARY OF EVALUATION OF CURRENT GROUNDWATER MONITORING PROGRAM^{a/}
OPERABLE UNIT 4
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Monitoring Location	Operable Unit	Qualitative Evaluation		Temporal Evaluation		Spatial Evaluation			Summary	
		Abandon/Retain?		Abandon/Retain?		Slope Factor			Abandon/Retain?	
		Abandon	Retain	Abandon	Retain	Low ^{b/}	Medium ^{c/}	High ^{d/}	Abandon	Retain
JMM-7R	OU4 Upgradient		✓	✓		✓				✓
JMM-8	OU4 Plume		✓		✓			✓		✓
JMM-9	OU4 Plume		✓		✓	✓				✓
JMM-14	OU4 Cross Gradient		✓	✓			✓			✓
JMM-15	OU4 Cross Gradient		✓	✓			✓			✓
JMM-30	OU4 Down Gradient		✓	✓				✓		✓
JMM-33	OU4 Cross Gradient		✓	✓				✓		✓
JMM-41D	OU4 Down Gradient	✓		✓					✓	
JMM-42D	OU4 Cross Gradient		✓	✓						✓
JMM-43D	OU4 Cross Gradient	✓		✓					✓	
JMM-44	OU4 Upgradient	✓		✓				✓		✓
JMM-46	OU4 Plume		✓		✓		✓			✓
JMM-52R	OU4 Plume		✓		✓					✓
JMM-56	OU4 Plume		✓		✓		✓			✓
JMM-57	OU4 Plume		✓		✓	✓				✓
JMM-64	OU4 Down Gradient		✓		✓			✓		✓
JMM-65	OU4 Cross Gradient		✓		✓			✓		✓

^{a/} "Current" groundwater sampling event -- July 2000.

^{b/} Low = slope factor sum of 0.0 to 0.84

^{c/} Medium = slope factor sum of 0.85 to 1.84

^{d/} High = slope factor sum of 1.85 to 3.85

6.3.5 Cost Evaluation

The OU4 groundwater extraction and treatment system for the main CAH plume, completed in July 1995, consists of 31 extraction wells, two air-stripping towers, and 25 injection wells. The treatment system for the OU4 “hot spot”, consisting of a 300-foot-long interceptor trench, ozone and hydrogen peroxide reactors, and a discharge hookup to the CWSID sanitary sewer, went on-line in April 1999. In 1992, the present worth of capital and O&M costs for the OU4 main plume pump and treat system was projected to be \$3,022,000 (JMM, 1992b). The present worth of capital and O&M costs for the OU4 “hot spot” interceptor-trench system was projected to be \$1,104,000 (Montgomery Watson, 2000).

The actual capital cost for installation of the OU4 main plume extraction and treatment system was \$1,057,000 (in 1995 dollars), and the actual capital cost for the “hot spot” interceptor-trench system was \$507,000 (in 1999 dollars). The annual O&M costs for both systems were estimated to be \$317,000 for 1999 (Parsons, 2000). The cumulative costs to date, calculated by accruing capital expenditures and annual O&M from 1995 to the present, are approximately \$3,150,000 (Table 6.23). To date, a total mass of about 57 pounds of VC (50 pounds of VC during the period 1995 through 1999; and 7 pounds of VC from 1999 through the present) has been removed from groundwater at OU4 (Section 6.3.2.1). Based on the cumulative total capital and O&M costs to date, the cost per pound to remove VC from groundwater at OU4 is approximately \$55,250.

In the ROD for OU4 (JMM, 1992b) the time required to achieve the RAOs was estimated to be approximately 5 years. Based on this estimate, VC removal should have been completed by the end of the year 2000. Trend analyses of available data indicate that the concentrations of VC throughout much of the OU4 attainment area may be reduced to below 2 µg/L by the end of the year 2003 under current operating conditions (Section 6.3.2; Figure 6.16). However, it is unlikely that RAOs for groundwater will have been achieved at all locations within the OU4 area of attainment by the end of 2003. If the current rate of VC removal (about 7 pounds per year) is maintained through that period, then by the end of the year 2003, a total of about 78 pounds of VC will have been removed from groundwater at OU4 (Figure 6.26). If the annual O&M costs remain constant, at about \$317,000 per year of operation (in constant 1999 dollars), and no additional capital expenditures accrue, the removal of 78 pounds of VC from OU4 groundwater will have been accomplished at a cost of about \$53,000 per pound (in current [year 1999] dollars (Table 6.23; Figure 6.26). If, as is likely, continuation of groundwater extraction and treatment for a significantly longer period of time is necessary to achieve RAOs at OU4, cumulative system OM&M costs will be correspondingly greater.

6.3.6 Alternative Technology Evaluation

Contaminants in groundwater at DDHU OU4, primarily CAH (*cis*-1,2-DCE and VC), are apparently attributable to releases of solvent and petroleum hydrocarbon wastes from former Burial Sites 4A, 4B, 4C, 4D, and 4E (main plume) and former waste oil pits between Buildings 16C and 15C (“hot spot” plume). An apparent source of CAH, located in the vicinity of monitoring wells JMM-34 and JMM-58, may also be

TABLE 6.23
SUMMARY OF CAPITAL, OPERATION, MAINTENANCE,
AND MONITORING COSTS
OPERABLE UNIT 4
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Item	Cost
Capital Costs	
OU4 "Main Plume" System ^{a/}	\$1,057,000
OU4 "Hot Spot" System ^{b/}	\$507,000
Estimated Annual OM&M Costs ^{b/}	\$317,000
Total Cost to Date ^{b/}	\$3,149,000
Cost Per Pound of Vinyl Chloride Removed	
Mass of vinyl chloride removed to date (pounds)	~ 57
Cost ^{b/} per pound of vinyl chloride removed (to date)	\$55,200
Current rate of vinyl chloride mass removal (pounds per year)	7
Mass of vinyl chloride removed by end of year 2003 at current removal rate (pounds)	78
Cost ^{b/} per pound of vinyl chloride removed by end of year 2003	\$52,600

^{a/} 1995 dollars

^{b/} 1999 dollars.

Figure 6.26 Cumulative Costs and VC Mass Removal for OU4 ETI System

contributing CAH mass to the plume. Section 3 provides a comprehensive discussion of the current understanding of the nature and extent of contamination at OU4.

As a consequence of the low concentrations of CAH remaining in groundwater at most locations in OU4, active groundwater extraction technologies are, and will continue to be relatively ineffective for purposes of groundwater remediation (Section 6.3.2). One or more alternative remedial technology(ies) may be better suited to complete the cleanup of OU4 groundwater to the VC MCL.

The primary factors affecting the identification and application of alternative remedial technologies at OU4 include the following:

- The source areas at the former Burial Sites 4A, 4B, 4C, 4D, and 4E may contain residual or PCE/TCE source mass, commingled with petroleum hydrocarbon compounds. A continuing TCE source also may be present at the “hot spot”. Anaerobic reductive dechlorination of PCE/TCE in groundwater is occurring in, and downgradient of, these source areas, resulting in continued contribution of *cis*-1,2-DCE and VC mass to the dissolved CAH plume.
- A suspected source area may be present in the subsurface, in the vicinity of monitoring wells JMM-34 and JMM-58. This source may be contributing VC mass to the OU4 plume, but is not well characterized.
- The site hydrogeology at DDHU OU4 is characterized by moderate- to high-permeability sands and gravels in the uppermost (shallow) water-bearing unit. The water table within the shallow water-bearing unit is encountered at a depth of 6 to 9 feet bgs. The unit is about 20 feet thick, is underlain by a ubiquitous low-permeability silty clay aquitard, and has a relatively flat groundwater gradient. These characteristics generally facilitate *in situ* technologies, in that contaminated groundwater is at relatively shallow depths, so that alternative electron donors (anthropogenic carbon source) or acceptors (e.g., atmospheric oxygen) are readily introduced into the groundwater system. Furthermore, as a consequence of the presence of the aquitard at relatively shallow depths, vertical migration of contaminants to deeper water-bearing zones is not a significant concern.
- Observed decreases in concentrations of dissolved organic carbon and increases in ORP in groundwater near the source areas are indicative of alteration of local geochemistry to less-reducing conditions. Changes in groundwater geochemistry to less-reducing conditions may be causing the rates of reductive dechlorination of CAH to decline.
- The OU4 groundwater plume is anaerobic, resulting in low VC degradation rates, via oxidation mechanisms. If the concentration of dissolved oxygen in the plume could be raised, oxidation of VC could be enhanced. However, continued reductive dechlorination of remaining PCE/TCE/DCE source mass would be adversely affected by increased levels of dissolved oxygen.
- The physico-chemical characteristics of VC (i.e., high volatility, moderate solubility, low degree of sorption to soil particles, and susceptibility to

biodegradation through aerobic oxidation) indicate that this chemical will migrate readily with groundwater flow away from anaerobic source areas to more aerobic environments. After migrating to environments that are relatively more aerobic, VC in groundwater is likely to be mineralized (degrade to innocuous byproducts).

- The exposure pathways analysis conducted in the BRA for OU4 indicated that there are no current significant risks to human health or the environment from exposure to contaminants in soil or groundwater at OU4. The ROD established groundwater remediation criteria to ensure protection of receptors under a potential future residential land use scenario; accordingly, potential future risks may be associated with extraction of shallow groundwater for potable use under a residential scenario (DLA, 1992b; Montgomery Watson, 2000). DDHU is currently under USACE jurisdiction, and is undergoing conversion for redevelopment as an industrial area. Institutional controls limiting access to, and future use of groundwater at OU4 are currently in place. Assuming that exposures under a future industrial use of the facility are similar to those under its past military supply-depot use, no potential future exposure pathways are likely to be completed (DLA, 1992b).

Alternative technologies considered for application at DDHU OU4 must be capable of addressing the RAOs established in the ROD (Table 6.1). In particular, candidate technologies must meet the requirements of the cleanup RAO, which requires reduction of COC concentrations in groundwater to levels below federal MCLs (e.g., 2 µg/L for VC). Technologies considered for *ex situ* treatment of extracted groundwater must meet the required discharge criteria for reinjection into the shallow aquifer (main plume) and discharge to the sanitary sewer (“hot spot” plume). The following technologies are considered potential candidates for remediation of OU4 groundwater:

- Source excavation and disposal,
- Physical containment of sources and dissolved CAH,
- Dual-phase (groundwater and soil-vapor) extraction,
- *In situ* oxidation,
- Enhanced biodegradation/carbon addition,
- Air sparging, and
- ETI shutdown and monitored rebound followed by monitored natural attenuation (MNA).

Of these technologies, only enhanced biodegradation, air sparging, and MNA are discussed in detail. Potentially-severe limitations are associated with implementation of the other alternative technologies at OU4. The primary limiting factors include:

- Source excavation/disposal and *in situ* oxidation require precise identification of source areas. As discussed in Section 3, remaining source material at OU4 likely is isolated, discontinuous in the subsurface, or at relatively low concentrations in soil.
- Physical containment would require installation of a low-permeability cap over source areas and a subsurface barrier and/or hydraulic controls (e.g., continued groundwater extraction). The dimensions of the main plume at OU4 indicate that construction of a similarly large containment system (on the order of 500 feet by 500 feet, extending to a depth of 25 feet) would be necessary. The costs of construction of a containment system at this scale would be prohibitive.
- Dual-phase extraction and *in-situ* oxidation, considered for implementation at former Burial Sites 4A 4B, 4C, 4D, and 4E, also require identification of CAH sources. In addition, implementation of dual-phase extraction would require treatment of extracted groundwater and soil vapor for several years, resulting in high OM&M costs.

Based on these limitations, source-area excavation, physical containment, dual-phase extraction, and *in situ* oxidation are not appropriate technologies for remediation of groundwater at OU4. The other alternative technologies considered for groundwater at OU4 (enhanced biodegradation/carbon addition, air sparging, and/or MNA) are discussed in greater detail as follow.

Enhanced Biodegradation/Carbon Addition

Control of CAH sources by means of carbon amendment/addition could be readily implemented at OU4. In order for reductive dechlorination of TCE to *cis*-1,2-DCE, VC, ethene, and innocuous byproducts to occur, a reducing, anaerobic environment must prevail. The reductive dechlorination process occurs naturally in the subsurface when an adequate supply of bio-available carbon, either naturally occurring or introduced, is sufficient to promote the development of anaerobic (reducing) conditions. Complete dechlorination of TCE and DCE may occur within the anaerobic zone. However if the carbon source becomes depleted before the soluble TCE mass has been completely degraded, or if the rate of TCE transport out of the anaerobic zone exceeds the rate of TCE dechlorination, a dissolved CAH plume may persist.

The rates of reductive dechlorination near OU4 source areas may be declining as groundwater geochemistry becomes more aerobic and less reducing. Addition of carbon to the subsurface is intended to create a permeable reactive zone within which geochemical conditions in groundwater become anaerobic, thereby promoting the occurrence of reductive dechlorination of CAH and ensuring that degradation of CAH continues near OU4 source areas. While the rate of reductive dechlorination of VC is relatively slow compared with the rates of TCE and DCE degradation under anaerobic conditions, VC degrades rapidly under oxidizing, aerobic conditions. Therefore, in order for VC to degrade completely to carbon dioxide, water, and chloride, it is essential that an aerobic zone exist in groundwater downgradient from the reductive zone. This aerobic zone can be naturally-occurring, or can be physically induced (e.g., through installation and operation of an air-sparging system at a location downgradient from the carbon-addition zone).

Typical carbon source materials used for construction of a permeable reactive zone may be soluble, or selected to provide a slow rate of carbon release to groundwater. Soluble carbon sources include lactate, butyrate, acetate and sugars. Soluble carbon is quickly degraded by native bacteria, and creates anaerobic zones soon after its introduction into the saturated zone. These soluble carbon sources are transported with groundwater, and move as a solute front. Because the added carbon gradually moves away from the point(s) at which it is introduced to the subsurface (generally near contaminant source areas), addition of soluble carbon generally does not provide long-term (e.g., 10 years or more) control of mass flux from contaminant sources. Therefore, sources of soluble carbon generally require frequent replacement because their beneficial effects may be short-lived.

Slow-release carbon sources include hydrogen-release compound (HRC) and food-grade vegetable oil. Although HRC is a slow-release source, it also moves as a solute front and does not provide long-term control of mass flux from a contaminant source area. In contrast, vegetable oil tends to adsorb to soil particles, and is less mobile and does not move as a solute front. Vegetable oil has a solubility in the approximate range of 100 to 1,000 mg/L (low to moderate solubility), and therefore does not dissolve readily in groundwater. As a consequence of these properties, a single injection of a vegetable oil carbon source near a contaminant source area will remain in the vicinity of its point of introduction.

The octanol/water partition coefficient for TCE is approximately 300 [unitless] (Yaws, 1998), indicating that TCE has a much greater affinity for entering an organic NAPL than to dissolve into groundwater. As a result, a secondary effect of carbon addition (as vegetable oil) is that TCE tends to partition from groundwater into the vegetable oil. Therefore, much of the dissolved TCE mass will sorb into the vegetable oil and become immobilized. This effect was quite pronounced during a recent pilot study at DDHU OU2 -- the concentrations of dissolved TCE near the point of oil injection were reduced from 640 µg/L to 4 µg/L within 60 days of oil injection (Parsons ES, 1999).

Carbon addition/amendment to the subsurface at the OU4 source area would probably be accomplished using biopolymer slurry trenching. A narrow trench would be excavated downgradient from the source area and filled with a biopolymer slurry liquid shoring system. This trenching method allows a smaller excavation to be used, thereby reducing the amount of excavated soil material that may require offsite disposal. Vegetable oil would be mixed in a pugmill with a dry carrier sand, and the oil/sand mixture would be placed in the excavation, resulting in a permeable reactive barrier wall through which contaminated groundwater would move.

Introduction of oil into the subsurface to create a reactive zone is a remedial technology that has been accepted by the USEPA and UDEQ. A vegetable oil injection pilot test was performed at DDHU OU2 in 1999 (Parsons ES, 1999). Based on the results of this pilot test, and with USEPA and UDEQ approval, two permeable reactive zones were installed at two different sites at DDHU in 2000 (Parsons ES, 2000a). One reaction zone consisted of vegetable oil placed at the base of an excavation to create a "smear zone" for treatment of TCE migrating to groundwater from the vadose zone. The other reaction zone was constructed using 10 vertical wells in inject vegetable oil, mixed with potable water, directly into the saturated zone.

Creation of an anaerobic zone to promote reductive dechlorination of CAH has considerable potential for control the flux of CAH in groundwater, thereby enhancing attenuation of dissolved CAH plume. However, potentially-adverse side effects may be associated with carbon addition. These may include:

1. Generation of VC at a rate that exceeds the capacity of the groundwater system to oxidize/mineralize VC, thus potentially contributing to the formation or expansion of a VC plume.
2. Generation of soluble arsenic compounds at a rate greater than can be oxidized and precipitated can create a dissolved arsenic plume in, and immediately downgradient from the reaction zone.
3. Generation of elevated concentrations of methane by methanogenic bacteria degrading vegetable oil under anaerobic conditions.

These possible side effects have not yet been evaluated in detail. However, installation of a biosparging curtain downgradient from the carbon reaction zone should alleviate potential adverse effects associated with the generation of VC, soluble arsenic, or methane under anaerobic and reducing conditions.

Air Sparging

Air sparging is an alternative remedial technology that involves injecting atmospheric oxygen into the subsurface in those parts of the VC plume that are currently anaerobic. The goal of installing an active air-sparging system would be to oxygenate the groundwater, thereby promoting an aerobic groundwater regime in order to enhance the potential for aerobic biodegradation of VC to carbon dioxide and chloromethane.

Assuming that air sparging would be implemented within the 2- μ g/L VC area of attainment at OU4, which currently covers an area greater than 1,000,000 square feet, and using an assumed radius of influence for an air sparging well of 15 feet, more than 1,000 sparging wells would be required to implement the technology. Therefore, air sparging at OU4 is an alternative remedial option that should be considered only in conjunction with carbon substrate addition. Air sparging at OU4 would be implemented in the form of an air sparging curtain immediately downgradient of the sources of CAH in OU4 groundwater, in the vicinity of extraction wells EW-6, EW-7, and EW-9. This air sparging curtain would create aerobic conditions immediately downgradient of the OU4 source area, and would provide a mechanism to aerobically degrade VC emanating from OU4. Air sparging in this area would also generate an environment that would precipitate arsenic compounds mobilized under anaerobic conditions established by the upgradient reactive carbon zone.

ETI Shutdown and Monitored Rebound/Monitored Natural Attenuation

The relatively low concentrations of VC and *cis*-1,2-DCE remaining in groundwater throughout much of OU4 suggest that complete shutdown of the existing main plume ETI system may be a viable option. If the main plume ETI system is shut down, groundwater conditions at OU4 will have to be monitored for a significant length of time (1 year at a

minimum) to ensure that concentrations of VC and *cis*-1,2-DCE do not increase to unacceptable levels following system shutdown (“rebound”). The areal extent of contaminated groundwater at OU4 would also have to be monitored to ensure that CAH do not migrate to downgradient exposure points and threaten potential receptors. If the results of monitoring indicate that CAH in OU4 groundwater are not rebounding to unacceptable levels or migrating to previously-uncontaminated areas, MNA may be a viable long-term alternative for achieving closure of OU4. The potential applicability of MNA as a long-term remedial option for groundwater at OU4 is based on the following observations:

1. The concentrations of VC in OU4 groundwater are less than 5 µg/L at most locations distal from the OU4 source area, and the concentrations of *cis*-1,2-DCE generally are well below the 70-µg/l MCL for *cis*-1,2-DCE;
2. The interceptor-trench extraction system at the OU4 “hot spot” is appropriately located to intercept CAH mass that may move with groundwater from the OU4 source area, thereby preventing continued migration of CAH mass across the western boundary of DDHU; and
3. No completed pathways exist for exposure of potential receptors to OU4 groundwater under current or planned future land uses.

The low residual concentrations of TCE and *cis*-1,2-DCE at locations outside of the OU4 source area also indicate that little chemical mass is available to generate additional mass of VC, so that VC concentrations probably will continue to decline at locations downgradient of the OU4 source area, as a consequence of attenuation mechanisms (advection, dispersion, dilution, sorption and volatilization) after the ETI system has been shut down.

SECTION 7

RECOMMENDATIONS

The preceding sections provided an overview and evaluation of the remedial decision process that resulted in installation of the current groundwater extraction-and-treatment systems at DDHU OU1 and OU4, and a review of system performance to date. Based on these reviews and the conclusions presented, recommendations that have the potential to immediately improve system performance (in the short term) can be made. Opportunities that may provide a framework for directing remedial activities at the site in the future (in the longer term) are also identified.

7.1 SHORT-TERM RECOMMENDATIONS

System Improvements

Based on the current performance and the historical results of the groundwater extraction-and-treatment systems at OU1 and OU4, the existing systems are inefficient at removing dissolved vinyl chloride and *cis*-1,2-DCE mass. At OU1 and OU4 the CAH plumes are in the last stages of natural attenuation. Reductive dechlorination of *cis*-1,2-DCE is still in process and generating vinyl chloride. However, the reducing environment is not conducive to the breakdown of vinyl chloride, which requires an aerobic environment to facilitate natural attenuation. Thus, the vinyl chloride persists in both plume areas. The extraction and treatment systems at both OUs are more than adequate to contain the CAH plumes; however, none of the wells is effective at capturing and removing a significant amount of CAH mass from groundwater. As discussed in Section 6, use of the extraction-and-treatment systems to achieve the clean-up criteria outlined in Section 5, within the projected timeframe, is not an efficient remediation approach. Therefore, the following recommendations are made to improve the methods of remediating the OU1 and OU4 groundwater.

Recommendation 1: Turn off the existing pump-and-treat system at OU1 and monitor groundwater quality for CAHs for one year.

Rationale: As discussed in Section 6, the plume at OU1 is in the end stages of natural attenuation. Based on the mass of vinyl chloride removed to date, the relatively low mass that likely remains in OU1 groundwater, the current low mass removal rate of the existing groundwater extraction system, and the likelihood that little TCE/DCE source mass remains, continued groundwater extraction and treatment is not an effective means of removing the remaining CAH mass to meet RAOs. Cessation of pumping at OU1 would allow the following to occur:

- Observe if there are temporal increases in vinyl chloride concentrations in groundwater. Such increases (known as a “rebound effect”) commonly occur after pumping ceases.
- Reduce the volume of water requiring treatment or disposal by 100 percent.
- Reduce service time required for extraction and injection wells.
- Reduce the overall system OM&M cost by lowering labor, utility, and analytical expenses.
- Monitoring the concentration of CAHs in groundwater for one year after system shutdown will determine how active (i.e., shrinking, stable, expanding) the CAH plume is under natural (non-pumping) conditions, and will provide information of use in identifying the most effective means of treating the remaining CAH in groundwater.

Recommendation 2: Turn off the existing pump-and-treat system at OU4 and monitor groundwater quality for CAHs for one year.

Rationale: As discussed in Section 6, the plume at OU4 is in the end stages of natural attenuation. Although reductive dechlorination of *cis*-1,2-DCE is still occurring, the area of the vinyl chloride plume that exceeds the MCL of 2 µg/L is relatively small. It is possible that none of the extraction wells is needed to contain the OU4 plume. Cessation of pumping at OU4 would allow the following to occur:

- Observe if there are temporal increases in vinyl chloride concentrations in groundwater.
- Reduce the volume of water requiring treatment or disposal by 100 percent.
- Reduce service time required for extraction and injection wells.
- Reduce the overall system OM&M cost by lowering labor, utility, and analytical expenses.
- Monitoring the concentration of CAHs in groundwater for one year after system shutdown will determine how active (i.e., shrinking, stable, expanding) the CAH plume is under natural (non-pumping) conditions, and will provide information of use in identifying the most effective means of treating the remaining CAH in groundwater.

Recommendation 3: Bypass the treatment system at the OU4 hot spot extraction trench, and conduct a pilot test to sample and analyze untreated groundwater from the trench and monitor for CAH concentrations. A pilot test would consist of installing a sump that bypasses the treatment system, and delivering groundwater from the extraction trench into the sump. The groundwater in the sump would be sampled and analyzed for CAH.

If CAH concentrations exceed MCLs, the groundwater would be directed to the treatment system before disposal to the sewer system. If CAH concentrations do not exceed MCLs, the groundwater will be discharged directly from the sump into the sewer system.

Rationale: As discussed in Section 6, the concentrations of vinyl chloride in groundwater samples collected from the trench, prior to treatment, are below the MCL (2 µg/L) for vinyl chloride. It appears that the groundwater is sufficiently aerated in the trench to volatilize the vinyl chloride, and thereby decreasing the concentrations of vinyl chloride in captured groundwater. Cessation of treatment of the extracted groundwater, in conjunction with a pilot test to evaluate the quality of the groundwater produced by the trench would allow the following to occur:

- Reduce the volume of water requiring treatment.
- Reduce service time required for the treatment system.
- Reduce the overall system OM&M cost by lowering labor, utility, and analytical expenses associated with treatment.

Monitoring Program Improvements at OU1

It was estimated that the annual costs associated with current groundwater LTM program at OU1 are approximately \$72,000 (in constant 2000 dollars; Table 6.7). The total cost of monitoring at OU1 for a ten-year period of system operation that might be required before vinyl chloride concentrations decrease to levels below the MCL of 2 µg/L could range to \$717,000. The number of wells currently sampled during each semi-annual monitoring event, the frequency of sampling, and sampling procedures, were reviewed as part of the RPO evaluation. It is recognized that the sampling frequency should be appropriate to detect migration of the plume such that potential receptors are protected and trends in analyte concentrations can be identified. Sampling procedures and protocols were also reviewed. The number of monitoring wells included in the current groundwater-monitoring program was optimal for the preextraction plume. Considering that the size of the vinyl chloride plume has been reduced since inception of the groundwater pump-and-treat system, recommendations have been made to reduce the number of monitoring wells required to monitor conditions in the plume. A short-term opportunity exists to revise the groundwater monitoring program while providing sufficient data to monitor changes at OU1.

Recommendation 4: Reduce the frequency of sampling from semi-annual to annual, and reduce the number of wells sampled during long-term groundwater monitoring.

Rationale: There are no current or potential receptors imminently at risk through identified exposure pathways, and vinyl chloride concentrations in OU1 groundwater are generally stable or decreasing (Section 6). Therefore, semi-annual monitoring is probably excessive. The available historical data provide a sufficient baseline for interpreting trends in CAH concentrations.

The spatial distribution of the current sampling points was reviewed, recognizing that it may not be appropriate or necessary to conduct LTM at all wells that were installed during site characterization activities. Using a screening-level geostatistical evaluation, it was determined that sampling fewer wells could provide sufficient data to monitor plume migration, configuration, and concentration trends. At a minimum, 5 monitoring wells upgradient and cross gradient from the plume could be removed from the monitoring program, thereby reducing the number of wells sampled from 15 wells to 10, while still providing the same level of information necessary to achieve monitoring objectives. Wells recommended for abandonment include JMM-6, JMM-29, JMM-48, JMM-62, and JMM-63.

Monitoring Program Improvements at OU4

It was estimated that annual costs associated with the current groundwater LTM program at OU4 approximately \$77,000 (in constant 2000 dollars; Table 6.18). The total cost of monitoring at OU4 for a ten-year period of current system operation that might be required before vinyl chloride concentrations decrease to levels below the MCL of 2 µg/L could range to \$768,000. The number of wells currently sampled during each semi-annual monitoring event, the frequency of sampling, and sampling procedures, were reviewed as part of the RPO evaluation. Considering that the size of the vinyl chloride plume has been reduced since inception of the groundwater pump-and-treat system, recommendations have been made to reduce the number of monitoring wells required to monitor conditions in the plume. A short-term opportunity exists to revise the groundwater monitoring program while providing sufficient data to monitor conditions at OU4.

Recommendation 5: Reduce the frequency of sampling from semi-annual to annual, and reduce the number of wells sampled during long-term groundwater monitoring.

Rationale: There are no current or potential receptors imminently at risk through identified exposure pathways, and because vinyl chloride concentrations in OU4 groundwater are generally stable or decreasing (Section 6). Therefore, semi-annual monitoring is probably excessive. The available historical data provide a sufficient baseline for interpreting trends in CAH concentrations.

The spatial distribution of the current sampling points was reviewed, recognizing that it may not be appropriate or necessary to conduct LTM at all wells that were installed during site characterization activities. Using a screening-level evaluation, it was determined that sampling fewer wells could provide sufficient data to monitor plume migration, configuration, and concentration trends. At a minimum, two wells could be removed from the monitoring program. JMM-41D and JMM-43D are screened in the artesian aquifer, located below the confining clay layer at the base of the shallow water table aquifer, where CAH contamination is present. CAH have not been detected in these two wells since monitoring began. Because these wells are not completed in the shallow aquifer, and are outside the OU4 plume, it is recommended that these wells be removed from the monitoring program, thereby reducing the number of wells sampled in the monitoring program at OU4, from 17 to 15.

7.1.1 Cost Impact

Traditionally, long-term costs have been estimated and reported as net present worth (NPW) costs, in which the lump-sum value that must be invested at the present time was calculated using an adjustment rate that accounts for inflation and the cost of funds (i.e., interest) in order to meet future expenditures to be paid over time. However, federal funding for specific projects is obtained via annual appropriations that must be authorized by Congress for each fiscal year. Therefore, NPW cost estimates are not appropriate for Federal remediation projects such as the cleanup of groundwater at DDHU. The option of investing the NPW value of long-term O&M costs, to be drawn on as necessary to meet expenditures throughout the full O&M period, is simply not available for federally-funded projects. Rather, estimates of O&M costs through the duration of remediation activities were generated by projecting the annual O&M costs, in 2000 dollars, through the remaining project life cycle (a “constant-dollar analysis”). The remaining project life cycle is determined by the amount of contaminant that currently remains in the plume and the time that it will take to reduce contaminant concentrations to below the cleanup level.

Remediation Systems

The plumes at both OU1 and OU4 are in the final stages of natural attenuation (Section 6). The current pump and treat systems are not effectively removing vinyl chloride and *cis*-1,2-DCE mass at either site, because there is not a significant amount of mass remaining in groundwater. Terminating operation of the pump-and-treat systems at OU1 and OU4 can result in significant savings (Table 7.1). Annually, the savings can amount to \$165,000 at OU1 and \$317,000 at OU4 (in year 2000 dollars). Over a period of ten years, potential savings could total approximately \$4.8 million if both systems are turned off.

Monitoring Program

Revising the LTM programs by decreasing the number of wells sampled and the sampling frequency produces estimated cost savings of about \$30,000 per year for OU1 and \$30,000 per year for OU4. Over a 10-year period this amounts to a total savings of \$600,000 (in constant year 2000 dollars) for compliance monitoring costs at both OU1 and OU4.

7.2 LONG-TERM OPPORTUNITIES

Opportunity 1: Perform monitored natural attenuation at both OU1 and OU4.

This long-term opportunity essentially consists of letting natural attenuation complete the process of removing the CAHs from the groundwater. The plumes at both OU1 and OU4 are in the final stages of reductive dechlorination of CAHs. Presently, vinyl chloride persists in the groundwater for two reasons:

- *Cis*-1,2-DCE is being degraded via reductive dechlorination mechanisms, which produce vinyl chloride; and

TABLE 7.1
SHORT-TERM RECOMMENDATIONS
OPERABLE UNITS 1 AND 4
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Recommendation	Annual Cost Savings	Cost Savings Over Ten-Year Period ^{a/}	Reduction in Time to Meet Cleanup Goals	Difficulty of Implementation	Cost to Implement
Recommendation No. 1 – Turn off the existing pump-and-treat system at OU1 and monitor groundwater quality for CAHs for one year.	\$165 K	\$1.65 M	None	Moderate – Requires regulatory approval.	\$25K
Recommendation No. 2 Turn off the existing pump-and-treat system at OU4 and monitor groundwater quality for CAHs for one year.	\$317 K	\$3.17 M	None	Moderate – Requires regulatory approval.	\$25K
Recommendations Nos. 3 Turn off the treatment system at the OU4 hot spot extraction trench, and conduct a pilot test to sample groundwater from the trench and monitor for CAH concentrations.	\$25 K ^{b/}	TBD	None	Low – Requires regulatory approval.	\$25K
Recommendation No. 4 Reduce the frequency of sampling from semi-annual to annual, and reduce the number of wells sampled during long-term groundwater monitoring at OU1.	\$30 K	\$300 K	None	Low – Requires regulatory approval.	\$5K
Recommendation No. 5 Reduce the frequency of sampling from semi-annual to annual, and reduce the number of wells sampled during long-term groundwater monitoring at OU4.	\$30 K	\$300 K	None	Low – Requires regulatory approval.	\$5K
TOTAL	\$567 K	\$5.4 M			\$85K

^{a/} Estimated costs given in 2000 dollars (constant dollars). Estimated time remaining for reduction of vinyl chloride below MCL of 2 µg/L under monitored natural attenuation is 10 years.

^{b/} O&M costs for the extraction trench are included in the total O&M costs for OU4, and were not provided to Parsons ES separately. However, for purposes of this report, Parsons ES estimated the O&M cost for the extraction trench to be \$25,000.

- Although vinyl chloride is still being generated, concentrations are gradually decreasing through dilution and aerobic degradation, and also as a consequence of declining source mass of *cis*-1,2-DCE in the plume. By ceasing operation of the extraction and treatment systems at both OU1 and OU4, it can be determined if natural attenuation processes will be sufficient to remove the remaining mass of vinyl chloride from groundwater. Trend analyses indicate (Section 6) that the vinyl chloride in most of the current plume areas of attainment will be cleaned up by the year 2003. No trend is evident in the areas of highest vinyl chloride concentrations, so that it is not possible to predict when vinyl chloride concentrations are reduced to below MCLs.

Opportunity 2: Monitor groundwater quality at the OU4 extraction trench and, as appropriate, terminate operation.

The extraction trench located at the boundary of DDHU can continue to operate as a mitigating measure to remove CAH that potentially could migrate off-facility during monitored natural attenuation at OU4. A sump can be installed to intercept extracted groundwater before it enters the treatment plant. The groundwater can then be analyzed for concentrations of vinyl chloride and *cis*-1,2-DCE. If CAH concentrations are above MCLs (2 µg/L for vinyl chloride and 70 µg/L for *cis*-1,2-DCE), then extracted groundwater can be sent through the treatment system before disposal. If CAH concentrations are below MCLs, then the groundwater can be disposed directly into the sanitary sewer.

This opportunity takes advantage of the current groundwater monitoring program at the extraction trench, and adds potential cost savings by utilizing the treatment system only when necessary. Use of the extraction trench to capture CAH that could migrate off site during monitored natural attenuation could delay or eliminate the need to recommence pump-and-treat system operation if CAH concentrations increase during monitored natural attenuation.

Opportunity 3: If CAH concentrations in the groundwater show significant rebound and potential for off-site migration, then operate a modified pump-and-treat system as recommended in Section 6.

This long-term opportunity is recommended only in the event that natural attenuation mechanisms are not sufficient to prevent off-site migration of CAHs in groundwater.

7.2.1 Costs

Table 7.2 presents the long-term opportunities, together with estimated cost savings. The cost savings for Opportunity No. 1 are essentially the cost savings realized by implementing the short-term recommendations. A total savings of \$567,000 per year could be realized by shutting down both pump-and-treat systems and conducting annual groundwater monitoring. The cost savings for ceasing operation of the OU4 extraction trench are minimal, and are realized by bypassing the treatment system when CAH concentrations are below MCLs. O&M costs for the extraction trench are included in the total O&M costs for OU4, and were not provided to Parsons ES separately. However, for

TABLE 7.2
LONG-TERM OPPORTUNITIES
OPERABLE UNITS 1 AND 4
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Opportunity	Annual Cost Savings	Cost Savings Over Ten-Year Period ^{a/}	Reduction in Time to Meet Cleanup Goals	Difficulty of Implementation	Cost to Implement
Opportunity No. 1 – Implemented monitored natural attenuation at OU1 and OU4.	\$567 K	\$5.7 M	None	Moderate – Requires regulatory approval	\$50K
Opportunity No. 2 – Monitor groundwater quality at the OU4 "Hot Spot" extraction trench, and, as appropriate, terminate operations.	\$25 K ^{b/}	\$250 K	None	Moderate – Requires regulatory approval	\$25K
Opportunity No. 3 – Implement modified pump and treat systems, if monitoring of CAHs in groundwater shows both rebound and continued migration offsite.	\$262 K	\$2.62 M	None	Moderate – Requires regulatory approval	\$50K

^{a/} Estimated costs given in 2000 dollars (constant dollars). Estimated time remaining for reduction of vinyl chloride below MCL of 2 µg/L under monitored natural attenuation is 10 years.

^{b/} O&M costs for the extraction trench are included in the total O&M costs for OU4, and were not provided to Parsons ES separately. However, for purposes of this report, Parsons ES estimated the O&M cost for the extraction trench to be \$25,000.

purposes of this report, Parsons ES estimated the annual O&M cost for the extraction trench to be \$25,000.

If it is apparent that operation of the pump-and-treat systems is necessary to contain the CAH plumes, then operating only three of the 16 extraction wells at OU1 can result in an annual O&M savings of \$135,000. Operating 19 of the 31 extraction wells at OU4 can result in an annual O&M savings of \$127,000, as compared with the current system. This would produce annual cost savings of \$262,000 if Opportunity No. 3 is implemented (Table 7.2).

SECTION 8

IMPLEMENTATION PLAN

8.1 SHORT TERM RECOMMENDATIONS

The following section is a summary of what is required for implementation of the RPO recommendations. Based on a review of the data collected to date, it appears that the short-term recommendations made in Section 7.1 can be implemented by the Base contractor.

Recommendations 1 and 2: Discontinue pumping at all wells in OU1 and OU4, and monitor groundwater quality annually.

- Well shutdown should be planned to coincide with a scheduled groundwater monitoring event (e.g., March 2001). Prior to cessation of pumping, collect water-level measurements and a round of groundwater samples from each of the operating extraction wells. Water levels and analytical results from the samples will be used to confirm historical concentrations in extraction-well discharge, and to establish initial conditions against which potential future plume migration or changes in concentrations can be evaluated.
- At the appropriate time, shut down the pump-and-treat systems.
- Prepare the systems for a 12-month shutdown period.
- Semi-annual groundwater monitoring should continue following shutdown of these wells to evaluate temporal changes in chemical concentrations, potential changes in plume configuration, and the possible effects of natural attenuation. As noted in Section 6, MNA cannot be fully evaluated during active groundwater extraction because the effects of pumping can mask some natural-attenuation indicators.
- At the end of the 12-month period, conduct a scheduled groundwater monitoring event, including collection of water-level measurements and groundwater samples. The results of this monitoring event can be compared with the results of the previous annual monitoring event to evaluate changes in chemical concentrations and plume configuration, and also can be used in a detailed evaluation of natural attenuation.

Recommendation 3: Turn off the treatment system at the OU4 "hot spot" extraction trench, and conduct a pilot test to sample groundwater from the trench and monitor for CAH concentrations.

- Install a sump that will collect groundwater extracted by the trench before it enters the treatment system.
- Collect groundwater samples from the sump and analyze for vinyl chloride and *cis*-1,2-DCE.
- If concentrations of vinyl chloride and *cis*-1,2-DCE remain within acceptable treatment system effluent limits established in the ROD (Section 5), continue discharge of water directly to the sanitary sewer.
- If concentrations of vinyl chloride and *cis*-1,2-DCE are above the acceptable treatment system effluent limits, direct the water through the treatment system prior to discharge to the sanitary sewer.
- If CAH concentrations in the extracted groundwater are consistently below the MCLs for vinyl chloride and *cis*-1,2-DCE, then the treatment system at the OU4 extraction trench can be bypassed, as appropriate.

Recommendations 4 and 5: Reduce the frequency of groundwater monitoring from semi-annual to annual, and reduce the number of wells sampled during long-term groundwater monitoring at OU1 and OU4.

Annual groundwater monitoring probably should not be implemented until the results of the pump-and-treat shut-down period have been evaluated. Results of the 12-month trial period will be reported by the facility contractor in the quarterly OM&M reports, to maintain consistency for data reduction. An evaluation of the results obtained during the trial period will be presented in the final version of this report.

8.2 LONG-TERM OPPORTUNITIES

Opportunity 1: Implement monitored natural attenuation at both OU1 and OU4.

Monitored natural attenuation at OU1 and OU4 should be evaluated at the pilot scale before proceeding to full-scale implementation. A detailed assessment of the potential for MNA can be conducted using the monitoring data to be collected immediately prior to shutdown of the pump-and-treat systems, and at the conclusion of the 12-month monitoring period after system shutdown. Detailed instructions for conducting MNA evaluations are provided in existing protocol documents (e.g., USEPA, 1998).

Opportunity 2: Monitor groundwater quality at the OU4 extraction trench and, as appropriate, terminate operation.

The long-term opportunity at the OU4 extraction trench is actually two-fold:

- A pilot test to monitor CAH concentrations in extracted groundwater before the water is directed to the treatment system can assist in evaluating whether treatment of the water is necessary prior to disposal in the sanitary sewer. If the results of the pilot test indicate that groundwater will not require treatment after extraction, then

cost savings will be realized through termination of the treatment system at the extraction trench.

- Conducting the pilot test at the extraction trench concurrently with monitored natural attenuation may assist in evaluating whether the extraction trench is needed to capture CAH that would have been contained by an active pump-and-treat system. If necessary, the extraction trench can remain in operation as a low-cost alternative to operation of a modified pump-and-treat system.

Opportunity 3: If CAH concentrations in the groundwater show significant rebound, together with potential for off-site migration, then operate a modified pump-and-treat system as recommended in Section 6.

This long-term opportunity should be considered only if natural attenuation processes are not sufficient to prevent CAH from migrating off site. At OU1, the size of the plume and the current concentrations of vinyl chloride and *cis*-1,2-DCE indicate that off-site migration of the plume will not occur. At OU4, plume size and current concentrations indicate that a significant increase in plume size and CAH concentrations will probably not occur after the pump-and-treat system is shut down. As a contingency, the OU4 extraction trench can be used to intercept CAHs that might otherwise migrate off-site.

SECTION 9

REFERENCES

- Air Force Center for Environmental Excellence (AFCEE). 1997. *Long-Term Monitoring Optimization Guide*. Brooks Air Force Base, Texas. October.
- AFCEE and Air Force Base Conversion Agency (AFBCA). 1999. *Draft Final Remedial Process Optimization Handbook*. Prepared by Parsons Engineering Science for AFCEE, Brooks Air Force Base, Texas. December.
- American Society for Testing and Materials (ASTM). 1999. *Standard Provisional Guide for Risk-Based Corrective Action*. ASTM Provisional Standard PS104-98.
- Bear, J., and Y. Sun. 1998. Optimization of pump-treat-inject (PTI) design for the remediation of a contaminated aquifer – multi-stage design with chance constraints. *Journal of Contaminant Hydrology* 29:225-244.
- Burris, DR. 1992. *In Situ Treatment Zones -- General Concepts and Approaches*. Association of Ground-Water Scientists and Engineers 1992 Educational Program, Aquifer Restoration-- Pump-and-Treat and the Alternatives, Las Vegas, Nevada, September 30 - October 2.
- Defense Distribution Depot Hill, Utah, Ogden Site (DDHU). 1998a. *Five-Year Review, Operable Unit 1*. July.
- DDHU. 1998b. *Five-Year Review, Operable Unit 4*. September.
- Environmental Science and Engineering (ESE). 1986. *Geohydrological Investigation and Evaluation at DDOU, Part II*. Geohydrological Characterization.
- Defense Logistics Agency (DLA). 1992a. *Final Record of Decision and Responsiveness Summary for Operable Unit 1*. Defense Depot Ogden, Utah. Prepared by James M. Montgomery Consulting Engineers, Inc. June 10.
- DLA. 1992b. *Final Record of Decision and Responsiveness Summary for Operable Unit 4*. Defense Depot Ogden, Utah. Prepared by James M. Montgomery Consulting Engineers, Inc. August 3.
- Federal Remediation Technologies Roundtable. 1995. *Guide to Documenting Cost and Performance for Remediation Projects*. March.
- Feth, J.H., D.A. Barker, L.G. Moore, R.J. Brown, and C.E. Veirs. 1966. *Lake Bonneville: Geology and Hydrology of the Weber Delta District, including Ogden, Utah*: US Geological Survey Professional Paper 518.

- Gibbons, R.D. 1994. *Statistical Methods for Groundwater Monitoring*. John Wiley & Sons, Inc., New York.
- Gilbert, G.K. 1890. *Lake Bonneville*. U.S. Geological Survey, Monograph 1.
- Hintze, L.F. 1988. *Geologic History of Utah*. Brigham Young University Geology Studies, Special Publication 7.
- International Technology Corporation (IT). 1999. *Final Closure Report. OU4 Hotspot Remediation*. November.
- James M. Montgomery Consulting Engineers, Inc. (JMM). 1989. *Phase I Remedial Investigation Report for DDOU*.
- JMM. 1990. *Phase II Remedial Investigation Report for DDOU*.
- JMM. 1991a. *Draft Final Remedial Investigation/Feasibility Study Report for Operable Unit 1*. July.
- JMM. 1991b. *Draft Final Remedial Investigation/Feasibility Study Report for Operable Unit 4*. September.
- JMM. 1993a. *Ground-Water Monitoring Plan for Operable Unit 1, Defense Distribution Depot, Ogden, Utah*. February.
- JMM. 1993b. *Ground-Water Monitoring Plan for Operable Unit 4, Defense Distribution Depot, Ogden, Utah*. May.
- JMM. 1993c. *100 Percent Remedial Design Report for Operable Unit 4*. May.
- JMM. 1994. *Phase II Geoprobe Investigation Report for Operable Unit 4*.
- JMM. 1995. *Phase III Geoprobe Investigation Letter Report*.
- Klienfelder Inc. 1999. *Groundwater Treatment System Evaluation Report, Defense Depot, Hill, Utah, Operable Unit #1, Fourth Year*. April.
- Lohman, __. 1979. *Ground-Water Hydraulics*. Geological Survey Professional Paper 708.
- Montgomery Watson. 1996. *Investigation and Alternative Analysis Report for Operable Unit 4 Hotspot*. Source Area Addendum. March.
- Montgomery Watson. 1997a. *Final OU4 Hotspot Exploration Trench Report*. April.
- Montgomery Watson. 1997b. *Final Operable Unit 4 Hotspot Design Concept for the OU4 Hotspot Ground-water Remediation System*. June.
- Montgomery Watson. 1997c. *1997 Ground-water Elevation Survey Letter Reports*. Defense Distribution Depot Hill, Utah.

- Montgomery Watson. 1999. *Explanation of Significant Difference to the Record of Decision for Operable Unit 4*. January.
- Montgomery Watson. 2000. *Final Record of Decision Amendment for Operable Unit 4*. Prepared for U.S. Army Corps of Engineers. March.
- OHM Remediation Services Corporation (OHM). 1999. *Fourth Year Report O&M of Groundwater Pump and Treat Systems, Operable Unit 4 and Operable Unit 4 Hotspot, Defense Distribution Depot Hill, Utah-Ogden Site*. November.
- OHM. 2000. *Year 5 Second Quarter Operations Report, Operable Unit 4 and Operable Unit 4 Hot Spot, Defense Distribution Depot Hill, Utah–Ogden Site*. February.
- Parmley, R.O. (ed.). 1995. *Field Engineer's Manual*. McGraw-Hill Publishers, Inc., New York. 2nd Edition.
- Parsons ES. 1995. *Environmental Baseline Survey and CERCA Letter Report*. July.
- Parsons ES. 1996. *Environmental Baseline Survey and CERFA Letter Report*. Final. DDOU, Ogden Site, Utah.
- Parsons ES. 2000a. *Final Report, OU2 Groundwater Plume Evaluation for Treatment Method Alternative*. March.
- Parsons ES. 2000b. *Final Work Plan for Remedial Process Optimization Evaluation at Defense Depot Hill, Utah*. July.
- Smith, R. 1999. Personal communication. DDHU project manager.
- Thomas, H.E., and W.B. Nelson. 1948. Ground water in the East Shore area, Utah; part 1, Bountiful District, Davis County. Utah State Engineer Technical Publication 5, in *Utah State Engineer 26th Biennial Report*, pp. 52-206.
- United States Army Corps of Engineers (USACE). 1991a. *Draft Final Remedial Investigation/Feasibility Study Report for Operable Unit 1*. Defense Depot Ogden, Utah.
- USACE. 1991b. *Draft Final Remedial Investigation/Feasibility Study Report for Operable Unit 4*. Defense Depot Ogden, Utah.
- US Army Environmental Health Agency (USAEHA). 1981.
- USAEHA. 1984.
- USAEHA. 1985.
- USAEHA. 1987.
- US Army Toxic and Hazardous Materials Agency (USATHAMA). 1980. *Installation Assessment of DDOU*. Report No. 166.
- US Environmental Protection Agency (USEPA). 1984. ????

- USEPA. 1985b. *Guidance on Feasibility Studies under CERCLA*.
- USEPA. 1986b. *RCRA Ground Water Technical Enforcement Guidance Document (TEGD)*. OSWER-9950.1. September.
- USEPA. 1987. *RI/FS Improvements*. OSWER Directive 9355.0-20.
- USEPA. 1988a. *Guidance on Remedial Actions for Contaminated Ground Water at Superfund Sites*. OSWER Directive 9283.1-02. EPA/540/G-88/003.
- USEPA. 1988b. *CERCLA Compliance with Other Laws Manual*. OSWER Directive 9234.1-01. August.
- USEPA. 1989. *Statistical Analysis of Ground-Water Monitoring Data at RCRA Facilities*. Interim Final Guidance. April.
- USEPA. 1989a. *Guidance for Conducting Remedial Investigations and Feasibility Studies under CERCLA*. Office of Emergency and Remedial Response, OSWER Directive 9355.3-01. EPA/540/G-89/004.
- USEPA. 1989b. *Transport and Fate of Contaminants in the Subsurface*. U.S. Environmental Protection Agency, Robert S. Kerr Environmental Research Laboratory. EPA/625/489/019.
- USEPA. 1989c. *CERCLA. Compliance with other Laws Manual: Part II. Clean Air Act and Other Environmental Statutes and State Requirements*. OSWER Directive 9234.1-02. August.
- USEPA . 1992a. Methods for evaluating the attainment of cleanup standards. *Ground Water 2*. July.
- USEPA. 1992b. *Statistical Analysis of Ground-Water Monitoring Data at RCRA Facilities*. Addendum to Interim Final Guidance. July.
- USEPA. 1993. *Guidance for Evaluating the Technical Impracticability of Groundwater Restoration*, Office of Solid Waste and Emergency Response, September, EPA-540-R-93-080.
- USEPA. 1994. *Methods for Monitoring Pump-and-Treat Performance*. Office of Research and Development. EPA/600/R-94/123.
- USEPA. 1996. *Guidance for Evaluation of Federal Agency Demonstrations that Remedial Actions Are Operating Properly and Successfully Under CERCLA Section 120(h)(3)* (interim). Office of Solid Waste and Emergency Response.
- USEPA. 1997. *Test Methods for Evaluating Solid Waste: Physical/Chemical Methods*. SW-846. Third edition, Update III. Published November 1986. Promulgated June 1997.
- USEPA. 1997. *Technology Support Center Issue. The Lognormal Distribution in Environmental Applications*. December.

Wiedemeier, T.H., Swanson, M.A., Moutoux, D.E., Gordon, E.K., Wilson, J.T., Wilson, B.H., Kampbell, D.H., Haas, P.E., Miller, R.N., Hansen, J.E., and F.H. Chapelle. 1998. *Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Ground Water*. EPA/600/R-98/128. September.

Wiedemeier et al., 2000. *Designing Monitoring Programs to Effectively Evaluate the Performance of Natural Attenuation*. January.

APPENDIX A
NATURAL ATTENUATION

APPENDIX A
NATURAL ATTENUATION
(PROPERTIES OF CHEMICALS OF POTENTIAL CONCERN
AND
THEIR MOVEMENT AND FATE IN THE ENVIRONMENT)

The risk-based paradigm, established by the U.S. EPA as part of the Superfund program, consists of four basic technical elements that progress logically to a quantitative evaluation of the site-specific risks to human health and the environment. The elements required for risk-based site assessments are:

- hazard identification,
- exposure assessment,
- toxicity assessment, and
- risk characterization.

Hazard identification consists of identifying the site-specific constituents of potential concern and contaminated media that represent potential threats to human health and the environment. This identification is accomplished by reviewing the available site characterization information, and evaluating the hazard potential of detected constituents, based on their known effects to human and/or environmental receptors. This evaluation establishes the list of constituents of potential concern that will form the basis for subsequent risk-based analysis.

The *exposure assessment* is used to develop an understanding of the movement of constituents of potential concern from contaminated media at the site, through the environment, to a point of contact with human or environmental receptors. Site-specific factors examined in the exposure assessment include identification of contaminated media, evaluation of the physical and chemical properties controlling the occurrence, movement and fate of site-related constituents in the environment, and a qualitative assessment of the rates and directions of chemical migration. General considerations governing the movement and fate of site-related constituents in the environment are discussed in this section.

The toxicological effects of site-related constituents and contaminated media on potential receptors are evaluated as part of the *toxicity assessment*. The effects of concern include acute and chronic effects, and address both carcinogenic and non-

carcinogenic toxicological endpoints. This information is used to estimate the toxicological effect to a receptor that could result from a specific intake (“dose”) of the constituent. *Risk characterization* integrates the information from the hazard identification, exposure assessment, and toxicity assessment to develop a quantitative evaluation of the risk associated with a site. The risk characterization thus begins with the identification of site-related constituents, projects their release and movement in the environment, estimates their uptake by potential human and environmental receptors, and evaluates the possible toxicological effects of these chemical “doses” on receptors as a measure of potential risk

Consideration of the physical and chemical properties of the chemicals of potential environmental concern is critical in evaluating the fate of those chemicals in the environment, and the possible range in performance of various remedial alternatives (Nyer and Skladany, 1989). A general review of the properties of the volatile organic chemicals that have been detected in groundwater beneath OU1, George Air Force Base (GAFB), is therefore appropriate.

A1.0 CHEMICAL STRUCTURE AND ITS INFLUENCE ON CHEMICAL PROPERTIES

A1.1 Organic Compounds at GAFB OU1

Several volatile organic compounds, including the volatile halogenated organic compounds tetrachloroethene (PCE), trichloroethene (TCE), isomers of dichloroethene (DCE) and dichloroethane (DCA), and the volatile aromatic compounds toluene and xylene isomers (BTEX compounds), have been detected in groundwater beneath, and down-gradient of GAFB OU1. These chemicals have been detected at concentrations judged to be above background and are considered to be site-related at OU1, as a probable consequence of historic activities on the facility. The volatile organic compounds that have been detected are of two general types: organic solvents, and constituents of petroleum fuels.

Organic Solvents

Various types of industrial solvents are typically used for cleaning and degreasing, paint thinning, and adhesive mixing. Solvents generally consist of volatile organic compounds, together with an inert base. These are mixed in varying proportions depending on specific applications. The compounds that have been identified in groundwater at GAFB OU1, including PCE, TCE, 1,1-DCA, 1,1-DCE, cis-1,2-DCE, and 1,1,2-trichloroethane (1,1,2-TCA), are generally considered to be constituents of solvents (Howard, 1990b).

Petroleum Distillate Fuels

Petroleum fuels are distillates of crude petroleum comprising a complex mixture predominantly composed of paraffins, cycloparaffins and aromatic groups, together with other minor constituents added as octane enhancers, or to improve evaporation and condensation characteristics of the fuel. The aromatic BTEX compounds are primary constituents of petroleum- distillate fuels, and are chemicals of potential environmental

concern in fuels because they are relatively toxic, and can be mobile in the environment (California Department of Health Services, 1988).

Nearly all organic chemicals are products or byproducts of the refining and processing of crude petroleum. Petroleum hydrocarbon compounds are composed of carbon and hydrogen atoms, arranged into an almost infinite number of discrete molecules. These molecules are classified as alkanes, alkenes, and aromatic hydrocarbons, on the basis of their structure.

Halogenated hydrocarbon compounds are composed primarily of carbon and hydrogen atoms, arranged into an almost infinite number of discrete molecules, with one or more halogen atoms (usually, chlorine, bromine, or fluorine), attached to the hydrocarbon structure as a functional group (Dickerson *et al.*, 1970). Alkanes contain only carbon-carbon single bonds, while alkenes contain carbon-carbon double bonds, which tend to increase the polarity and solubility of the molecule (Schwarzenbach *et al.*, 1993). Aromatic hydrocarbon compounds are based on the benzene ring structure, with conjugated carbon-carbon double bonds, which imparts some unique properties. The monoaromatic compounds (benzene, toluene, ethylbenzene, and xylene isomers), are very soluble in water, as compared with most alkanes and alkenes. Their high solubility causes aromatic compounds to be quite mobile in the environment (Zemo *et al.*, 1995).

The number of carbon atoms, the nature of the carbon-carbon bonds, and the number of halogen functional groups in a halogenated hydrocarbon compound have major effects on its properties (Nyer and Skladany, 1989; Schwarzenbach *et al.*, 1993). Halogenated hydrocarbons are nonelectrolytes, in that they do not dissociate into cations and anions in aqueous solution, but rather dissolve as neutral species. Halogen functional groups, and alkene bonds, increase the polarity of halocarbon molecules; and the halogen functional groups associate with water molecules by hydrogen bridging, which increases the solubility of polar nonelectrolytes, as compared to non-halogenated hydrocarbons of similar structure (Luckner and Schestakow, 1991). Halocarbon solubility rapidly decreases as the number of carbon atoms, and/or the number of halogen atoms in the compound increase(s); vapor pressures also decrease as carbon or halogen numbers increase. High vapor pressures indicate that a compound is readily volatilized; low vapor pressures are associated with chemicals that are semi-volatile or non-volatile. For all classes of halogenated hydrocarbons, aqueous solubility decreases, and the tendency of the hydrocarbon compound to sorb to soil particles (or "partition" to soil), increases as the number of halogen atoms and molecular weight increase (Schwarzenbach *et al.*, 1993). A summary of all the volatile organic compounds that have been detected in groundwater at GAFB OU1, together with the chemical properties of each compound, that influence its mobility in the environment, is presented in Table A.1.

A1.2 Exposure Pathways and Routes of Chemical Migration

As described in the Superfund Public Health Evaluation Manual (U.S. EPA, 1986), an exposure pathway consists of four necessary elements:

1. A source and mechanism of chemical release to the environment;
2. An environmental transport medium for the released chemical;

Table A.1 Properties of Selected Organic Compounds

3. A point of potential contact for human or environmental receptors with the contaminated medium (referred to as the exposure point); and
4. A receptor exposure route at the exposure point.

An exposure pathway is complete when all four elements are present and is incomplete when elements are missing. Exposure estimates can only be calculated for completed exposure pathways.

Two general pathways – surface pathways and subsurface pathways – can function as potential routes of chemical migration from source areas to other media, and/or to potential receptors. Surface transport mechanisms can include surface-water runoff; entrainment and transport of soil (as sediment) during precipitation events; overland flow from springs and seeps; airborne transport of fugitive dusts, aerosols, or vapors; and anthropogenic transport (e.g., excavation and removal of soil). Subsurface transport mechanisms can include movement of site-related constituents as a free phase (“non-aqueous phase”), as a dissolved phase in infiltrating precipitation, or in water within the saturated zone; and as a vapor phase in unsaturated pore spaces.

The four environmental media in which transport of site-related constituents can occur, potentially resulting in exposure of susceptible populations to chemicals, are groundwater, surface water and sediment, soil, and air. Numerous factors can affect the migration and potential bioavailability of chemicals, including:

<u>Groundwater</u>	<u>Surface Water and Sediment</u>
Direction of flow	Flow velocity
Gradient	Slope
Hydraulic conductivity	Discharge rate
Chemical partitioning	Sediment load
<u>Soil</u>	<u>Air</u>
Chemistry of soil	Temperature
Degree of saturation	Wind velocity
Chemical partitioning	Chemical volatility

The results of intensive site investigations indicate that groundwater is the only environmental medium at GAFB OU1 that has been adversely affected by volatile organic chemicals (Sections 1 and 2 of the report). Despite extensive sample-collection programs, no discrete sources of volatile organic chemicals in soil have been identified; and the depth to groundwater and stratigraphic position of water-bearing units (the Upper

and Lower Aquifers) beneath extensive silty clay units indicates that volatilization to the atmosphere is probably not an important fate mechanism for chemicals at GAFB OU1. The general physical and chemical characteristics governing the movement and fate of constituents of potential concern in groundwater are detailed in the following sections.

A1.3 Physico-Chemical Transport and Attenuation Mechanisms

Several transport processes control the physical movement of chemicals through soils, as non-aqueous phase liquid (NAPL), dissolved (aqueous) phase, and sorbed (solid) phase. When initially released to the subsurface environment, petroleum hydrocarbons and organic solvents are usually in the NAPL (oil) phase. Once a chemical has been introduced into the environment, it interacts with the surrounding soils. The major processes affecting chemicals in the subsurface include sorption to soil, diffusion, dissolution, chemical and biological degradation, and volatilization (Nyer and Skladany, 1989).

Under particular conditions, chemicals can exist in the environment in any of four different phases – as pure compound or in a chemical mixture; dissolved in water; sorbed to soil particles; or as a vapor. The degree to which a particular chemical is segregated among these phases, under specified conditions of temperature, pressure, and moisture content, in a particular soil matrix, is known as *partitioning*. Two basic types of partitioning are significant when evaluating the fate and transport of most chemical compounds. The first is partitioning of a single compound from a pure chemical phase or chemical mixture into air and/or water (e.g., partitioning of BTEX constituents from free-phase fuel oil into water in the unsaturated zone). After removal from the pure chemical phase or chemical mixture, compounds dissolved in water or present in the vapor phase will partition among the three phases in the subsurface environment, becoming dissolved in water, sorbed to soil, or volatilized in soil gas. The partitioning of a particular compound among the three phases, and its subsequent migration and fate in the environment, depends on its chemical properties (Jury *et al.*, 1983), including:

- solubility of the compound in water;
- chemical air-gas diffusion coefficient (related to the chemical's volatility);
- chemical water-liquid diffusion coefficient;
- chemical organic-carbon partition coefficient;
- Henry's Law constant for the chemical; and
- rate of chemical decay.

Subsurface transport of chemicals as NAPL, dissolved-phase, or vapor-phase, like movement of any liquid in the subsurface, is driven by potential gradients – gravitational, hydraulic, or chemical. In the unsaturated zone, gravitational and hydraulic potential gradients are primarily vertical, so that the direction of movement is generally downward. In some situations, NAPLs denser than water will migrate through the soil in the unsaturated zone until they reach the capillary fringe, (in which the soil is fully saturated,

but hydrostatic pressure is less than atmospheric pressure) above the water table. At that point, the NAPL spreads until sufficient pressure (NAPL head) develops to enable the liquid to penetrate the capillary fringe and migrate to the water table (Mallon, 1989). As water percolates through the unsaturated zone, chemicals present as non-aqueous phase, a sorbed phase, or a vapor phase, can be dissolved and migrate with the infiltrating water to the water table. Dissolved constituents are carried downward in percolating water ("advective transport"). Volatilized compounds move in response to chemical concentration gradients between soil moisture and air-filled pore spaces ("diffusive transport"). If the relative vapor density of the volatile phase is greater than that of air, some chemical migration in the vapor phase may be downward (Mallon, 1989). In general, however, vapor-phase migration is from the subsurface to the atmosphere.

The transport rate of dissolved constituents in the unsaturated zone depends primarily on the permeability of the soil, its water content, and the concentrations of dissolved chemicals in percolating water. The transport of volatilized compounds in the unsaturated zone depends primarily on the permeability of the soil, its water content, and the ambient air temperature and barometric pressure. Below the water table, there are no continuous air-filled pores, and vapor-phase transport does not occur. Depending on local conditions, the primary mechanism by which dissolved constituents migrate in the saturated zone is usually advective transport, and the direction and rate of advective transport are controlled primarily by the hydraulic conductivity of the soil, and local hydraulic gradients (Neff *et al.*, 1994; Reilly *et al.*, 1987; U.S. EPA, 1989a). However, under conditions of very low groundwater flow velocities, chemical diffusive mechanisms, driven by chemical concentration gradients, and controlled primarily by site-specific chemical diffusion coefficients, is the primary transport mechanism in the subsurface (Gillham and Cherry, 1982).

The physico-chemical mechanisms governing the migration of contaminants in the subsurface at GAFB OU1 include volatilization, dissolution, dispersion, diffusion, and sorption. Examination of the chemical properties that control these mechanisms (volatility, solubility, and solid/liquid partitioning) with respect to current conditions in the physical environment can assist in predicting how site-related chemicals will interact with the environment, and how site conditions might influence the fate of the contaminants of potential concern. Representative chemical properties for the identified site-related contaminants are summarized in Table A.1. (Note that the literature values, reported by different workers, for a particular chemical property can vary widely. The values listed in Table A.1 represent chemical property values judged to be most representative, or are in the median range of values reported for a particular chemical.)

A1.3.1 Volatility

Volatilization is the process by which a constituent is converted from a solid or liquid phase to vapor, ultimately resulting in transfer of the chemical to the atmosphere. The volatility of a particular chemical is a function of that chemical's vapor pressure and Henry's Law constant. The vapor pressure of a substance at a reference temperature is the pressure exerted by the vapor phase of the substance in equilibrium with the liquid or solid phase of the substance, at that temperature. A chemical with a high vapor pressure has a greater tendency to volatilize to the atmosphere than does a chemical with a low vapor pressure. The Henry's Law constant is a measure of the relative tendency of a

chemical to move between the dissolved phase and vapor phase, and is a function of the vapor pressure and solubility of the chemical. A chemical with a high Henry's Law constant will have a high ratio of chemical concentration in the vapor phase compared with that chemical's concentration in the dissolved phase, and again will be more likely to volatilize to the surrounding atmosphere.

A1.3.2 Solubility

The aqueous solubility of a chemical species provides an indication of how readily that particular chemical could dissolve into and migrate with groundwater. Volatile organic compounds (e.g., the BTEX constituents) are moderately soluble, as a consequence of their molecular structure; and the attached chlorine atoms confer a moderate degree of solubility on substituted hydrocarbon compounds.

Constituents having moderate to high solubilities may be available for transport as a dissolved phase in the subsurface. The less soluble chemicals will become absorbed or occluded in soil, and are unlikely to migrate with infiltrating vadose-zone water, or in groundwater.

A1.3.3 Solid/Liquid Partitioning

The rate of migration of a chemical in the subsurface also depends on the tendency of that chemical to partition between the dissolved (in water) and solid phases (on soil particles). Partitioning of a chemical between the dissolved phase and solid phase is commonly referred to as *soil adsorption* ("sorption"), and is quantified by the soil partition coefficient or distribution coefficient (K_d), which is the proportionality constant relating the amount of chemical sorbed to soil and the concentration at equilibrium in soil water (McCall *et al.*, 1983):

$$C_{sorbed} = K_d \times C_{dissolved} \quad (\text{A-1}) \text{ where}$$

C_{sorbed} = Concentration of chemical sorbed to soil [M/L³];

K_d = Soil partition coefficient [L³/M]; and

$C_{dissolved}$ = Concentration of chemical in adjacent soil water, at equilibrium with sorbed phase in soil [M/L³].

This description of the process assumes that partitioning between the sorbed and dissolved phases is completely reversible, and that the equilibrium isotherm relating the relative concentrations in the two phases is linear (Neff *et al.*, 1994; Lyman *et al.*, 1990).

Soils are extremely heterogeneous mixtures of different particle types, composition, and sizes. Because of this heterogeneity, the partition coefficient for a particular chemical is usually regarded as a site-specific property, and is likely to vary substantially with location, depending on the chemical composition and grain-size distribution of the soil used for determination of the partition coefficient. However, sorption studies on a wide variety of nonpolar organic compounds and soil and sediment types indicate that organic matter in soil controls sorption where there is sufficient organic matter present

(more than about 0.1 percent organic carbon). This observation has been used as the basis for normalizing the linear partition coefficient to the concentration of total organic carbon in the soil (Karickhoff *et al.*, 1979; Karickhoff, 1981). The normalized partition coefficient for a particular chemical (K_{oc}) is calculated from the results of sorption studies, using

$$K_{oc} = \frac{K_d}{f_{oc}} \quad (\text{A-2})$$

where

K_{oc} = Organic carbon partition coefficient [L^3/M]; and

f_{oc} = Fraction of organic carbon in the soil [].

If the organic carbon content of a particular soil is known or can be estimated, the fraction of organic carbon can be used, together with published values of organic carbon partition coefficients (Table A.1) to evaluate chemical partitioning, using

$$K_d = f_{oc} \times K_{oc} \quad (\text{A-3})$$

All hydrocarbon compounds, and most other chemicals, sorb to soil to a greater or lesser degree; the fraction of sorbed hydrocarbons increases as the concentration of organic carbon in the soil increases. Chemicals having larger values of partition coefficients will be more strongly adsorbed to soil, and less mobile in the environment (Nyer and Skladany, 1989). Most fuel constituents and organic solvents have relatively large partition coefficient values (Table A.1), are strongly sorbed to soil particles, and travel only slowly in the dissolved (aqueous) phase.

A2.0 FATE OF CHEMICALS OF POTENTIAL CONCERN IN THE ENVIRONMENT

A2.1 Volatilization

In many circumstances, low-molecular-weight compounds will volatilize (evaporate) in the vadose-zone and diffuse upward in soil gas. Included in this category are volatile and volatile substituted hydrocarbon compounds, alkanes up through dodecane, and aromatic and substituted aromatic compounds through naphthalene (Neff *et al.*, 1994). The rates of volatilization of different hydrocarbons are directly proportional to their vapor pressures.

Because all volatile organic chemicals, including TCE and the DCE isomers have relatively high vapor pressures (Table A.1), volatilization is perhaps the most important fate mechanism removing these chemicals from the unsaturated environment near land surface. However, once a chemical has been dissolved in water, its potential for volatilization from the saturated zone in the subsurface is limited, because vapor transfer across the capillary fringe can be very slow (McCarthy and Johnson, 1992). For example, Chiang *et al.* (1989) demonstrated that less than 5 percent of the mass of dissolved BTEX

is lost to volatilization in the saturated groundwater environment. Rivett (1995) observed that for dissolved-phase plumes deeper than about one meter below the air/water interface, only low chemical concentrations would be detectable in soil gas due to the downward movement of groundwater near the water table. This suggests that very little, if any, chemical mass will be lost to volatilization, in areas in which chemicals occur in groundwater at depths greater than a few feet below the water table. The impact of volatilization is further diminished by the presence of clay layers within the sandy intervals.

A2.2 Dissolution

Chemicals with higher aqueous solubilities will tend to dissolve into the aqueous phase, and to migrate slowly through soil, transported by infiltrating vadose-zone water, or in groundwater. Dissolved-phase transport can occur in either the unsaturated or saturated zone. The unsaturated zone extends from land surface to the top of the water table, while the saturated zone generally includes all earth material below the water table. Dissolved constituents can enter the unsaturated zone via infiltration of water that contains chemicals, dissolved from an above-ground surface source, or the constituents can become dissolved as percolating water passes over a source of constituents in soil.

Chlorinated solvent constituents are moderately soluble (Table A.1), with aqueous solubilities ranging from 150 milligrams per liter (mg/L) for PCE to about 5,500 mg/L (1,1-DCA). Therefore, TCE and the other solvent constituents detected at GAFB OUI can be relatively mobile in the aqueous environment, depending on local conditions.

A2.3 Dispersion

Solutes in transit through a groundwater system are affected by hydraulic and chemical processes, including advection, diffusion, dispersion, retardation, and chemical decay. A rigorous analysis of chemical transport in a ground-water system should examine the effects of all these processes. After a chemical has been dissolved in vadose-zone water or groundwater, it migrates in the dissolved phase through the unsaturated and saturated systems, under the influence of local hydraulic and/or chemical potentials. Depending on local conditions, the physical laws that govern fluid motion are such that water tends to move from areas of relatively greater hydraulic potential (“head”) to areas of relatively lower hydraulic potential. The linear path along which water moves from a region of greater hydraulic potential to a region of lower hydraulic potential is known as a *flowpath*, and the change in hydraulic potential along that flowpath is known as a *hydraulic gradient*. Movement of groundwater in a flow system therefore occurs from *up-gradient* areas to *down-gradient* areas.

Transport of a chemical in the dissolved phase is usually regarded as the net effect of two processes – advection and dispersion (Gillham and Cherry, 1982). Advective transport is that component of movement of a solute that is attributable to the movement of the water in which it is dissolved. In other words, after some period of time, a chemical dissolved in groundwater will migrate a certain distance from the original source of the chemical, as a consequence of the movement of water in the subsurface. In the absence of other effects (e.g., sorption), the migration velocity of the center of mass of a dissolved chemical slug is the average groundwater flow velocity.

As the dissolved chemical moves away from its source, it is affected by dispersive processes – mechanical mixing of the dissolved chemical, and molecular diffusion. Mechanical mixing occurs because each molecule of dissolved chemical follows a slightly different flowpath through the pore spaces within the porous medium; each also moves at a slightly different velocity. As groundwater, containing dissolved chemical, moves along its tortuous flowpath in the subsurface, it tends to mix with water that contains no chemical (or contains the chemical at lower concentrations), diluting the dissolved-phase chemical. Molecular diffusion, occurring in the presence of a chemical concentration gradient, causes dissolved-phase chemical to migrate from areas of relatively higher concentration to areas of relatively lower concentration. (Because molecular diffusion operates on a microscopic scale, and because diffusive velocities are generally much lower than the advective transport velocity of dissolved-phase chemical, the effects of mechanical mixing in most groundwater systems are generally much greater than the effects due to chemical diffusion.) The net effect of dispersive processes acting on the dissolved chemical as it migrates through a porous medium, is that the mass of chemical becomes distributed through an ever-increasing volume of earth material. This results in a decrease in chemical concentration with increasing distance down-gradient from the chemical source.

B2.4 Retardation

As water, containing dissolved-phase chemical, moves through earth materials, the chemical tends to partition between the sorbed and dissolved phases (Section A.1.3.3). In most systems, chemical partitioning occurs at a rate that maintains chemical equilibrium (as expressed by the partition coefficient) between the sorbed and dissolved phases. Partitioning to the solid phase tends to remove a certain amount of chemical from the dissolved phase in groundwater, effectively slowing the rate of chemical migration, with respect to the rate of movement of the groundwater in which the chemical is dissolved. This phenomenon is known as *retardation*; and the ratio of the velocity of the retarded chemical to local groundwater flow velocity is known as the *retardation coefficient* (**R**):

$$R = \frac{V_{groundwater}}{V_{chemical}} = 1 + \left[\left(\frac{\rho}{n_e} \right) \times K_d \right] \quad (\text{A-4})$$

where

$V_{groundwater}$ = average groundwater flow velocity [L/T],

$V_{chemical}$ = average velocity of center of mass of dissolved chemical slug [L/T],

ρ = unit weight of porous medium [M/L³], and

n_e = effective porosity of the medium [].

All the solvent constituents detected at GAFB OU1 have relatively high organic-carbon partitioning coefficients (Section A1.3.3), ranging from about 45 milliliters per gram (mL/g) for cis-1,2-DCE to 107 mL/g (TCE; Table A.1). This indicates that these

solvent constituents will preferentially sorb to soil; and their migration can be significantly retarded with respect to the velocity of groundwater movement.

A3.0 CHEMICAL AND BIOLOGICAL DEGRADATION

A3.1 Biodegradation Processes

Nearly all soils contain colonies of bacteria and fungi that are capable of biodegrading at least some organic compounds. Soil bacteria and fungi are tremendously diverse, and readily adapt to utilizing different types of organic molecules as their sole or supplemental carbon source (Scow, 1990). Many genera of microorganisms are able to completely oxidize saturated, and to a lesser extent, aromatic hydrocarbons and heterocyclic compounds, to carbon dioxide and water. Although all organic compounds found in petroleum-based fuels can be degraded by bacteria (Dragun, 1988), the rates of fuel hydrocarbon degradation are much lower under anoxic than oxygen-rich conditions (Nyer and Skladany, 1989). Following a release of a petroleum-derived product to soil, different hydrocarbon classes are degraded simultaneously, but at widely varying rates, by indigenous microbiota. Normal alkanes of low molecular weight (C-8 to C-22) are metabolized most rapidly, followed by isoalkanes and higher-molecular-weight normal alkanes, olefins, monoaromatic compounds (benzenes), and polynuclear aromatic hydrocarbon (PAH) compounds (Howard *et al.*, 1991; Neff *et al.*, 1994; Park *et al.*, 1990).

During biodegradation, microorganisms transform available nutrients (the “substrate”) into forms useful for energy and cell reproduction by facilitating thermodynamically advantageous reduction/oxidation (redox) reactions involving the transfer of electrons from electron donors to electron acceptors. This results in oxidation of the electron donor and reduction of the electron acceptor. Electron donors can include natural organic material and anthropogenic hydrocarbon compounds. Electron acceptors are elements or compounds that occur in relatively oxidized states and can accept electrons generated during substrate oxidation. Without the complete transfer of electrons to an electron acceptor, a substrate cannot be fully oxidized. Electron acceptors commonly occurring in groundwater include dissolved oxygen (DO), nitrate, ferric iron (iron III), manganese, sulfate, carbon dioxide, and highly chlorinated solvents [e.g., TCE, TCA, and polychlorinated benzenes].

The driving force of biodegradation is electron transfer, which is quantified by the Gibbs free energy of the reaction (ΔG°_r) (Stumm and Morgan, 1981; Bouwer, 1994; Godsey, 1994). The value of ΔG°_r represents the quantity of free energy consumed ($\Delta G^{\circ}_r > 0$) or yielded ($\Delta G^{\circ}_r < 0$) to the system during the reaction. Although thermodynamically favorable, most of the reactions involved in biodegradation of fuel hydrocarbons or chlorinated aliphatic hydrocarbons (CAHs) cannot proceed abiotically because of the lack of activation energy. Microorganisms are capable of providing the necessary activation energy; however, they will facilitate only those redox reactions that have a net yield of energy (i.e., $\Delta G^{\circ}_r < 0$). Microorganisms preferentially utilize electron acceptors while metabolizing fuel hydrocarbons (Bouwer, 1992). DO is utilized first as the prime electron acceptor. After the DO is consumed, anaerobic microorganisms typically use native electron acceptors in the following order of preference: nitrate, manganese, ferric iron hydroxide, sulfate, and finally carbon dioxide. Chlorinated solvents are generally

used as electron acceptors when aquifer conditions are such that sulfate or carbon dioxide is the preferred electron acceptor.

In addition to being controlled by the energy yield of the reaction, the expected sequence of redox processes also is a function of the oxidizing potential of the groundwater. This potential is a measure of the relative tendency of a solution or chemical reaction to accept or transfer electrons. As each subsequent electron acceptor is utilized, the groundwater becomes more reducing, and the oxidation/reduction potential (ORP) of the water decreases. The main force driving this change in redox potential is microbially mediated redox reactions. ORP can be used as an indicator of which redox reactions may be operating at a site. Environmental conditions and microbial competition ultimately determine which processes will dominate.

In contrast to fuel hydrocarbons, biodegradation of chlorinated solvent constituents is generally favored by low dissolved oxygen (anaerobic conditions) and reducing conditions (USEPA, 1998). Depending on the types and concentrations of electron acceptors present (e.g., nitrate, sulfate, carbon dioxide), pH conditions, and ORP, anaerobic biodegradation can occur by denitrification, manganese reduction, ferric iron reduction, sulfate reduction, or methanogenesis. Other, less common anaerobic degradation mechanisms such as manganese or nitrate reduction or reductive dechlorination may dominate if the physical and chemical conditions in the subsurface favor use of these electron acceptors.

When hydrocarbons are utilized as the primary electron donor for microbial metabolism, they typically are completely degraded or detoxified (Bouwer, 1992). When hydrocarbon compounds are not present in sufficient quantities to act as the primary metabolic substrate, they cannot support microbial growth as the sole electron donors. In this case, the contaminant can still be degraded, but the microorganisms will obtain the majority of their energy from alternative substrates in the aqueous environment. This type of metabolic degradation is referred to as “secondary utilization” because the hydrocarbon compound contributes only a small fraction of the energy and carbon needed for cell production and maintenance (Bouwer, 1992).

A3.2 Chemical Degradation as a First-Order Process

Because biodegradation may be the most important fate process removing organic chemicals from the environment, an evaluation of biodegradation rate constants is necessary to adequately assess the fate and transport of contaminants in the subsurface. While several different representations of the processes by which chemical degradation occurs at the microscopic level in the environment are currently in use, all require detailed knowledge of *in-situ* physical, chemical, and biological conditions (e.g., Baveye and Valocchi, 1989). For example, to properly account for biodegradation at a microscopic level, one must accurately describe such parameters as nutrient availability, cellular diffusion, cellular growth dynamics, the microscopic dimensions of individual pores, inter-pore substrate concentrations, and factors controlling potential changes in soil porosity and permeability; and must then incorporate these parameters into a nonlinear mathematical representation of process dynamics.

Fortunately, this level of effort may not be necessary. Two of the principal models proposed by researchers to describe degradation processes at the cell level (the biofilm and Monod kinetic models), can be simplified to a first-order kinetic approximation under certain limiting conditions or at field scales (Bouwer and McCarty, 1984; MacQuarrie *et al.*, 1990). In addition, several authors have noted that first-order, or pseudo-first-order kinetics approximate the rate of hydrocarbon degradation observed at individual study sites (Berry-Spark *et al.*, 1988; Chiang *et al.*, 1989; Dragun, 1988; Kemblowski *et al.*, 1987). The use of first-order kinetics assumes that the rate of change in chemical concentration with time (t) is dependent only on the concentration of the chemical in soil or ground water (C):

$$\frac{\partial C}{\partial t} = \mu C \quad (\text{A-5})$$

where μ is a first-order rate constant [1/T]. The chemical concentration in soil or groundwater at a given time can be found by integrating Equation B-5 to obtain:

$$C = C_0 e^{-\mu t} \quad (\text{A-6})$$

where C_0 is the initial concentration of the chemical.

Ranges of first-order rate constants have been estimated and tabulated for a number of organic chemicals (see, for example, Howard *et al.*, 1991 and Wiedemeier *et al.*, 1999). If neither site-specific information, nor tabulated rate constants are available, the first-order rate constant for a particular chemical can be estimated from reported half-life data, using:

$$\mu = \frac{\ln(2)}{\tau_{1/2}} \quad (\text{A-7})$$

where

$$\tau_{1/2} = \text{constituent half-life (days).}$$

A3.3 Degradation of Halogenated Compounds

Chlorinated solvents can also be transformed, directly or indirectly, by biological or abiotic processes (Mallon, 1989; USEPA, 1998). CAHs may undergo biodegradation along three different pathways: use as an electron acceptor, use as an electron donor, or cometabolism (degradation resulting from exposure to a catalytic enzyme fortuitously produced during an unrelated process). At a particular location, one or all of these processes may be operating, although at many sites the use of CAHs as electron acceptors appears to be the most likely.

In a pristine aquifer, native organic carbon is utilized as an electron donor, and DO is utilized first as the prime electron acceptor. Where anthropogenic carbon (e.g., fuel hydrocarbons, less-chlorinated CAHs, or chlorinated benzenes with four or fewer chlorine atoms) is present, it also may be utilized as an electron donor. Most chlorinated solvents that can act as electron donors have thus far only been demonstrated to do so

under aerobic conditions, with the notable exception of vinyl chloride (Bradley and Chapelle, 1996). After the DO is consumed, anaerobic microorganisms typically use native electron acceptors (as available) in the following order of preference: nitrate, ferric oxyhydroxide, sulfate, and finally carbon dioxide. Evaluation of the distribution of these electron acceptors can provide evidence of where and how biodegradation of chlorinated solvents is occurring. A more complete description of the main types of biodegradation reactions affecting chlorinated solvents dissolved in groundwater is presented in the following subsections.

A3.3.1 Electron Acceptor Reactions (Reductive Dehalogenation)

Halogenated compounds are known to undergo chemical transformations, or degradation, in natural systems (Vogel and McCarty, 1985; Vogel *et al.*, 1987; Lesage *et al.*, 1990; Barbee, 1994), principally through the mechanism of sequential reductive dehalogenation, under anaerobic conditions. During this process, the halogenated hydrocarbon is used as an electron acceptor, not as a source of carbon, and a halogen atom is removed and replaced with a hydrogen atom at each reaction step (Criddle and McCarty, 1991). A typical reductive halogenation transformation sequence begins with a highly chlorinated alkene, e.g., TCE (Figure A.1). Through sequential reductive reactions, TCE is first transformed to 1,1-DCE, or either the *cis*- or *trans*- isomer of 1,2-DCE; and DCE is transformed to vinyl chloride. In the final reductive dehalogenation step, vinyl chloride is mineralized (changed to carbon dioxide, water, and hydrogen chloride). Minor amounts of other chlorinated chemicals (for example, 1,1-DCA) can also be generated during reductive dehalogenation reactions; however, the sequence

TCE --> DCE --> vinyl chloride

is most typical (Vogel *et al.*, 1987; Barbee, 1994). This chain of reaction products is referred to as “TCE and its *daughters*” (Barbee, 1994). In fact, the relative proportions of TCE and its daughters, and the relative locations at which these chemicals have been detected in groundwater at GAFB OU1, indicate that TCE was the primary chemical, originally introduced to the subsurface, and other halogenated chemicals have gradually appeared, at low concentrations, as the precursor chemical (TCE) has evolved in the subsurface along its degradation path (Figure A.1). Reductive dehalogenation of some compounds also has been shown to preferentially produce specific daughter compounds. For example, during reductive dehalogenation of TCE, all three isomers of DCE can theoretically be produced; however, Bouwer (1994) reports that under the influence of biodegradation, *cis*-1,2-DCE is a more common intermediate than *trans*-1,2-DCE, and that 1,1-DCE is the least prevalent intermediate of the three DCE isomers.

Reductive dehalogenation affects each of the chlorinated compounds differently. Of the ethenes, PCE is the most susceptible to reductive dehalogenation because it is the

Figure A.1 Reductive Dehalogenation of Chlorinated Ethenes

most highly oxidized. Conversely, VC is the least susceptible to reductive dehalogenation because it is the least oxidized of these compounds. In general, the rate of reductive dehalogenation of chlorinated solvents has been observed to decrease as the degree of chlorination decreases (Vogel and McCarty, 1985; Bouwer, 1994). Murray and Richardson (1993) have postulated that this rate decrease may explain the apparent accumulation of VC in TCE plumes that are undergoing reductive dehalogenation.

In addition to being affected by the degree of chlorination of the compound, reductive dehalogenation also can be controlled by the redox conditions of the site groundwater system. In general, reductive dehalogenation has been demonstrated under anaerobic nitrate- and sulfate-reducing conditions, but the most rapid biodegradation rates, affecting the widest range of compounds, occur under methanogenic conditions (Bouwer, 1994). Dehalogenation of TCE to DCE can proceed under mildly reducing conditions, such as nitrate reduction or ferric iron reduction (Vogel *et al.*, 1987), while the transformation of DCE to VC or the transformation from VC to ethene requires more strongly reducing conditions (Freedman and Gossett, 1989; DeStefano *et al.*, 1991; De Bruin *et al.*, 1992).

When chlorinated compounds are used as electron acceptors, there must be a biotically-available source of carbon for microbial growth in order for reductive dehalogenation to occur (Bouwer, 1994). Potential carbon sources/electron donors can include low-molecular-weight compounds (e.g., lactate, acetate, methanol, or glucose) present in natural organic matter, fuel hydrocarbons, or less-chlorinated solvents (as discussed below).

A3.3.2 Electron Donor Reactions

Under aerobic conditions some chlorinated solvents can be utilized as the primary substrate (i.e., electron donor) in biologically mediated redox reactions (McCarty and Semprini, 1994). In this type of reaction, the facilitating microorganism obtains energy and organic carbon from the degraded compound. In contrast to reactions in which the chlorinated compound is used as an electron acceptor, only the less oxidized chlorinated solvents (e.g., VC and DCE) may be utilized as electron donors in biologically mediated redox reactions. Chlorinated solvent oxidation may be characterized by a loss of solvent mass, a decreasing molar ratio of daughter solvents to other parent solvent compounds, and rarely, the production of chloromethane.

A3.3.3 Cometabolism

When a CAH is biodegraded through cometabolism, it serves as neither an electron acceptor nor a primary substrate in a biologically mediated redox reaction. Instead, an enzyme or cofactor that is fortuitously produced by organisms for other purposes catalyzes the degradation of the CAH. The organism receives no known benefit from the degradation of the CAH; rather the cometabolic degradation of the CAH may in fact be harmful to the microorganism responsible for the production of the enzyme or cofactor (McCarty and Semprini, 1994).

Cometabolism is best documented in aerobic environments, although it can potentially occur under anaerobic conditions. Under aerobic conditions, chlorinated ethenes, with the exception of PCE, are reported to be susceptible to cometabolic degradation (Murray

and Richardson, 1993; Vogel, 1994; McCarty and Semprini, 1994). Vogel (1994) further elaborates that the cometabolism rate increases as the degree of halogenation decreases.

In the cometabolic process, bacteria indirectly transform TCE (or other chlorinated compound) as they use BTEX or another substrate to meet their energy requirements. Therefore, TCE does not enhance the degradation of BTEX or other carbon sources, nor will its cometabolism interfere with the use of electron acceptors involved in the oxidation of those carbon sources. Aerobic cometabolism of ethenes may be characterized by loss of contaminant mass, the presence of intermediate degradation products (e.g., chlorinated oxides, aldehydes, ethanols, and epoxides; Figure A.2), and the presence of other products, such as chloroform (a degradation daughter product characteristic of the aerobic pathway), chloride, carbon dioxide, carbon monoxide, and a variety of organic acids (Miller and Guengerich, 1982; McCarty and Semprini, 1994). Cometabolism requires the presence of a suitable primary substrate, such as BTEX, phenol, or methane. Given this relationship, it would follow that depletion of suitable substrates (BTEX or other organic carbon sources) likely limits cometabolism of CAHs.

A3.4 Behavior of Chlorinated Solvent Plumes

Chlorinated solvent plumes can exhibit three types of behavior depending on the amount of solvent present, the amount of native and/or anthropogenic organic carbon in the subsurface, the distribution and concentration of natural electron acceptors, and the types of electron acceptors being utilized (USEPA, 1998). Individual plumes may exhibit all three types of behavior in different portions of the plume. The different types of plume behavior are summarized below.

A3.4.1 Type 1 Behavior

Type 1 behavior occurs where the primary substrate is anthropogenic carbon (e.g., BTEX or landfill leachate), that drives reductive dechlorination. When evaluating natural attenuation of a plume exhibiting Type 1 behavior, the following questions must be answered:

1. Is the electron donor supply adequate to allow microbial reduction of the chlorinated organic compounds to proceed? In other words, will the microorganisms deplete chlorinated aliphatic hydrocarbon compounds (CAHs) (used as electron acceptors) before they deplete the primary substrate (anthropogenic carbon)?
2. What is the role of competing electron acceptors (e.g., dissolved oxygen, nitrate, ferric iron and sulfate)?
3. Is VC being oxidized, or is it being reduced?

Type 1 behavior results in the rapid and extensive degradation of the highly chlorinated solvents such as PCE, TCE, or the DCE isomers.

Figure A.2 Aerobic Oxidation of Chlorinated Ethenes

A3.4.2 Type 2 Behavior

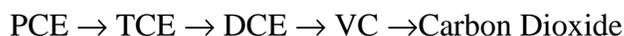
Type 2 behavior is the predominant process in areas that are characterized by relatively high concentrations of biologically-available native organic carbon. This natural carbon source drives reductive dehalogenation (i.e., the primary substrate for microorganism growth is native organic carbon). When evaluating natural attenuation of a Type 2 chlorinated solvent plume, the same questions as those posed in the description of Type 1 behavior must be answered. Type 2 behavior generally results in slower biodegradation of the highly chlorinated solvents than Type 1 behavior, but under the proper conditions (e.g., areas with naturally elevated levels of organic carbon), this type of behavior also can result in rapid degradation of these compounds.

A3.4.3 Type 3 Behavior

Type 3 behavior is the predominant process in areas that are characterized by low concentrations of native and/or anthropogenic carbon, and concentrations of DO that are greater than 1.0 milligram per liter (mg/L). Under such aerobic conditions, reductive dehalogenation will not occur, and there is little or no removal of PCE, TCE, or DCE. Biodegradation may proceed via the much slower process of cometabolism, but will be limited by the low concentrations of native or anthropogenic carbon. The most significant natural attenuation mechanisms for CAHs, in plumes exhibiting Type 3 behavior, will be advection, dispersion, and sorption. However, VC can be rapidly oxidized under these conditions, DCE may be oxidized, and cometabolism may also occur.

A3.4.4 Mixed Behavior

It is possible for a single chlorinated solvent plume to exhibit all three types of behavior in different parts of the plume. This can be beneficial for natural biodegradation of CAH plumes. For example, Wiedemeier *et al.* (1996a) describe a plume at Plattsburgh AFB, New York that exhibits Type 1 behavior in the source area and Type 3 behavior downgradient from the source. The most favorable scenario involves a plume in which PCE, TCE, and DCE are reductively dehalogenated (Type 1 or Type 2 behavior), then VC is oxidized (Type 3 behavior), either aerobically or via iron reduction. VC is oxidized to carbon dioxide in this type of plume and does not accumulate. The following sequence of reactions occurs in a plume that exhibits this type of mixed behavior:



In general, the TCE, DCE, and VC may attenuate at approximately the same rate, and thus these reactions may be confused with simple dilution. Note that no ethene is produced during this reaction. VC is removed from the system much faster under these conditions than it is under VC-reducing conditions.

A less desirable scenario, but one in which all contaminants may be entirely biodegraded, involves a plume in which all CAHs are reductively dehalogenated via Type 1 or Type 2 processes. VC is reduced to ethene, which may be further reduced to ethane or methane. The following sequence of reactions occur in this type of plume:

PCE → TCE → DCE → VC → Ethene or Ethane

Freedman and Gossett (1989) have investigated this sequence. In this type of plume, VC degrades more slowly than TCE, and thus tends to accumulate.

A3.5 Abiotic Degradation of Chlorinated Solvents

Chlorinated solvents dissolved in groundwater may also be degraded by abiotic mechanisms, although the reactions may not be complete and may result in the formation of a toxic intermediate. The most common abiotic reactions affecting chlorinated solvents are hydrolysis and dehydrohalogenation. Hydrolysis is a substitution reaction in which a halogen substituent is replaced with a hydroxyl (OH⁻) group from a water molecule. Dehydrohalogenation is an elimination reaction in which a halogen is removed from a carbon atom, followed by removal of a hydrogen atom from an adjacent carbon atom, with a double bond between the carbon atoms being produced. Other possible reactions include oxidation and reduction, although Butler and Barker (1996) note that no abiotic oxidation reactions involving common halogenated solvents have been reported in the literature. They also note that reduction reactions are most commonly microbially mediated.

Butler and Barker (1996) note that attributing changes in the presence, absence, or concentration of halogenated solvents to abiotic processes is usually difficult, particularly at the field scale, because solvents may undergo both biotic and abiotic degradation, and discerning the relative effects of each mechanism may not be possible. In addition, the breakdown products of some reactions such as hydrolysis (e.g., acids and alcohols) may be readily degraded (biotically or abiotically); so that these products also require additional analyses that may not be feasible for a field investigation (Butler and Barker, 1996). This makes collection and interpretation of field evidence to demonstrate hydrolysis difficult at best, and such evidence has not yet been successfully collected and presented (Butler and Barker, 1996). Evidence of dehydrohalogenation is also difficult to collect.

APPENDIX B
RISK-BASED CLEANUP LEVELS

APPENDIX B

RISK-BASED CLEANUP LEVELS

Groundwater (GW) risk-based concentrations (RBCs) and soil-to-GW RBCs have been derived for benzene, ethylene dibromide (EDB), and trichloroethene (TCE) based on an industrial groundskeeper dermal exposure scenario. For information purposed only, these RBCs (dermal exposure scenario) are compared with RBCs based on industrial-based drinking water (DW) RBCs and federal DW maximum contaminant levels (MCLs).

The dermal-based GW RBCs were calculated using the methodology described in USEPA's 1996 *Dermal Exposure Assessment: Principles and Applications* (EPA/600/8-91/011B) and the following assumptions:

- A groundskeeper may be dermally exposed to contaminants in groundwater while watering the grounds (e.g., lawn, flowerbeds, etc.);
- The dermal contact exposure route is the only significant, completed exposure route for the groundskeeper;
- An onsite well will be used to supply the water used by the groundskeeper;
- A groundskeeper may wear a short-sleeved shirt, shorts, and shoes while watering. Therefore, the hands, forearms, and lowerlegs will be the body-parts dermally exposed;
- The groundskeeper will water up to one time per week (assuming a two-week vacation per year), with one event per day and dermal contact occurring for 0.5 hour per event; and
- Dermal-based GW RBC calculations were based on a 1 in 1,000,000 (i.e., $1E-06$) risk goal (carcinogenicity is a more sensitive endpoint than noncancer effects).

Soil RBCs protective of migration-to-groundwater were derived using the methodology described in USEPA's 1996 *Soil Screening Guidance: User's Guide* (EPA/540/R-96/018) and *Technical Background Document* (EPA/540/R95/128), hereafter referred to as the USEPA SSL Guidance Document. USEPA-recommended chemical-specific parameters for benzene and TCE, soil-to-leachate default parameters, and the default dilution attenuation factor (DAF) of 20 (assuming a 0.5-acre source) were used in the calculations (refer to the USEPA SSL Guidance Document).

The results of the dermal-based GW RBC calculations are shown in Table B.1. Supporting calculations are provided as Attachment 1. As shown in Table B.1, RBCs based on potential dermal contact with contaminated GW ranged from 514 $\mu\text{g/L}$ (reasonable maximum exposure; RME) to 5,140 $\mu\text{g/L}$ (central tendency; CT) for benzene, 0.4 $\mu\text{g/L}$ (RME) to 4 $\mu\text{g/L}$ (CT) for EDB, and 1,260 $\mu\text{g/L}$ (RME) to 12,600

µg/L (CT) for TCE. For comparison purposes, drinking water-based RBCs ranged from 5 to 10 µg/L for benzene and 5 to 26 µg/L for TCE (Table 1).

**TABLE B.1
GROUNDWATER RBCs**

Contaminant	Groundskeeper RBC _{dermal} (µg/L) ^{a/}		RBC _{DW} (µg/L) ^{b/}	
	RME ^{c/}	CT ^{d/}	RME Industrial- Based RBC ^{e/}	Residential-Based MCL
Benzene	514	5,140	10	5
Ethylene Dibromide	0.4	4	0.003	0.05
TCE	1,260	12,600	26	5

^{a/} RBC_{dermal} = risk-based groundwater concentration based on dermal contact with groundwater for a industrial groundskeeper; µg/L = micrograms per liter.

^{b/} RBC_{DW} = risk-based groundwater concentration based on potential ingestion of groundwater.

^{c/} RME = Reasonable maximum exposure.

^{d/} CT = Central tendency exposure.

^{e/} Assumed ingestion of one liter per day, 250 days per year for 25 years.

The results of the migration-to-groundwater soil RBC calculations are shown in Table 2. Supporting calculations are provided in Attachment 1. As shown in Table B.2, soil RBCs protective of migration-to-groundwater and potential dermal contact (groundskeeper) with GW ranged from 4 mg/kg (RME) to 34 mg/kg (CT) for benzene, 0.003 mg/kg (RME) to 0.03 mg/kg (CT) for EDB, and 14 mg/kg (RME) to 140 mg/kg (CT) for TCE. For comparison purposes, soil RBCs protective of migration-to-groundwater and potential residential/industrial ingestion ranged from 0.03 to 0.07 mg/kg for benzene and 0.06 to 0.3 mg/kg for TCE.

**TABLE B.2
MIGRATION-TO-GROUNDWATER SOIL RBCs**

Contaminant	Groundskeeper RBC _{soil-to-GW} Based on Dermal Contact with Groundwater (mg/kg) ^{a/}		RBC _{soil-to-GW} Based on Potential Ingestion of Groundwater (mg/kg)	
	RME ^{b/}	CT ^{c/}	RME Industrial- Based	Residential (MCL-based)
Benzene	4	35	0.07	0.03
Ethylene Dibromide	0.003	0.03	0.00002	0.0003
TCE	14	140	0.3	0.06

^{a/} RBC_{soil-to-GW} = risk-based soil concentration protective of potential migration to groundwater; mg/kg = milligrams per kilogram.

^{b/} RME = Reasonable maximum exposure.

^{c/} CT = Central tendency exposure.

APPENDIX C

CAPTURE ZONE ANALYSIS DOCUMENTATION

The raw data generated for Figure 6.4 are included in the following pages. The data were generated in Quickflow™ using the following parameters:

Hydraulic conductivity (ft/day)	Aquifer thickness (ft)	Gradient (ft/ft)	Porosity (dimensionless)
75.4	17	0.0022	0.30

mda

32 0 0 0

7.540000e+01 1.700000e+01 0.000000e+00 1.000000e+00

3.000000e-01 1.000000e-03 0.000000e+00

-9.577850e+03 -5.264285e+03 2.500000e+01

2.200000e-03 2.819960e+00 1.631916e+01 9.597114e-01 -2.809877e-01

0.000000e+00 2.500000e+07 2.500000e+07 0.000000e+00 0.000000e+00 0.000000e+00

-7.487076e+03 -4.028585e+03 1.528000e+03 3.330000e-01

-7.188546e+03 -4.303659e+03 1.344000e+03 3.330000e-01

-7.935168e+03 -4.015442e+03 -1.407000e+03 3.330000e-01

-7.402104e+03 -4.488699e+03 1.323000e+03 3.330000e-01

-6.970452e+03 -4.293675e+03 8.000000e+02 3.330000e-01

-6.775429e+03 -4.132456e+03 1.357000e+03 3.330000e-01

-7.056262e+03 -4.657719e+03 5.010000e+02 3.330000e-01

-7.604929e+03 -4.649918e+03 6.750000e+02 3.330000e-01

-7.771349e+03 -4.790335e+03 7.310000e+02 3.330000e-01

-6.788430e+03 -4.363884e+03 6.680000e+02 3.330000e-01

-8.215105e+03 -4.579710e+03 -1.166000e+03 3.330000e-01

-8.503740e+03 -5.116114e+03 -1.920000e+02 3.330000e-01

-8.235908e+03 -5.186323e+03 3.980000e+02 3.330000e-01

-7.934272e+03 -4.980898e+03 7.780000e+02 3.330000e-01

-8.324318e+03 -5.408089e+03 -1.309000e+03 3.330000e-01

-7.570228e+03 -5.348282e+03 -1.405000e+03 3.330000e-01

-7.352922e+03 -5.212326e+03 -8.770000e+02 3.330000e-01

-7.007081e+03 -4.869084e+03 -1.065000e+03 3.330000e-01

-6.780854e+03 -4.666260e+03 -1.868000e+03 3.330000e-01

-7.586951e+03 -3.593451e+03 -9.320000e+02 3.330000e-01

-7.007081e+03 -3.687062e+03 9.410000e+02 3.330000e-01

-6.936872e+03 -3.312617e+03 -6.560000e+02 3.330000e-01

-6.575429e+03 -3.715666e+03 7.310000e+02 3.330000e-01

-7.265162e+03 -3.261260e+03 -2.200000e+02 3.330000e-01

-6.521292e+03 -3.382175e+03 -3.220000e+02 3.330000e-01

-6.321068e+03 -3.519992e+03 -5.090000e+02 3.330000e-01

-6.146847e+03 -3.582400e+03 -2.110000e+02 3.330000e-01

-6.250860e+03 -3.728017e+03 1.015000e+03 3.330000e-01

-6.024633e+03 -3.738418e+03 -1.049000e+03 3.330000e-01
-6.578499e+03 -3.977648e+03 1.112000e+03 3.330000e-01
-6.492689e+03 -4.142946e+03 5.090000e+02 3.330000e-01
-6.461485e+03 -4.514792e+03 -1.460000e+02 3.330000e-01

30

-1.035056e+04 -3.293637e+03
-1.031039e+04 -3.418931e+03
-1.027022e+04 -3.544224e+03
-1.023005e+04 -3.669518e+03
-1.018988e+04 -3.794811e+03
-1.014971e+04 -3.920104e+03
-1.010954e+04 -4.045398e+03
-1.006936e+04 -4.170691e+03
-1.002919e+04 -4.295984e+03
-9.989023e+03 -4.421278e+03
-9.948854e+03 -4.546571e+03
-9.908683e+03 -4.671865e+03
-9.868513e+03 -4.797158e+03
-9.828343e+03 -4.922452e+03
-9.788172e+03 -5.047745e+03
-9.748002e+03 -5.173039e+03
-9.707831e+03 -5.298332e+03
-9.667661e+03 -5.423625e+03
-9.627491e+03 -5.548919e+03
-9.587320e+03 -5.674212e+03
-9.547150e+03 -5.799506e+03
-9.506979e+03 -5.924799e+03
-9.466810e+03 -6.050092e+03
-9.426639e+03 -6.175386e+03
-9.386469e+03 -6.300680e+03
-9.346299e+03 -6.425973e+03
-9.306128e+03 -6.551266e+03
-9.265958e+03 -6.676560e+03
-9.225787e+03 -6.801853e+03
-9.185617e+03 -6.927146e+03

0
0
1.000000e+05
35 35 2 1 0 15 15 10 0 15 15
-1.424131e+04 1.591426e+03 -1.189804e+04 2.207486e+03
1.000000e+00 0.000000e+00 3.000000e+01 2.000000e+03
well.map
9 12 9 14 15 11 9
0
-9.627092e+03 -5.813303e+03 -6.240663e+03 -2.842916e+03
3.000000e+01 2.000000e+01
2.374910e+03 2.374910e+02 0
3.650000e+02 1.000000e+00 4.749821e+02 0 2
1.979092e+03
0 1 9600 0 1 8 1 0
0 0
0.000000e+00 0.000000e+00
8
1 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
1.010000e+02
0

The raw data generated for Figure 6.5 are included in the following pages. The data were generated in QuickflowTM using the following parameters:

Hydraulic conductivity (ft/day)	Aquifer thickness (ft)	Gradient (ft/ft)	Porosity (dimensionless)
30.0	17	0.0022	0.30

mda

32 0 0 0

3.000000e+01 1.700000e+01 0.000000e+00 1.000000e+00

3.000000e-01 1.000000e-03 0.000000e+00

-9.577850e+03 -5.264285e+03 2.500000e+01

2.200000e-03 1.122000e+00 1.631916e+01 9.597114e-01 -2.809877e-01

0.000000e+00 2.500000e+07 2.500000e+07 0.000000e+00 0.000000e+00 0.000000e+00

-7.487076e+03 -4.028585e+03 1.528000e+03 3.330000e-01

-7.188546e+03 -4.303659e+03 1.344000e+03 3.330000e-01

-7.935168e+03 -4.015442e+03 -1.407000e+03 3.330000e-01

-7.402104e+03 -4.488699e+03 1.323000e+03 3.330000e-01

-6.970452e+03 -4.293675e+03 8.000000e+02 3.330000e-01

-6.775429e+03 -4.132456e+03 1.357000e+03 3.330000e-01

-7.056262e+03 -4.657719e+03 5.010000e+02 3.330000e-01

-7.604929e+03 -4.649918e+03 6.750000e+02 3.330000e-01

-7.771349e+03 -4.790335e+03 7.310000e+02 3.330000e-01

-6.788430e+03 -4.363884e+03 6.680000e+02 3.330000e-01

-8.215105e+03 -4.579710e+03 -1.166000e+03 3.330000e-01

-8.503740e+03 -5.116114e+03 -1.920000e+02 3.330000e-01

-8.235908e+03 -5.186323e+03 3.980000e+02 3.330000e-01

-7.934272e+03 -4.980898e+03 7.780000e+02 3.330000e-01

-8.324318e+03 -5.408089e+03 -1.309000e+03 3.330000e-01

-7.570228e+03 -5.348282e+03 -1.405000e+03 3.330000e-01

-7.352922e+03 -5.212326e+03 -8.770000e+02 3.330000e-01

-7.007081e+03 -4.869084e+03 -1.065000e+03 3.330000e-01

-6.780854e+03 -4.666260e+03 -1.868000e+03 3.330000e-01

-7.586951e+03 -3.593451e+03 -9.320000e+02 3.330000e-01

-7.007081e+03 -3.687062e+03 9.410000e+02 3.330000e-01

-6.936872e+03 -3.312617e+03 -6.560000e+02 3.330000e-01

-6.575429e+03 -3.715666e+03 7.310000e+02 3.330000e-01

-7.265162e+03 -3.261260e+03 -2.200000e+02 3.330000e-01

-6.521292e+03 -3.382175e+03 -3.220000e+02 3.330000e-01

-6.321068e+03 -3.519992e+03 -5.090000e+02 3.330000e-01

-6.146847e+03 -3.582400e+03 -2.110000e+02 3.330000e-01

-6.250860e+03 -3.728017e+03 1.015000e+03 3.330000e-01

-6.024633e+03 -3.738418e+03 -1.049000e+03 3.330000e-01
-6.578499e+03 -3.977648e+03 1.112000e+03 3.330000e-01
-6.492689e+03 -4.142946e+03 5.090000e+02 3.330000e-01
-6.461485e+03 -4.514792e+03 -1.460000e+02 3.330000e-01

30

-1.035056e+04 -3.293637e+03
-1.031039e+04 -3.418931e+03
-1.027022e+04 -3.544224e+03
-1.023005e+04 -3.669518e+03
-1.018988e+04 -3.794811e+03
-1.014971e+04 -3.920104e+03
-1.010954e+04 -4.045398e+03
-1.006936e+04 -4.170691e+03
-1.002919e+04 -4.295984e+03
-9.989023e+03 -4.421278e+03
-9.948854e+03 -4.546571e+03
-9.908683e+03 -4.671865e+03
-9.868513e+03 -4.797158e+03
-9.828343e+03 -4.922452e+03
-9.788172e+03 -5.047745e+03
-9.748002e+03 -5.173039e+03
-9.707831e+03 -5.298332e+03
-9.667661e+03 -5.423625e+03
-9.627491e+03 -5.548919e+03
-9.587320e+03 -5.674212e+03
-9.547150e+03 -5.799506e+03
-9.506979e+03 -5.924799e+03
-9.466810e+03 -6.050092e+03
-9.426639e+03 -6.175386e+03
-9.386469e+03 -6.300680e+03
-9.346299e+03 -6.425973e+03
-9.306128e+03 -6.551266e+03
-9.265958e+03 -6.676560e+03
-9.225787e+03 -6.801853e+03
-9.185617e+03 -6.927146e+03

0
0
1.000000e+05
35 35 2 1 0 15 15 10 0 15 15
-1.424131e+04 1.591426e+03 -1.189804e+04 2.207486e+03
1.000000e+00 0.000000e+00 3.000000e+01 2.000000e+03
well.map
9 12 9 14 15 11 9
0
-9.627092e+03 -5.813294e+03 -6.240663e+03 -2.842916e+03
3.000000e+01 2.000000e+01
2.374910e+03 2.374910e+02 0
3.650000e+02 1.000000e+00 4.749821e+02 0 2
1.979092e+03
0 1 9600 0 1 8 1 0
0 0
0.000000e+00 0.000000e+00
8
1 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
1.010000e+02
0

The raw data generated for Figure 6.6 are included in the following pages. The data were generated in Quickflow™ using the following parameters:

Hydraulic conductivity (ft/day)	Aquifer thickness (ft)	Gradient (ft/ft)	Porosity (dimensionless)
100.0	17	0.0022	0.30

mda

32 0 0 0

1.000000e+02	1.700000e+01	0.000000e+00	1.000000e+00		
3.000000e-01	1.000000e-03	0.000000e+00			
-9.577850e+03	-5.264285e+03	2.500000e+01			
2.200000e-03	3.740000e+00	1.631916e+01	9.597114e-01	-2.809877e-01	
0.000000e+00	2.500000e+07	2.500000e+07	0.000000e+00	0.000000e+00	0.000000e+00
-7.487076e+03	-4.028585e+03	1.528000e+03	3.330000e-01		
-7.188546e+03	-4.303659e+03	1.344000e+03	3.330000e-01		
-7.935168e+03	-4.015442e+03	-1.407000e+03	3.330000e-01		
-7.402104e+03	-4.488699e+03	1.323000e+03	3.330000e-01		
-6.970452e+03	-4.293675e+03	8.000000e+02	3.330000e-01		
-6.775429e+03	-4.132456e+03	1.357000e+03	3.330000e-01		
-7.056262e+03	-4.657719e+03	5.010000e+02	3.330000e-01		
-7.604929e+03	-4.649918e+03	6.750000e+02	3.330000e-01		
-7.771349e+03	-4.790335e+03	7.310000e+02	3.330000e-01		
-6.788430e+03	-4.363884e+03	6.680000e+02	3.330000e-01		
-8.215105e+03	-4.579710e+03	-1.166000e+03	3.330000e-01		
-8.503740e+03	-5.116114e+03	-1.920000e+02	3.330000e-01		
-8.235908e+03	-5.186323e+03	3.980000e+02	3.330000e-01		
-7.934272e+03	-4.980898e+03	7.780000e+02	3.330000e-01		
-8.324318e+03	-5.408089e+03	-1.309000e+03	3.330000e-01		
-7.570228e+03	-5.348282e+03	-1.405000e+03	3.330000e-01		
-7.352922e+03	-5.212326e+03	-8.770000e+02	3.330000e-01		
-7.007081e+03	-4.869084e+03	-1.065000e+03	3.330000e-01		
-6.780854e+03	-4.666260e+03	-1.868000e+03	3.330000e-01		
-7.586951e+03	-3.593451e+03	-9.320000e+02	3.330000e-01		
-7.007081e+03	-3.687062e+03	9.410000e+02	3.330000e-01		
-6.936872e+03	-3.312617e+03	-6.560000e+02	3.330000e-01		
-6.575429e+03	-3.715666e+03	7.310000e+02	3.330000e-01		
-7.265162e+03	-3.261260e+03	-2.200000e+02	3.330000e-01		
-6.521292e+03	-3.382175e+03	-3.220000e+02	3.330000e-01		
-6.321068e+03	-3.519992e+03	-5.090000e+02	3.330000e-01		
-6.146847e+03	-3.582400e+03	-2.110000e+02	3.330000e-01		
-6.250860e+03	-3.728017e+03	1.015000e+03	3.330000e-01		

-6.024633e+03 -3.738418e+03 -1.049000e+03 3.330000e-01
-6.578499e+03 -3.977648e+03 1.112000e+03 3.330000e-01
-6.492689e+03 -4.142946e+03 5.090000e+02 3.330000e-01
-6.461485e+03 -4.514792e+03 -1.460000e+02 3.330000e-01

30

-1.035056e+04 -3.293637e+03
-1.031039e+04 -3.418931e+03
-1.027022e+04 -3.544224e+03
-1.023005e+04 -3.669518e+03
-1.018988e+04 -3.794811e+03
-1.014971e+04 -3.920104e+03
-1.010954e+04 -4.045398e+03
-1.006936e+04 -4.170691e+03
-1.002919e+04 -4.295984e+03
-9.989023e+03 -4.421278e+03
-9.948854e+03 -4.546571e+03
-9.908683e+03 -4.671865e+03
-9.868513e+03 -4.797158e+03
-9.828343e+03 -4.922452e+03
-9.788172e+03 -5.047745e+03
-9.748002e+03 -5.173039e+03
-9.707831e+03 -5.298332e+03
-9.667661e+03 -5.423625e+03
-9.627491e+03 -5.548919e+03
-9.587320e+03 -5.674212e+03
-9.547150e+03 -5.799506e+03
-9.506979e+03 -5.924799e+03
-9.466810e+03 -6.050092e+03
-9.426639e+03 -6.175386e+03
-9.386469e+03 -6.300680e+03
-9.346299e+03 -6.425973e+03
-9.306128e+03 -6.551266e+03
-9.265958e+03 -6.676560e+03
-9.225787e+03 -6.801853e+03
-9.185617e+03 -6.927146e+03

0
0
1.000000e+05
35 35 2 1 0 15 15 10 0 15 15
-1.424131e+04 1.591426e+03 -1.189804e+04 2.207486e+03
1.000000e+00 0.000000e+00 3.000000e+01 2.000000e+03
well.map
9 12 9 14 15 11 9
0
-9.627092e+03 -5.813294e+03 -6.240663e+03 -2.842916e+03
3.000000e+01 2.000000e+01
2.374910e+03 2.374910e+02 0
3.650000e+02 1.000000e+00 4.749821e+02 0 2
1.979092e+03
0 1 9600 0 1 8 1 0
0 0
0.000000e+00 0.000000e+00
8
1 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
1.010000e+02
0

The raw data generated for Figure 6.7 are included in the following pages. The data were generated in QuickflowTM using the following parameters:

Hydraulic conductivity (ft/day)	Aquifer thickness (ft)	Gradient (ft/ft)	Porosity (dimensionless)
30.0	17	0.0022	0.30

mda

2 0 0 0
3.000000e+01 1.700000e+01 0.000000e+00 1.000000e+00
3.000000e-01 1.000000e-03 0.000000e+00
-9.577850e+03 -5.264285e+03 2.500000e+01
2.200000e-03 1.122000e+00 1.631916e+01 9.597114e-01 -2.809877e-01
0.000000e+00 2.500000e+07 2.500000e+07 0.000000e+00 0.000000e+00 0.000000e+00
-7.487076e+03 -4.028585e+03 1.528000e+03 3.330000e-01
-7.401382e+03 -4.488266e+03 1.323000e+03 3.330000e-01
40
-1.042679e+04 -2.785650e+03
-1.039095e+04 -2.902936e+03
-1.035510e+04 -3.020222e+03
-1.031925e+04 -3.137509e+03
-1.028340e+04 -3.254795e+03
-1.024755e+04 -3.372081e+03
-1.021170e+04 -3.489367e+03
-1.017586e+04 -3.606653e+03
-1.014001e+04 -3.723939e+03
-1.010416e+04 -3.841225e+03
-1.006831e+04 -3.958511e+03
-1.003246e+04 -4.075797e+03
-9.996615e+03 -4.193083e+03
-9.960767e+03 -4.310370e+03
-9.924918e+03 -4.427656e+03
-9.889070e+03 -4.544942e+03
-9.853222e+03 -4.662228e+03
-9.817374e+03 -4.779514e+03
-9.781525e+03 -4.896800e+03
-9.745677e+03 -5.014086e+03
-9.709829e+03 -5.131372e+03
-9.673980e+03 -5.248658e+03
-9.638133e+03 -5.365944e+03
-9.602284e+03 -5.483230e+03
-9.566436e+03 -5.600517e+03

-9.530588e+03 -5.717803e+03
-9.494739e+03 -5.835089e+03
-9.458891e+03 -5.952375e+03
-9.423043e+03 -6.069662e+03
-9.387194e+03 -6.186948e+03
-9.351347e+03 -6.304233e+03
-9.315498e+03 -6.421520e+03
-9.279649e+03 -6.538806e+03
-9.243802e+03 -6.656092e+03
-9.207953e+03 -6.773378e+03
-9.172104e+03 -6.890664e+03
-9.136257e+03 -7.007950e+03
-9.100408e+03 -7.125236e+03
-9.064561e+03 -7.242522e+03
-9.028712e+03 -7.359809e+03
0
0
1.000000e+05
35 35 2 1 0 15 15 10 0 15 15
-1.424131e+04 1.591426e+03 -1.189804e+04 2.207486e+03
1.000000e+00 0.000000e+00 3.000000e+01 2.000000e+03
well.map
9 12 9 14 15 11 9
0
-9.800886e+03 -6.039741e+03 -6.063354e+03 -2.712517e+03
3.000000e+01 2.000000e+01
2.374910e+03 2.374910e+02 0
3.650000e+02 1.000000e+00 4.749821e+02 0 2
1.979092e+03
0 1 9600 0 1 8 1 0
0 0
0.000000e+00 0.000000e+00
8
1 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
1.010000e+02

The raw data generated for Figure 6.8 are included in the following pages. The data were generated in Quickflow™ using the following parameters:

Hydraulic conductivity (ft/day)	Aquifer thickness (ft)	Gradient (ft/ft)	Porosity (dimensionless)
30.0	17	0.0022	0.30

mda

3 0 0 0

3.000000e+01 1.700000e+01 0.000000e+00 1.000000e+00

3.000000e-01 1.000000e-03 0.000000e+00

-9.577850e+03 -5.264285e+03 2.500000e+01

2.200000e-03 1.122000e+00 1.631916e+01 9.597114e-01 -2.809877e-01

0.000000e+00 2.500000e+07 2.500000e+07 0.000000e+00 0.000000e+00 0.000000e+00

-7.487076e+03 -4.028585e+03 1.528000e+03 3.330000e-01

-7.188546e+03 -4.303659e+03 1.344000e+03 3.330000e-01

-7.401382e+03 -4.488266e+03 1.323000e+03 3.330000e-01

40

-1.042679e+04 -2.785650e+03

-1.039095e+04 -2.902936e+03

-1.035510e+04 -3.020222e+03

-1.031925e+04 -3.137509e+03

-1.028340e+04 -3.254795e+03

-1.024755e+04 -3.372081e+03

-1.021170e+04 -3.489367e+03

-1.017586e+04 -3.606653e+03

-1.014001e+04 -3.723939e+03

-1.010416e+04 -3.841225e+03

-1.006831e+04 -3.958511e+03

-1.003246e+04 -4.075797e+03

-9.996615e+03 -4.193083e+03

-9.960767e+03 -4.310370e+03

-9.924918e+03 -4.427656e+03

-9.889070e+03 -4.544942e+03

-9.853222e+03 -4.662228e+03

-9.817374e+03 -4.779514e+03

-9.781525e+03 -4.896800e+03

-9.745677e+03 -5.014086e+03

-9.709829e+03 -5.131372e+03

-9.673980e+03 -5.248658e+03

-9.638133e+03 -5.365944e+03

-9.602284e+03 -5.483230e+03

-9.566436e+03 -5.600517e+03

-9.530588e+03 -5.717803e+03

-9.494739e+03 -5.835089e+03
-9.458891e+03 -5.952375e+03
-9.423043e+03 -6.069662e+03
-9.387194e+03 -6.186948e+03
-9.351347e+03 -6.304233e+03
-9.315498e+03 -6.421520e+03
-9.279649e+03 -6.538806e+03
-9.243802e+03 -6.656092e+03
-9.207953e+03 -6.773378e+03
-9.172104e+03 -6.890664e+03
-9.136257e+03 -7.007950e+03
-9.100408e+03 -7.125236e+03
-9.064561e+03 -7.242522e+03
-9.028712e+03 -7.359809e+03
0
0
1.000000e+05
35 35 2 1 0 15 15 10 0 15 15
-1.424131e+04 1.591426e+03 -1.189804e+04 2.207486e+03
1.000000e+00 0.000000e+00 3.000000e+01 2.000000e+03
well.map
9 12 9 14 15 11 9
0
-1.261510e+04 -5.092807e+03 -8.104439e+03 -1.402765e+03
3.000000e+01 2.000000e+01
2.374910e+03 2.374910e+02 0
3.650000e+02 1.000000e+00 4.749821e+02 0 2
1.979092e+03
0 1 9600 0 1 8 1 0
0 0
0.000000e+00 0.000000e+00
8
1 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
1.010000e+02
0

The raw data generated for Figure 6.17 are included in the following pages. The data were generated in Quickflow™ using the following parameters:

Hydraulic conductivity (ft/day)	Aquifer thickness (ft)	Gradient (ft/ft)	Porosity (dimensionless)
30.9	17	0.0022	0.30

mda

55 0 0 0

3.090000e+01 1.700000e+01 0.000000e+00 1.000000e+00

2.000000e-01 1.000000e-03 0.000000e+00

1.921460e+03 -7.149288e+03 2.500000e+01

2.000000e-03 1.050600e+00 1.448429e+02 -8.175762e-01 -5.758204e-01

0.000000e+00 2.500000e+07 2.500000e+07 0.000000e+00 0.000000e+00 0.000000e+00

-3.092825e+03 -3.561067e+03 9.050000e+02 2.500000e-01

-3.124555e+03 -3.807093e+03 5.010000e+02 2.500000e-01

-3.194970e+03 -3.967945e+03 7.700000e+02 2.500000e-01

-2.880861e+03 -4.568550e+03 3.470000e+02 2.500000e-01

-2.580559e+03 -4.534032e+03 2.890000e+02 2.500000e-01

-2.280256e+03 -4.568550e+03 2.890000e+02 2.500000e-01

-2.894668e+03 -3.574445e+03 -1.733000e+03 2.500000e-01

-2.649594e+03 -3.591704e+03 -1.540000e+02 2.500000e-01

-3.301975e+03 -3.974849e+03 -1.713000e+03 2.500000e-01

-3.467659e+03 -4.582357e+03 -9.050000e+02 2.500000e-01

-1.883304e+03 -4.585809e+03 -5.780000e+02 2.500000e-01

-1.583002e+03 -4.654844e+03 -2.890000e+02 2.500000e-01

-3.388268e+03 -4.230278e+03 -1.160000e+02 2.500000e-01

-3.182889e+03 -4.874030e+03 -6.350000e+02 2.500000e-01

-3.058626e+03 -5.001745e+03 -2.022000e+03 2.500000e-01

-2.882587e+03 -5.188140e+03 -1.733000e+03 2.500000e-01

-2.873801e+03 -4.847044e+03 2.700000e+02 2.500000e-01

-2.544315e+03 -4.887837e+03 2.890000e+02 2.500000e-01

-2.280727e+03 -4.999948e+03 6.550000e+02 2.500000e-01

-2.547215e+03 -5.184659e+03 9.630000e+02 2.500000e-01

-2.326132e+03 -5.265485e+03 4.040000e+02 2.500000e-01

-2.680341e+03 -5.267863e+03 -6.740000e+02 2.500000e-01

-1.980244e+03 -4.819753e+03 7.320000e+02 2.500000e-01

-1.583245e+03 -5.052722e+03 5.390000e+02 2.500000e-01

-1.880400e+03 -5.266674e+03 3.080000e+02 2.500000e-01

-1.282524e+03 -4.804301e+03 -9.600000e+01 2.500000e-01

-9.449561e+02 -4.944558e+03 -6.930000e+02 2.500000e-01

-1.194566e+03 -5.151377e+03 7.700000e+01 2.500000e-01

-9.306926e+02 -5.255976e+03 5.800000e+01 2.500000e-01
-1.375236e+03 -5.503209e+03 6.160000e+02 2.500000e-01
-9.639740e+02 -5.593544e+03 7.120000e+02 2.500000e-01
-5.919362e+02 -5.128794e+03 -4.240000e+02 2.500000e-01
-2.828951e+02 -5.190602e+03 -5.390000e+02 2.500000e-01
-5.800499e+02 -5.390290e+03 1.752000e+03 2.500000e-01
-2.805179e+02 -5.395044e+03 7.890000e+02 2.500000e-01
-6.808997e+02 -5.639443e+03 1.020000e+03 2.500000e-01
-5.656951e+02 -5.928369e+03 4.620000e+02 2.500000e-01
-2.785978e+02 -5.791220e+03 3.270000e+02 2.500000e-01
-2.785978e+02 -6.005172e+03 -4.430000e+02 2.500000e-01
-5.821529e+02 -6.054545e+03 -5.200000e+02 2.500000e-01
-9.542821e+02 -5.953055e+03 6.740000e+02 2.500000e-01
-9.597681e+02 -6.139577e+03 -1.160000e+02 2.500000e-01
-1.330069e+03 -5.818650e+03 7.510000e+02 2.500000e-01
-1.584250e+03 -5.794877e+03 9.430000e+02 2.500000e-01
-1.556821e+03 -6.054545e+03 -5.580000e+02 2.500000e-01
-1.282524e+03 -6.122205e+03 -5.780000e+02 2.500000e-01
-1.980152e+03 -5.852479e+03 -6.350000e+02 2.500000e-01
-1.926207e+03 -5.699788e+03 4.620000e+02 2.500000e-01
-2.279491e+03 -5.718328e+03 -1.350000e+02 2.500000e-01
-1.326474e+02 -5.342105e+03 -3.000000e+02 2.500000e-01
-1.912578e+02 -5.490026e+03 5.010000e+02 2.500000e-01
-1.856759e+02 -5.590501e+03 5.200000e+02 2.500000e-01
-1.800939e+02 -5.690977e+03 2.310000e+02 2.500000e-01
-1.326474e+02 -5.838898e+03 -6.160000e+02 2.500000e-01
-3.810439e+02 -5.590501e+03 5.780000e+02 2.500000e-01

50

1.599910e+03 -4.153790e+03
1.542577e+03 -4.252915e+03
1.485243e+03 -4.352039e+03
1.427910e+03 -4.451164e+03
1.370576e+03 -4.550289e+03
1.313243e+03 -4.649413e+03
1.255910e+03 -4.748538e+03

1.198576e+03 -4.847662e+03
1.141243e+03 -4.946787e+03
1.083909e+03 -5.045912e+03
1.026576e+03 -5.145036e+03
9.692424e+02 -5.244161e+03
9.119091e+02 -5.343286e+03
8.545756e+02 -5.442410e+03
7.972422e+02 -5.541535e+03
7.399088e+02 -5.640659e+03
6.825754e+02 -5.739784e+03
6.252421e+02 -5.838909e+03
5.679087e+02 -5.938033e+03
5.105752e+02 -6.037158e+03
4.532418e+02 -6.136282e+03
3.959084e+02 -6.235407e+03
3.385750e+02 -6.334532e+03
2.812416e+02 -6.433656e+03
2.239082e+02 -6.532781e+03
1.665748e+02 -6.631906e+03
1.092414e+02 -6.731030e+03
5.190801e+01 -6.830155e+03
-5.425372e+00 -6.929279e+03
-6.275875e+01 -7.028404e+03
-1.200923e+02 -7.127529e+03
-1.774257e+02 -7.226653e+03
-2.347590e+02 -7.325778e+03
-2.920924e+02 -7.424902e+03
-3.494258e+02 -7.524027e+03
-4.067592e+02 -7.623151e+03
-4.640926e+02 -7.722276e+03
-5.214261e+02 -7.821401e+03
-5.787595e+02 -7.920525e+03
-6.360929e+02 -8.019650e+03
-6.934263e+02 -8.118775e+03
-7.507596e+02 -8.217899e+03

-8.080930e+02 -8.317023e+03
-8.654266e+02 -8.416148e+03
-9.227599e+02 -8.515273e+03
-9.800933e+02 -8.614397e+03
-1.037427e+03 -8.713522e+03
-1.094760e+03 -8.812647e+03
-1.152094e+03 -8.911771e+03
-1.209427e+03 -9.010896e+03
0
0
1.000000e+05
35 35 2 1 0 15 15 10 0 15 15
-1.424131e+04 1.591426e+03 -1.189804e+04 2.207486e+03
5.000000e-01 5.000000e-01 3.000000e+01 2.000000e+03
well.map
9 12 9 14 15 11 9
0
-4.580917e+03 1.009500e+03 -7.339408e+03 -2.358854e+03
3.000000e+01 2.000000e+01
1.500000e+02 1.500000e+01 0
3.650000e+02 1.000000e+00 3.000000e+01 0 2
1.979092e+03
0 19600 0 1 8 1 0
0 0
0.000000e+00 0.000000e+00
8
1 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
1.010000e+02
0

The raw data generated for Figure 6.18 are included in the following pages. The data were generated in Quickflow™ using the following parameters:

Hydraulic conductivity (ft/day)	Aquifer thickness (ft)	Gradient (ft/ft)	Porosity (dimensionless)
50.0	17	0.0022	0.30

mda

55 0 0 0

5.000000e+01 1.700000e+01 0.000000e+00 1.000000e+00

2.000000e-01 1.000000e-03 0.000000e+00

1.921460e+03 -7.149288e+03 2.500000e+01

2.000000e-03 1.700000e+00 1.448429e+02 -8.175762e-01 -5.758204e-01

0.000000e+00 2.500000e+07 2.500000e+07 0.000000e+00 0.000000e+00 0.000000e+00

-3.092825e+03 -3.561067e+03 9.050000e+02 2.500000e-01

-3.124555e+03 -3.807093e+03 5.010000e+02 2.500000e-01

-3.194970e+03 -3.967945e+03 7.700000e+02 2.500000e-01

-2.880861e+03 -4.568550e+03 3.470000e+02 2.500000e-01

-2.580559e+03 -4.534032e+03 2.890000e+02 2.500000e-01

-2.280256e+03 -4.568550e+03 2.890000e+02 2.500000e-01

-2.894668e+03 -3.574445e+03 -1.733000e+03 2.500000e-01

-2.649594e+03 -3.591704e+03 -1.540000e+02 2.500000e-01

-3.301975e+03 -3.974849e+03 -1.713000e+03 2.500000e-01

-3.467659e+03 -4.582357e+03 -9.050000e+02 2.500000e-01

-1.883304e+03 -4.585809e+03 -5.780000e+02 2.500000e-01

-1.583002e+03 -4.654844e+03 -2.890000e+02 2.500000e-01

-3.388268e+03 -4.230278e+03 -1.160000e+02 2.500000e-01

-3.182889e+03 -4.874030e+03 -6.350000e+02 2.500000e-01

-3.058626e+03 -5.001745e+03 -2.022000e+03 2.500000e-01

-2.882587e+03 -5.188140e+03 -1.733000e+03 2.500000e-01

-2.873801e+03 -4.847044e+03 2.700000e+02 2.500000e-01

-2.544315e+03 -4.887837e+03 2.890000e+02 2.500000e-01

-2.280727e+03 -4.999948e+03 6.550000e+02 2.500000e-01

-2.547215e+03 -5.184659e+03 9.630000e+02 2.500000e-01

-2.326132e+03 -5.265485e+03 4.040000e+02 2.500000e-01

-2.680341e+03 -5.267863e+03 -6.740000e+02 2.500000e-01

-1.980244e+03 -4.819753e+03 7.320000e+02 2.500000e-01

-1.583245e+03 -5.052722e+03 5.390000e+02 2.500000e-01

-1.880400e+03 -5.266674e+03 3.080000e+02 2.500000e-01

-1.282524e+03 -4.804301e+03 -9.600000e+01 2.500000e-01

-9.449561e+02 -4.944558e+03 -6.930000e+02 2.500000e-01

-1.194566e+03 -5.151377e+03 7.700000e+01 2.500000e-01

-9.306926e+02 -5.255976e+03 5.800000e+01 2.500000e-01
-1.375236e+03 -5.503209e+03 6.160000e+02 2.500000e-01
-9.639740e+02 -5.593544e+03 7.120000e+02 2.500000e-01
-5.919362e+02 -5.128794e+03 -4.240000e+02 2.500000e-01
-2.828951e+02 -5.190602e+03 -5.390000e+02 2.500000e-01
-5.800499e+02 -5.390290e+03 1.752000e+03 2.500000e-01
-2.805179e+02 -5.395044e+03 7.890000e+02 2.500000e-01
-6.808997e+02 -5.639443e+03 1.020000e+03 2.500000e-01
-5.656951e+02 -5.928369e+03 4.620000e+02 2.500000e-01
-2.785978e+02 -5.791220e+03 3.270000e+02 2.500000e-01
-2.785978e+02 -6.005172e+03 -4.430000e+02 2.500000e-01
-5.821529e+02 -6.054545e+03 -5.200000e+02 2.500000e-01
-9.542821e+02 -5.953055e+03 6.740000e+02 2.500000e-01
-9.597681e+02 -6.139577e+03 -1.160000e+02 2.500000e-01
-1.330069e+03 -5.818650e+03 7.510000e+02 2.500000e-01
-1.584250e+03 -5.794877e+03 9.430000e+02 2.500000e-01
-1.556821e+03 -6.054545e+03 -5.580000e+02 2.500000e-01
-1.282524e+03 -6.122205e+03 -5.780000e+02 2.500000e-01
-1.980152e+03 -5.852479e+03 -6.350000e+02 2.500000e-01
-1.926207e+03 -5.699788e+03 4.620000e+02 2.500000e-01
-2.279491e+03 -5.718328e+03 -1.350000e+02 2.500000e-01
-1.326474e+02 -5.342105e+03 -3.000000e+02 2.500000e-01
-1.912578e+02 -5.490026e+03 5.010000e+02 2.500000e-01
-1.856759e+02 -5.590501e+03 5.200000e+02 2.500000e-01
-1.800939e+02 -5.690977e+03 2.310000e+02 2.500000e-01
-1.326474e+02 -5.838898e+03 -6.160000e+02 2.500000e-01
-3.810439e+02 -5.590501e+03 5.780000e+02 2.500000e-01

50

1.599910e+03 -4.153790e+03
1.542577e+03 -4.252915e+03
1.485243e+03 -4.352039e+03
1.427910e+03 -4.451164e+03
1.370576e+03 -4.550289e+03
1.313243e+03 -4.649413e+03
1.255910e+03 -4.748538e+03

1.198576e+03 -4.847662e+03
1.141243e+03 -4.946787e+03
1.083909e+03 -5.045912e+03
1.026576e+03 -5.145036e+03
9.692424e+02 -5.244161e+03
9.119091e+02 -5.343286e+03
8.545756e+02 -5.442410e+03
7.972422e+02 -5.541535e+03
7.399088e+02 -5.640659e+03
6.825754e+02 -5.739784e+03
6.252421e+02 -5.838909e+03
5.679087e+02 -5.938033e+03
5.105752e+02 -6.037158e+03
4.532418e+02 -6.136282e+03
3.959084e+02 -6.235407e+03
3.385750e+02 -6.334532e+03
2.812416e+02 -6.433656e+03
2.239082e+02 -6.532781e+03
1.665748e+02 -6.631906e+03
1.092414e+02 -6.731030e+03
5.190801e+01 -6.830155e+03
-5.425372e+00 -6.929279e+03
-6.275875e+01 -7.028404e+03
-1.200923e+02 -7.127529e+03
-1.774257e+02 -7.226653e+03
-2.347590e+02 -7.325778e+03
-2.920924e+02 -7.424902e+03
-3.494258e+02 -7.524027e+03
-4.067592e+02 -7.623151e+03
-4.640926e+02 -7.722276e+03
-5.214261e+02 -7.821401e+03
-5.787595e+02 -7.920525e+03
-6.360929e+02 -8.019650e+03
-6.934263e+02 -8.118775e+03
-7.507596e+02 -8.217899e+03

-8.080930e+02 -8.317023e+03
-8.654266e+02 -8.416148e+03
-9.227599e+02 -8.515273e+03
-9.800933e+02 -8.614397e+03
-1.037427e+03 -8.713522e+03
-1.094760e+03 -8.812647e+03
-1.152094e+03 -8.911771e+03
-1.209427e+03 -9.010896e+03
0
0
1.000000e+05
35 35 2 1 0 15 15 10 0 15 15
-1.424131e+04 1.591426e+03 -1.189804e+04 2.207486e+03
5.000000e-01 5.000000e-01 3.000000e+01 2.000000e+03
well.map
9 12 9 14 15 11 9
0
-4.580917e+03 1.009501e+03 -7.339408e+03 -2.358854e+03
3.000000e+01 2.000000e+01
1.500000e+02 1.500000e+01 0
3.650000e+02 1.000000e+00 3.000000e+01 0 2
1.979092e+03
0 19600 0 1 8 1 0
0 0
0.000000e+00 0.000000e+00
8
1 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
1.010000e+02
0

The raw data generated for Figure 6.19 are included in the following pages. The data were generated in Quickflow™ using the following parameters:

Hydraulic conductivity (ft/day)	Aquifer thickness (ft)	Gradient (ft/ft)	Porosity (dimensionless)
15.0	17	0.0022	0.30

mda

55 0 0 0

1.500000e+01	1.700000e+01	0.000000e+00	1.000000e+00		
2.000000e-01	1.000000e-03	0.000000e+00			
1.921460e+03	-7.149288e+03	2.500000e+01			
2.000000e-03	5.100001e-01	1.448429e+02	-8.175762e-01	-5.758204e-01	
0.000000e+00	2.500000e+07	2.500000e+07	0.000000e+00	0.000000e+00	0.000000e+00
-3.092825e+03	-3.561067e+03	9.050000e+02	2.500000e-01		
-3.124555e+03	-3.807093e+03	5.010000e+02	2.500000e-01		
-3.194970e+03	-3.967945e+03	7.700000e+02	2.500000e-01		
-2.880861e+03	-4.568550e+03	3.470000e+02	2.500000e-01		
-2.580559e+03	-4.534032e+03	2.890000e+02	2.500000e-01		
-2.280256e+03	-4.568550e+03	2.890000e+02	2.500000e-01		
-2.894668e+03	-3.574445e+03	-1.733000e+03	2.500000e-01		
-2.649594e+03	-3.591704e+03	-1.540000e+02	2.500000e-01		
-3.301975e+03	-3.974849e+03	-1.713000e+03	2.500000e-01		
-3.467659e+03	-4.582357e+03	-9.050000e+02	2.500000e-01		
-1.883304e+03	-4.585809e+03	-5.780000e+02	2.500000e-01		
-1.583002e+03	-4.654844e+03	-2.890000e+02	2.500000e-01		
-3.388268e+03	-4.230278e+03	-1.160000e+02	2.500000e-01		
-3.182889e+03	-4.874030e+03	-6.350000e+02	2.500000e-01		
-3.058626e+03	-5.001745e+03	-2.022000e+03	2.500000e-01		
-2.882587e+03	-5.188140e+03	-1.733000e+03	2.500000e-01		
-2.873801e+03	-4.847044e+03	2.700000e+02	2.500000e-01		
-2.544315e+03	-4.887837e+03	2.890000e+02	2.500000e-01		
-2.280727e+03	-4.999948e+03	6.550000e+02	2.500000e-01		
-2.547215e+03	-5.184659e+03	9.630000e+02	2.500000e-01		
-2.326132e+03	-5.265485e+03	4.040000e+02	2.500000e-01		
-2.680341e+03	-5.267863e+03	-6.740000e+02	2.500000e-01		
-1.980244e+03	-4.819753e+03	7.320000e+02	2.500000e-01		
-1.583245e+03	-5.052722e+03	5.390000e+02	2.500000e-01		
-1.880400e+03	-5.266674e+03	3.080000e+02	2.500000e-01		
-1.282524e+03	-4.804301e+03	-9.600000e+01	2.500000e-01		
-9.449561e+02	-4.944558e+03	-6.930000e+02	2.500000e-01		
-1.194566e+03	-5.151377e+03	7.700000e+01	2.500000e-01		

-9.306926e+02 -5.255976e+03 5.800000e+01 2.500000e-01
-1.375236e+03 -5.503209e+03 6.160000e+02 2.500000e-01
-9.639740e+02 -5.593544e+03 7.120000e+02 2.500000e-01
-5.919362e+02 -5.128794e+03 -4.240000e+02 2.500000e-01
-2.828951e+02 -5.190602e+03 -5.390000e+02 2.500000e-01
-5.800499e+02 -5.390290e+03 1.752000e+03 2.500000e-01
-2.805179e+02 -5.395044e+03 7.890000e+02 2.500000e-01
-6.808997e+02 -5.639443e+03 1.020000e+03 2.500000e-01
-5.656951e+02 -5.928369e+03 4.620000e+02 2.500000e-01
-2.785978e+02 -5.791220e+03 3.270000e+02 2.500000e-01
-2.785978e+02 -6.005172e+03 -4.430000e+02 2.500000e-01
-5.821529e+02 -6.054545e+03 -5.200000e+02 2.500000e-01
-9.542821e+02 -5.953055e+03 6.740000e+02 2.500000e-01
-9.597681e+02 -6.139577e+03 -1.160000e+02 2.500000e-01
-1.330069e+03 -5.818650e+03 7.510000e+02 2.500000e-01
-1.584250e+03 -5.794877e+03 9.430000e+02 2.500000e-01
-1.556821e+03 -6.054545e+03 -5.580000e+02 2.500000e-01
-1.282524e+03 -6.122205e+03 -5.780000e+02 2.500000e-01
-1.980152e+03 -5.852479e+03 -6.350000e+02 2.500000e-01
-1.926207e+03 -5.699788e+03 4.620000e+02 2.500000e-01
-2.279491e+03 -5.718328e+03 -1.350000e+02 2.500000e-01
-1.326474e+02 -5.342105e+03 -3.000000e+02 2.500000e-01
-1.912578e+02 -5.490026e+03 5.010000e+02 2.500000e-01
-1.856759e+02 -5.590501e+03 5.200000e+02 2.500000e-01
-1.800939e+02 -5.690977e+03 2.310000e+02 2.500000e-01
-1.326474e+02 -5.838898e+03 -6.160000e+02 2.500000e-01
-3.810439e+02 -5.590501e+03 5.780000e+02 2.500000e-01

50

1.599910e+03 -4.153790e+03
1.542577e+03 -4.252915e+03
1.485243e+03 -4.352039e+03
1.427910e+03 -4.451164e+03
1.370576e+03 -4.550289e+03
1.313243e+03 -4.649413e+03
1.255910e+03 -4.748538e+03

1.198576e+03 -4.847662e+03
1.141243e+03 -4.946787e+03
1.083909e+03 -5.045912e+03
1.026576e+03 -5.145036e+03
9.692424e+02 -5.244161e+03
9.119091e+02 -5.343286e+03
8.545756e+02 -5.442410e+03
7.972422e+02 -5.541535e+03
7.399088e+02 -5.640659e+03
6.825754e+02 -5.739784e+03
6.252421e+02 -5.838909e+03
5.679087e+02 -5.938033e+03
5.105752e+02 -6.037158e+03
4.532418e+02 -6.136282e+03
3.959084e+02 -6.235407e+03
3.385750e+02 -6.334532e+03
2.812416e+02 -6.433656e+03
2.239082e+02 -6.532781e+03
1.665748e+02 -6.631906e+03
1.092414e+02 -6.731030e+03
5.190801e+01 -6.830155e+03
-5.425372e+00 -6.929279e+03
-6.275875e+01 -7.028404e+03
-1.200923e+02 -7.127529e+03
-1.774257e+02 -7.226653e+03
-2.347590e+02 -7.325778e+03
-2.920924e+02 -7.424902e+03
-3.494258e+02 -7.524027e+03
-4.067592e+02 -7.623151e+03
-4.640926e+02 -7.722276e+03
-5.214261e+02 -7.821401e+03
-5.787595e+02 -7.920525e+03
-6.360929e+02 -8.019650e+03
-6.934263e+02 -8.118775e+03
-7.507596e+02 -8.217899e+03

-8.080930e+02 -8.317023e+03
-8.654266e+02 -8.416148e+03
-9.227599e+02 -8.515273e+03
-9.800933e+02 -8.614397e+03
-1.037427e+03 -8.713522e+03
-1.094760e+03 -8.812647e+03
-1.152094e+03 -8.911771e+03
-1.209427e+03 -9.010896e+03
0
0
1.000000e+05
35 35 2 1 0 15 15 10 0 15 15
-1.424131e+04 1.591426e+03 -1.189804e+04 2.207486e+03
5.000000e-01 5.000000e-01 3.000000e+01 2.000000e+03
well.map
9 12 9 14 15 11 9
0
-4.580917e+03 1.009501e+03 -7.339408e+03 -2.358854e+03
3.000000e+01 2.000000e+01
1.500000e+02 1.500000e+01 0
3.650000e+02 1.000000e+00 3.000000e+01 0 2
1.979092e+03
0 19600 0 1 8 1 0
0 0
0.000000e+00 0.000000e+00
8
1 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
1.010000e+02
0

The raw data generated for Figure 6.20 are included in the following pages. The data were generated in Quickflow™ using the following parameters:

Hydraulic conductivity (ft/day)	Aquifer thickness (ft)	Gradient (ft/ft)	Porosity (dimensionless)
30.9	17	0.0022	0.30

mda

30 0 0 0

3.090000e+01 1.700000e+01 0.000000e+00 1.000000e+00

2.000000e-01 1.000000e-03 0.000000e+00

1.921460e+03 -7.149288e+03 2.500000e+01

2.000000e-03 1.050600e+00 1.448429e+02 -8.175762e-01 -5.758204e-01

0.000000e+00 2.500000e+07 2.500000e+07 0.000000e+00 0.000000e+00 0.000000e+00

-2.880861e+03 -4.568550e+03 3.470000e+02 2.500000e-01

-2.580559e+03 -4.534032e+03 2.890000e+02 2.500000e-01

-2.280256e+03 -4.568550e+03 2.890000e+02 2.500000e-01

-2.894668e+03 -3.574445e+03 -1.733000e+03 2.500000e-01

-2.649594e+03 -3.591704e+03 -1.540000e+02 2.500000e-01

-3.301975e+03 -3.974849e+03 -1.713000e+03 2.500000e-01

-3.467659e+03 -4.582357e+03 -9.050000e+02 2.500000e-01

-1.883304e+03 -4.585809e+03 -5.780000e+02 2.500000e-01

-3.388268e+03 -4.230278e+03 -1.160000e+02 2.500000e-01

-3.182889e+03 -4.874030e+03 -6.350000e+02 2.500000e-01

-2.544315e+03 -4.887837e+03 2.890000e+02 2.500000e-01

-2.280727e+03 -4.999948e+03 6.550000e+02 2.500000e-01

-1.980244e+03 -4.819753e+03 7.320000e+02 2.500000e-01

-1.583245e+03 -5.052722e+03 5.390000e+02 2.500000e-01

-1.880400e+03 -5.266674e+03 3.080000e+02 2.500000e-01

-1.375236e+03 -5.503209e+03 6.160000e+02 2.500000e-01

-9.639740e+02 -5.593544e+03 7.120000e+02 2.500000e-01

-5.800499e+02 -5.390290e+03 1.752000e+03 2.500000e-01

-6.808997e+02 -5.639443e+03 1.020000e+03 2.500000e-01

-1.330069e+03 -5.818650e+03 7.510000e+02 2.500000e-01

-1.912578e+02 -5.490026e+03 5.010000e+02 2.500000e-01

-1.856759e+02 -5.590501e+03 5.200000e+02 2.500000e-01

-1.800939e+02 -5.690977e+03 2.310000e+02 2.500000e-01

-3.810439e+02 -5.590501e+03 5.780000e+02 2.500000e-01

-3.060255e+03 -5.000540e+03 -1.000000e+03 2.500000e-01

-3.096943e+03 -3.558787e+03 9.050000e+02 2.500000e-01

-3.196415e+03 -3.970393e+03 7.700000e+02 2.500000e-01

-3.125536e+03 -3.803525e+03 5.010000e+02 2.500000e-01

-2.683096e+03 -5.267566e+03 -1.000000e+03 2.500000e-01

-2.882486e+03 -5.188562e+03 -1.000000e+03 2.500000e-01

50

1.586839e+03 -3.706040e+03

1.530575e+03 -3.824820e+03

1.474311e+03 -3.943601e+03

1.418046e+03 -4.062381e+03

1.361782e+03 -4.181162e+03

1.305517e+03 -4.299942e+03

1.249253e+03 -4.418723e+03

1.192988e+03 -4.537503e+03

1.136724e+03 -4.656284e+03

1.080460e+03 -4.775064e+03

1.024195e+03 -4.893845e+03

9.679307e+02 -5.012625e+03

9.116663e+02 -5.131406e+03

8.554018e+02 -5.250186e+03

7.991374e+02 -5.368967e+03

7.428729e+02 -5.487747e+03

6.866085e+02 -5.606528e+03

6.303441e+02 -5.725308e+03

5.740796e+02 -5.844089e+03

5.178152e+02 -5.962869e+03

4.615508e+02 -6.081649e+03

4.052863e+02 -6.200430e+03

3.490219e+02 -6.319211e+03

2.927575e+02 -6.437991e+03

2.364931e+02 -6.556771e+03

1.802286e+02 -6.675552e+03

1.239642e+02 -6.794333e+03

6.769975e+01 -6.913113e+03

1.143534e+01 -7.031894e+03

-4.482907e+01 -7.150674e+03

-1.010936e+02 -7.269455e+03

-1.573580e+02 -7.388235e+03

-2.136225e+02 -7.507016e+03
-2.698869e+02 -7.625796e+03
-3.261513e+02 -7.744577e+03
-3.824157e+02 -7.863357e+03
-4.386803e+02 -7.982138e+03
-4.949447e+02 -8.100918e+03
-5.512091e+02 -8.219698e+03
-6.074735e+02 -8.338479e+03
-6.637379e+02 -8.457260e+03
-7.200023e+02 -8.576040e+03
-7.762669e+02 -8.694820e+03
-8.325313e+02 -8.813602e+03
-8.887957e+02 -8.932382e+03
-9.450601e+02 -9.051162e+03
-1.001325e+03 -9.169942e+03
-1.057589e+03 -9.288723e+03
-1.113853e+03 -9.407503e+03
-1.170118e+03 -9.526284e+03
0
0
1.000000e+05
35 35 2 1 0 15 15 10 0 15 15
-1.424131e+04 1.591426e+03 -1.189804e+04 2.207486e+03
5.000000e-01 -5.000000e-01 3.000000e+01 2.000000e+03
well.map
9 12 9 14 15 11 9
0
-4.322425e+03 3.331569e+02 -6.739481e+03 -2.591781e+03
3.000000e+01 2.000000e+01
1.500000e+02 1.500000e+01 0
3.650000e+02 1.000000e+00 3.000000e+01 0 2
1.979092e+03
0 1 9600 0 1 8 1 0
0 0
0.000000e+00 0.000000e+00

8

1 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

1.010000e+02

0

APPENDIX D

MAROS SAMPLING LOCATION OPTIMIZATION RESULTS

MAROS Sampling Location Optimization Results

Project:

User Name:

Location: HILL

State: Utah

Analysis by DeLauney Method

Sampling Events Analyzed: From Sample Event 14 7/15/99
To Sample Event 14 7/15/99

Constituent	Well Name	Average Slope Factor	Eliminated?
cis-1,2-DICHLOROETHYLENE	JMM-48	0.485	<input type="checkbox"/>
	JMM-63	0.283	<input checked="" type="checkbox"/>
	JMM-62	0.103	<input type="checkbox"/>
	ESE-15	0.208	<input checked="" type="checkbox"/>
	JMM-59	0.005	<input checked="" type="checkbox"/>
	JMM-47	0.481	<input type="checkbox"/>
	JMM-29	0.237	<input type="checkbox"/>
	JMM-22	0.486	<input type="checkbox"/>
	JMM-20	0.404	<input type="checkbox"/>
	JMM-19	0.405	<input type="checkbox"/>
	JMM-17	0.199	<input type="checkbox"/>
	JMM-06	0.185	<input type="checkbox"/>
	JMM-03	0.469	<input type="checkbox"/>
	JA-09	0.346	<input checked="" type="checkbox"/>
JMM-60	0.075	<input checked="" type="checkbox"/>	
TRICHLOROETHYLENE (TCE)	JMM-29	0.000	<input type="checkbox"/>
	ESE-15	0.000	<input type="checkbox"/>
	JA-09	0.238	<input type="checkbox"/>
	JMM-03	0.117	<input type="checkbox"/>
	JMM-06	0.218	<input type="checkbox"/>
	JMM-17	0.000	<input type="checkbox"/>
	JMM-19	0.112	<input type="checkbox"/>
	JMM-47	0.158	<input type="checkbox"/>
	JMM-48	0.000	<input type="checkbox"/>
JMM-59	0.479	<input type="checkbox"/>	

Project:

User Name:

Location: HILL

State: Utah

JMM-60	0.216	<input type="checkbox"/>
JMM-62	0.000	<input type="checkbox"/>
JMM-63	0.000	<input checked="" type="checkbox"/>
JMM-22	0.214	<input type="checkbox"/>
JMM-20	0.512	<input type="checkbox"/>

VINYL CHLORIDE

JMM-03	0.374	<input type="checkbox"/>
JMM-62	0.099	<input type="checkbox"/>
JMM-60	0.135	<input type="checkbox"/>
JMM-59	0.355	<input type="checkbox"/>
JMM-48	0.186	<input type="checkbox"/>
JMM-47	0.294	<input type="checkbox"/>
JMM-29	0.000	<input type="checkbox"/>
JMM-22	0.577	<input type="checkbox"/>
JMM-20	0.065	<input type="checkbox"/>
JMM-19	0.340	<input type="checkbox"/>
JMM-06	0.297	<input type="checkbox"/>
JA-09	0.432	<input type="checkbox"/>
ESE-15	0.000	<input type="checkbox"/>
JMM-63	0.000	<input checked="" type="checkbox"/>
JMM-17	0.000	<input type="checkbox"/>

Note: The Delauney method results tell how important a well is in a given sampling event. The larger the SF value of a well, the more important it is.

Abandoned Sampling Locations by considering all COCs

Well Name	East Coord.	North Coord.	Abandoned?
ESE-15	1861088.375	337436.844	<input type="checkbox"/>
JA-09	1861716.000	336546.875	<input type="checkbox"/>
JMM-03	1861133.750	336809.250	<input type="checkbox"/>
JMM-06	1860411.375	336653.313	<input type="checkbox"/>
JMM-17	1860400.875	337247.844	<input type="checkbox"/>
JMM-19	1862189.500	335928.250	<input type="checkbox"/>
JMM-20	1862672.625	334940.469	<input type="checkbox"/>
JMM-22	1861153.500	336636.438	<input type="checkbox"/>
JMM-29	1860473.250	338118.438	<input type="checkbox"/>

Project:

User Name:

Location: HILL

State: Utah

JMM-47	1861932.500	336437.188	<input type="checkbox"/>
JMM-48	1862800.500	336218.875	<input type="checkbox"/>
JMM-59	1861444.125	336467.594	<input type="checkbox"/>
JMM-60	1862282.875	335667.469	<input type="checkbox"/>
JMM-62	1861489.250	337360.156	<input type="checkbox"/>
JMM-63	1860862.125	337799.469	<input checked="" type="checkbox"/>

To be conservative, a location is abandoned only when it is eliminated from all COCs.

MAROS Sampling Frequency Optimization Results

Project:

User Name:

Location: HILL

State: Utah

Analysis by Modified CES Method

Number of Sampling Events Analyzed 14

Recent Sampling Events: From Sample Event 8 1/15/97
To Sample Event 14 7/15/99

Constituent	Well Name	Sampling Frequency	Frequency based on current period	Frequency based on overall period
cis-1,2-DICHLOROETHYLENE	ESE-15	Annual	Annual	Annual
	JA-09	Biennial	Annual	Annual
	JMM-03	Annual	Annual	Annual
	JMM-06	Biennial	Annual	Annual
	JMM-17	Annual	Annual	Annual
	JMM-19	Biennial	Annual	Annual
	JMM-20	Annual	Annual	Annual
	JMM-22	Annual	Annual	Annual
	JMM-29	Biennial	Annual	Annual
	JMM-47	Biennial	Annual	Annual
	JMM-48	Annual	Annual	Annual
	JMM-59	Biennial	Annual	Annual
	JMM-60	Biennial	Annual	Annual
	JMM-62	Biennial	Annual	Annual
JMM-63	Biennial	Annual	Annual	
TRICHLOROETHYLENE (TCE)	ESE-15	Annual	Annual	Annual
	JA-09	Biennial	Annual	Annual
	JMM-03	Annual	Annual	Annual
	JMM-06	Biennial	Annual	Annual
	JMM-17	Annual	Annual	Annual
	JMM-19	Annual	Annual	Annual
	JMM-20	SemiAnnual	SemiAnnual	SemiAnnual
	JMM-22	Biennial	Annual	Annual
	JMM-29	Biennial	Annual	Annual

Project:

User Name:

Location: HILL

State: Utah

	JMM-47	Biennial	Annual	Annual
	JMM-48	Annual	Annual	Annual
	JMM-59	Annual	Annual	Annual
	JMM-60	Biennial	Annual	Annual
	JMM-62	Biennial	Annual	Annual
	JMM-63	Biennial	Annual	Annual
VINYL CHLORIDE	ESE-15	Annual	Annual	Annual
	JA-09	Annual	Annual	Annual
	JMM-03	Annual	Annual	Annual
	JMM-06	Annual	Annual	Annual
	JMM-17	Annual	Annual	Annual
	JMM-19	Annual	Annual	Annual
	JMM-20	Annual	Annual	Annual
	JMM-22	Annual	Annual	Annual
	JMM-29	Annual	Annual	Annual
	JMM-47	Annual	Annual	Annual
	JMM-48	Annual	Annual	Annual
	JMM-59	Annual	Annual	Annual
	JMM-60	Annual	Annual	Annual
	JMM-62	Annual	Annual	Annual
	JMM-63	Annual	Annual	Annual

Note: Modified CES (LLNL) method results in a recommended sampling interval for each well. This is based on analysis of concentration trend, so looks at specified sampling interval.

Summary - Final Recommendation for Sampling Frequency

Well Name	Sampling Frequency
ESE-15	Annual
JA-09	Annual
JMM-03	Annual
JMM-06	Annual
JMM-17	Annual
JMM-19	Annual
JMM-20	SemiAnnual
JMM-22	Annual

Project:

User Name:

Location: HILL

State: Utah

JMM-29	Annual
JMM-47	Annual
JMM-48	Annual
JMM-59	Annual
JMM-60	Annual
JMM-62	Annual
JMM-63	Annual

Note: the most stringent sampling frequency was chosen among all COCs.

MAROS COC Assessment

Project:

User Name:

Location: HILL

State: Utah

Toxicity:

Prevalence:

Mobility:

Contaminants of Concern (COC's)

TRICHLOROETHYLENE (TCE)

cis-1,2-DICHLOROETHYLENE

VINYL CHLORIDE

MAROS Mann-Kendall Statistics

Project:

User Name:

Location: HILL

State: Utah

Well	Source/ Tail	Coefficient of Variation	Mann-Kendall Statistic	Confidence in Trend	Concentration Trend
cis-1,2-DICHLOROETHYLENE					
JMM-60	S	8.9E-01	-29	97.4%	D
JMM-47	S	5.2E-01	-30	99.0%	D
JMM-19	S	3.0E-01	-12	77.0%	S
JMM-22	S	1.3E-01	10	72.7%	NT
JA-09	S	2.9E-01	-45	100.0%	D
JMM-03	T	0.0E+00	0	37.5%	S
JMM-62	T	4.4E-01	-41	99.8%	D
JMM-06	T	3.1E-01	-44	99.9%	D
JMM-17	T	0.0E+00	0	37.5%	S
JMM-63	T	3.5E-01	-52	100.0%	D
JMM-59	T	3.3E-01	-12	91.1%	PD
JMM-20	T	0.0E+00	0	37.5%	S
ESE-15	T	4.6E-01	-2	62.5%	S
JMM-48	T	0.0E+00	0	37.5%	S
JMM-29	T	4.3E-01	-44	99.9%	D
TRICHLOROETHYLENE (TCE)					
JA-09	S	2.3E-16	0	46.4%	S
JMM-22	S	2.3E-16	0	47.3%	S
JMM-19	S	2.7E-01	-15	82.8%	S
JMM-60	S	2.3E-16	0	47.3%	S
JMM-47	S	2.3E-16	0	46.9%	S
ESE-15	T	9.5E-02	-4	83.3%	S
JMM-63	T	2.3E-16	0	47.3%	S
JMM-62	T	2.3E-16	0	47.3%	S
JMM-03	T	8.6E-02	-1	50.0%	S
JMM-06	T	2.3E-16	0	47.3%	S
JMM-17	T	0.0E+00	0	37.5%	S
JMM-59	T	6.3E-01	11	88.6%	NT
JMM-48	T	0.0E+00	0	37.5%	S
JMM-29	T	2.3E-16	0	47.3%	S
JMM-20	T	1.0E+00	3	72.9%	NT
VINYL CHLORIDE					
JA-09	S	2.9E-01	-38	99.6%	D
JMM-47	S	5.3E-01	-37	99.5%	D
JMM-60	S	6.6E-01	-23	93.3%	PD
JMM-19	S	3.1E-01	-12	77.0%	S
JMM-22	S	2.4E-01	-27	94.3%	PD
JMM-20	T	0.0E+00	0	37.5%	S
JMM-06	T	2.7E-01	-7	65.8%	S
JMM-17	T	4.0E-01	-1	50.0%	S
JMM-29	T	2.7E-01	3	55.3%	NT

Project:

User Name:

Location: HILL

State: Utah

Well	Source/ Tail	Coefficient of Variation	Mann-Kendall Statistic	Confidence in Trend	Concentration Trend
VINYL CHLORIDE					
JMM-59	T	1.0E+00	-13	89.0%	NT
JMM-62	T	4.8E-01	-24	94.2%	PD
JMM-63	T	3.8E-01	-19	88.8%	S
ESE-15	T	4.0E-01	-1	50.0%	S
JMM-48	T	4.0E-01	-1	50.0%	S
JMM-03	T	4.0E-01	-1	50.0%	S

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A); Source/Tail (S/T)

MAROS Lines of Evidence Summary

Project:

User Name:

Location: HILL

State: Utah

Constituent	Well	Source/ Tail	Mann-Kendall	Linear Regression	Modeling	Empirical
cis-1,2-DICHLOROETHYLENE						
	JMM-60	S	D	D	N/A	N/A
	JMM-47	S	D	D	N/A	N/A
	JMM-19	S	S	D	N/A	N/A
	JMM-22	S	NT	NT	N/A	N/A
	JA-09	S	D	D	N/A	N/A
	JMM-03	T	S	S	N/A	N/A
	JMM-82	T	D	D	N/A	N/A
	JMM-06	T	D	D	N/A	N/A
	JMM-17	T	S	S	N/A	N/A
	JMM-63	T	D	D	N/A	N/A
	JMM-59	T	PD	D	N/A	N/A
	JMM-20	T	S	S	N/A	N/A
	ESE-15	T	S	D	N/A	N/A
	JMM-48	T	S	S	N/A	N/A
	JMM-29	T	D	D	N/A	N/A
TRICHLOROETHYLENE (TCE)						
	JA-09	S	S	S	N/A	N/A
	JMM-22	S	S	D	N/A	N/A
	JMM-19	S	S	D	N/A	N/A
	JMM-60	S	S	D	N/A	N/A
	JMM-47	S	S	S	N/A	N/A
	ESE-15	T	S	D	N/A	N/A
	JMM-63	T	S	D	N/A	N/A
	JMM-62	T	S	D	N/A	N/A
	JMM-03	T	S	D	N/A	N/A
	JMM-08	T	S	D	N/A	N/A
	JMM-17	T	S	S	N/A	N/A
	JMM-59	T	NT	PI	N/A	N/A
	JMM-48	T	S	S	N/A	N/A
	JMM-29	T	S	D	N/A	N/A
	JMM-20	T	NT	NT	N/A	N/A
VINYL CHLORIDE						
	JA-09	S	D	D	N/A	N/A
	JMM-47	S	D	D	N/A	N/A
	JMM-60	S	PD	D	N/A	N/A
	JMM-19	S	S	D	N/A	N/A
	JMM-22	S	PD	D	N/A	N/A
	JMM-20	T	S	S	N/A	N/A
	JMM-08	T	S	D	N/A	N/A
	JMM-17	T	S	D	N/A	N/A
	JMM-29	T	NT	NT	N/A	N/A

Project:

User Name:

Location: HILL

State: Utah

Constituent	Well	Source/ Tail	Mann-Kendall	Linear Regression	Modeling	Empirical
VINYL CHLORIDE						
	JMM-59	T	NT	D	N/A	N/A
	JMM-62	T	PD	D	N/A	N/A
	JMM-83	T	S	D	N/A	N/A
	ESE-15	T	S	D	N/A	N/A
	JMM-48	T	S	D	N/A	N/A
	JMM-03	T	S	D	N/A	N/A

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A); Source/Tail (S/T)

MAROS Site Results

Project:

User Name:

Location: HILL

State: Utah

Recommendation Basis:

Monitoring System Category from Compliance Monitoring Analysis Moderate

Number of Source Wells: 5 Number of Tail Wells: 10

Hydrogeology and Plume Information:

Main Constituents: Chlorinated Solvent Groundwater Seepage Velocity: 1000 ft/yr Current Plume Length: 2000 ft

Source Information: Current Plume Width: 1000 ft

Source Treatment: No Current Site Treatment

NAPL is not present at this site.

Down-gradient Information:

Distance from Source to Nearest:

Distance from Edge of Tail to Nearest:

Down-gradient receptor: 2500 ft

Down-gradient receptor: 1500 ft

Down-gradient property: 1500 ft

Down-gradient property: 500 ft

Compliance Monitoring/Remediation Optimization Results:

Preliminary Monitoring System Optimization Results: Based on site classification, source treatment and Monitoring System Category the following suggestions are made for site Sampling Frequency, Duration of Sampling, and Well Density. These criteria take into consideration: Plume Stability, Type of Plume, and Groundwater Velocity.

COC	Tail Stability	Source Stability	Design Category	Sampling Duration	Sampling Frequency	Sampling Density
cis-1,2-DICHLOROETHYLENE	PD	PD	L	Sample 2 more years	Biannually (6 months)	34
TRICHLOROETHYLENE (TCE)	S	PD	M	Sample 4 more years	Biannually (6 months)	34
VINYL CHLORIDE	PD	D	L	Sample 2 more years	Biannually (6 months)	34

Note:

Plume Status: (I) Increasing; (PI) Probably Increasing; (S) Stable; (NT) No Trend; (PD) Probably Decreasing; (D) Decreasing

Design Categories: (E) Extensive; (M) Moderate; (L) Limited (N/A) Not Applicable, Insufficient Data Available

MAROS Linear Regression Statistics

Project:

User Name:

Location: HILL

State: Utah

Constituent	Well	Source/ Tail	Average	Standard Deviation	Ln Slope	Coefficient of Variation	Confidence in Trend	Concentration Trend
cis-1,2-DICHLOROETHYLENE								
	JMM-60	S	6.3E-03	5.5E-03	-9.9E-04	8.9E-01	100.0%	D
	JMM-19	S	1.2E-02	3.6E-03	-1.8E-04	3.0E-01	100.0%	D
	JMM-22	S	6.3E-03	7.8E-04	7.4E-05	1.3E-01	86.3%	NT
	JA-09	S	5.0E-03	1.4E-03	-4.1E-04	2.9E-01	100.0%	D
	JMM-47	S	3.1E-03	1.6E-03	-7.6E-04	5.2E-01	100.0%	D
	JMM-17	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	100.0%	S
	JMM-03	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	100.0%	S
	JMM-20	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	100.0%	S
	ESE-15	T	1.4E-03	6.2E-04	-7.6E-04	4.6E-01	100.0%	D
	JMM-29	T	1.2E-03	5.3E-04	-5.2E-04	4.3E-01	100.0%	D
	JMM-48	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	100.0%	S
	JMM-06	T	1.3E-03	3.9E-04	-4.3E-04	3.1E-01	100.0%	D
	JMM-59	T	2.9E-03	9.6E-04	-4.0E-04	3.3E-01	100.0%	D
	JMM-62	T	2.0E-03	9.0E-04	-6.1E-04	4.4E-01	100.0%	D
	JMM-63	T	1.9E-03	6.5E-04	-6.3E-04	3.5E-01	100.0%	D
TRICHLOROETHYLENE (TCE)								
	JMM-60	S	5.0E-04	1.2E-11	-2.6E-34	2.5E-08	100.0%	D
	JMM-22	S	5.0E-04	1.2E-11	-2.6E-34	2.5E-08	100.0%	D
	JMM-19	S	5.9E-04	1.6E-04	-9.6E-05	2.7E-01	100.0%	D
	JA-09	S	5.0E-04	1.2E-11	0.0E+00	2.4E-08	100.0%	S
	JMM-47	S	5.0E-04	1.3E-11	0.0E+00	2.6E-08	100.0%	S
	ESE-15	T	5.5E-04	5.2E-05	-1.5E-04	9.5E-02	100.0%	D
	JMM-03	T	5.2E-04	4.5E-05	-6.2E-05	8.6E-02	100.0%	D
	JMM-48	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	100.0%	S
	JMM-63	T	5.0E-04	1.2E-11	-2.6E-34	2.5E-08	100.0%	D
	JMM-17	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	100.0%	S
	JMM-62	T	5.0E-04	1.2E-11	-2.6E-34	2.5E-08	100.0%	D
	JMM-20	T	1.1E-03	1.1E-03	1.1E-03	1.0E+00	67.8%	NT
	JMM-59	T	1.0E-03	6.4E-04	6.9E-04	6.3E-01	90.3%	PI
	JMM-29	T	5.0E-04	1.2E-11	-2.6E-34	2.5E-08	100.0%	D
	JMM-06	T	5.0E-04	1.2E-11	-2.6E-34	2.5E-08	100.0%	D
VINYL CHLORIDE								
	JA-09	S	3.6E-03	1.0E-03	-4.7E-04	2.9E-01	100.0%	D
	JMM-19	S	3.3E-03	1.0E-03	-2.3E-04	3.1E-01	100.0%	D
	JMM-22	S	6.9E-03	1.7E-03	-2.0E-04	2.4E-01	100.0%	D
	JMM-47	S	1.9E-03	9.6E-04	-8.1E-04	5.3E-01	100.0%	D
	JMM-60	S	1.2E-03	7.7E-04	-3.7E-04	6.6E-01	100.0%	D
	JMM-06	T	5.6E-04	1.5E-04	-2.1E-05	2.7E-01	100.0%	D
	JMM-48	T	6.3E-04	2.5E-04	-2.6E-04	4.0E-01	100.0%	D
	JMM-20	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	100.0%	S
	JMM-59	T	1.6E-03	1.6E-03	-1.0E-03	1.0E+00	100.0%	D
	ESE-15	T	6.3E-04	2.5E-04	-2.6E-04	4.0E-01	100.0%	D

Project:

User Name:

Location: HILL

State: Utah

Constituent	Well	Source/ Tail	Average	Standard Deviation	Ln Slope	Coefficient of Variation	Confidence in Trend	Concentration Trend
VINYL CHLORIDE								
	JMM-17	T	6.3E-04	2.5E-04	-2.6E-04	4.0E-01	100.0%	D
	JMM-62	T	7.8E-04	3.7E-04	-3.3E-04	4.8E-01	100.0%	D
	JMM-03	T	6.3E-04	2.5E-04	-2.6E-04	4.0E-01	100.0%	D
	JMM-63	T	7.2E-04	2.7E-04	-2.9E-04	3.8E-01	100.0%	D
	JMM-29	T	5.4E-04	1.4E-04	4.1E-05	2.7E-01	64.6%	NT

OU4

MAROS COC Assessment

Project: DDHU OU4

User Name: PARSONS

Location: OGDEN

State: Utah

Toxicity:

Contaminant of Concern	Representative Concentration (mg/L)	PRG (mg/L)	Percent Above PRG
VINYL CHLORIDE	9.3E-03	2.0E-05	46540.3%
BENZENE	7.4E-04	3.9E-04	89.2%

Note: Top COCs by toxicity were determined by examining a representative concentration for each compound over the entire site. The compound representative concentrations are then compared with the chosen PRG for that compound, with the percentage exceedence from the PRG determining the compound's toxicity. All compounds above exceed the PRG.

Prevalence:

Contaminant of Concern	Class	Total Wells	Total Excedences	Percent Excedences	Total detects
VINYL CHLORIDE	ORG	19	19	100.0%	19
BENZENE	ORG	19	19	100.0%	19

Note: Top COCs by prevalence were determined by examining a representative concentration for each well location at the site. The total exceedences (values above the chosen PRGs) are compared to the total number of wells to determine the prevalence of the compound.

Mobility:

Contaminant of Concern	Kd
VINYL CHLORIDE	0.042
BENZENE	0.0984

Note: Top COCs by mobility were determined by examining each detected compound in the dataset and comparing their mobilities (Koc's for organics, assume foc = 0.001, and Kd's for metals).

Contaminants of Concern (COC's)

BENZENE
TRICHLOROETHYLENE (TCE)
cis-1,2-DICHLOROETHYLENE
VINYL CHLORIDE

MAROS Mann-Kendall Statistics

Project: DDHU OU4

User Name: PARSONS

Location: OGDEN

State: Utah

Well	Source/ Tail	Coefficient of Variation	Mann-Kendall Statistic	Confidence in Trend	Concentration Trend
BENZENE					
JMM-57	S	3.5E-01	-32	97.1%	D
JMM-52	S	0.0E+00	0	0.0%	N/A
JMM-09	S	1.1E+00	-42	99.5%	D
JMM-56	S	2.2E-01	-3	72.9%	S
JMM-08	S	0.0E+00	0	0.0%	N/A
JMM-7R	S	0.0E+00	0	0.0%	N/A
JMM-44	T	0.0E+00	0	0.0%	N/A
HS-05	T	0.0E+00	0	0.0%	N/A
JMM-15	T	0.0E+00	0	0.0%	N/A
JMM-46	T	0.0E+00	0	0.0%	N/A
JMM-14	T	0.0E+00	0	0.0%	N/A
JMM-33	T	0.0E+00	0	0.0%	N/A
HS-06	T	0.0E+00	0	0.0%	N/A
JMM-30	T	0.0E+00	0	0.0%	N/A
HS-10	T	0.0E+00	0	0.0%	N/A
HS-07	T	0.0E+00	0	0.0%	N/A
JMM-64	T	0.0E+00	0	0.0%	N/A
JMM-65	T	0.0E+00	0	0.0%	N/A
HS-08	T	0.0E+00	0	0.0%	N/A
cis-1,2-DICHLOROETHYLENE					
JMM-09	S	2.9E+00	-78	100.0%	D
JMM-08	S	1.1E+00	-1	50.0%	NT
JMM-7R	S	0.0E+00	0	0.0%	N/A
JMM-57	S	5.8E-01	-57	99.9%	D
JMM-56	S	1.3E+00	-61	100.0%	D
JMM-30	T	2.3E-16	0	47.6%	S
JMM-15	T	3.3E-01	-14	78.2%	S
HS-07	T	0.0E+00	0	0.0%	N/A
HS-08	T	0.0E+00	0	0.0%	N/A
HS-05	T	0.0E+00	0	0.0%	N/A
HS-06	T	0.0E+00	0	0.0%	N/A
HS-10	T	0.0E+00	0	0.0%	N/A
JMM-14	T	0.0E+00	0	0.0%	N/A
JMM-46	T	6.0E-01	-19	86.1%	S
JMM-33	T	2.3E-16	0	47.6%	S
JMM-44	T	4.7E-01	57	100.0%	I
JMM-64	T	3.9E-01	-41	99.4%	D
JMM-65	T	2.9E+00	-22	89.8%	NT
TRICHLOROETHYLENE (TCE)					
JMM-57	S	1.4E-01	-6	61.7%	S
JMM-7R	S	0.0E+00	0	0.0%	N/A

Project: DDHU OU4

User Name: PARSONS

Location: OGDEN

State: Utah

Well	Source/ Tail	Coefficient of Variation	Mann-Kendall Statistic	Confidence in Trend	Concentration Trend
TRICHLOROETHYLENE (TCE)					
JMM-08	S	0.0E+00	0	0.0%	N/A
JMM-09	S	3.2E-01	-26	93.6%	PD
JMM-56	S	9.7E-01	-4	83.3%	S
HS-08	T	0.0E+00	0	0.0%	N/A
JMM-64	T	0.0E+00	0	0.0%	N/A
HS-07	T	0.0E+00	0	0.0%	N/A
HS-10	T	0.0E+00	0	0.0%	N/A
JMM-14	T	0.0E+00	0	0.0%	N/A
HS-06	T	0.0E+00	0	0.0%	N/A
JMM-44	T	0.0E+00	0	0.0%	N/A
JMM-15	T	0.0E+00	0	0.0%	N/A
JMM-65	T	0.0E+00	0	0.0%	N/A
HS-05	T	0.0E+00	0	0.0%	N/A
JMM-30	T	0.0E+00	0	0.0%	N/A
JMM-33	T	0.0E+00	0	0.0%	N/A
JMM-46	T	0.0E+00	0	0.0%	N/A
VINYL CHLORIDE					
JMM-57	S	9.2E-01	-46	99.4%	D
JMM-58	S	2.0E+00	-19	83.5%	NT
JMM-08	S	7.5E-01	-11	70.5%	S
JMM-52	S	2.1E+00	-3	67.5%	NT
JMM-7R	S	0.0E+00	0	0.0%	N/A
JMM-09	S	1.7E+00	-57	99.9%	D
JMM-64	T	5.6E-01	-42	99.5%	D
JMM-30	T	2.3E-16	0	47.8%	S
HS-05	T	0.0E+00	0	0.0%	N/A
JMM-65	T	2.3E-16	0	47.6%	S
JMM-33	T	2.5E-01	-13	74.1%	S
JMM-44	T	2.3E-16	0	47.8%	S
HS-10	T	0.0E+00	0	0.0%	N/A
JMM-14	T	0.0E+00	0	45.2%	S
JMM-15	T	2.5E-01	-13	74.1%	S
HS-07	T	0.0E+00	0	0.0%	N/A
JMM-46	T	6.8E-01	-21	86.0%	S
HS-08	T	0.0E+00	0	0.0%	N/A
HS-06	T	0.0E+00	0	0.0%	N/A

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A); Source/Tail (S/T)

MAROS Lines of Evidence Summary

Project: DDHU OU4

User Name: PARSONS

Location: OGDEN

State: Utah

Constituent	Well	Source/ Tail	Mann-Kendall	Linear Regression	Modeling	Empirical
BENZENE						
	JMM-57	S	D	D	N/A	N/A
	JMM-52	S	N/A	N/A	N/A	N/A
	JMM-09	S	D	D	N/A	N/A
	JMM-56	S	S	D	N/A	N/A
	JMM-08	S	N/A	N/A	N/A	N/A
	JMM-7R	S	N/A	N/A	N/A	N/A
	JMM-44	T	N/A	N/A	N/A	N/A
	HS-05	T	N/A	N/A	N/A	N/A
	JMM-15	T	N/A	N/A	N/A	N/A
	JMM-46	T	N/A	N/A	N/A	N/A
	JMM-14	T	N/A	N/A	N/A	N/A
	JMM-33	T	N/A	N/A	N/A	N/A
	HS-06	T	N/A	N/A	N/A	N/A
	JMM-30	T	N/A	N/A	N/A	N/A
	HS-10	T	N/A	N/A	N/A	N/A
	HS-07	T	N/A	N/A	N/A	N/A
	JMM-64	T	N/A	N/A	N/A	N/A
	JMM-65	T	N/A	N/A	N/A	N/A
	HS-08	T	N/A	N/A	N/A	N/A
cis-1,2-DICHLOROETHYLENE						
	JMM-09	S	D	D	N/A	N/A
	JMM-08	S	NT	D	N/A	N/A
	JMM-7R	S	N/A	N/A	N/A	N/A
	JMM-57	S	D	D	N/A	N/A
	JMM-56	S	D	D	N/A	N/A
	JMM-30	T	S	S	N/A	N/A
	JMM-15	T	S	I	N/A	N/A
	HS-07	T	N/A	N/A	N/A	N/A
	HS-08	T	N/A	N/A	N/A	N/A
	HS-05	T	N/A	N/A	N/A	N/A
	HS-06	T	N/A	N/A	N/A	N/A
	HS-10	T	N/A	N/A	N/A	N/A
	JMM-14	T	N/A	N/A	N/A	N/A
	JMM-46	T	S	D	N/A	N/A
	JMM-33	T	S	S	N/A	N/A
	JMM-44	T	I	I	N/A	N/A
	JMM-64	T	D	D	N/A	N/A
	JMM-65	T	NT	D	N/A	N/A
TRICHLOROETHYLENE (TCE)						
	JMM-57	S	S	D	N/A	N/A
	JMM-7R	S	N/A	N/A	N/A	N/A

Project: DDHU OU4

User Name: PARSONS

Location: OGDEN

State: Utah

Constituent	Well	Source/ Tail	Mann-Kendall	Linear Regression	Modeling	Empirical
TRICHLOROETHYLENE (TCE)						
	JMM-08	S	N/A	N/A	N/A	N/A
	JMM-09	S	PD	D	N/A	N/A
	JMM-56	S	S	D	N/A	N/A
	HS-08	T	N/A	N/A	N/A	N/A
	JMM-64	T	N/A	N/A	N/A	N/A
	HS-07	T	N/A	N/A	N/A	N/A
	HS-10	T	N/A	N/A	N/A	N/A
	JMM-14	T	N/A	N/A	N/A	N/A
	HS-06	T	N/A	N/A	N/A	N/A
	JMM-44	T	N/A	N/A	N/A	N/A
	JMM-15	T	N/A	N/A	N/A	N/A
	JMM-65	T	N/A	N/A	N/A	N/A
	HS-05	T	N/A	N/A	N/A	N/A
	JMM-30	T	N/A	N/A	N/A	N/A
	JMM-33	T	N/A	N/A	N/A	N/A
	JMM-46	T	N/A	N/A	N/A	N/A
VINYL CHLORIDE						
	JMM-57	S	D	D	N/A	N/A
	JMM-56	S	NT	D	N/A	N/A
	JMM-08	S	S	D	N/A	N/A
	JMM-52	S	NT	D	N/A	N/A
	JMM-7R	S	N/A	N/A	N/A	N/A
	JMM-09	S	D	D	N/A	N/A
	JMM-64	T	D	D	N/A	N/A
	JMM-30	T	S	S	N/A	N/A
	HS-05	T	N/A	N/A	N/A	N/A
	JMM-65	T	S	S	N/A	N/A
	JMM-33	T	S	D	N/A	N/A
	JMM-44	T	S	S	N/A	N/A
	HS-10	T	N/A	N/A	N/A	N/A
	JMM-14	T	S	S	N/A	N/A
	JMM-15	T	S	D	N/A	N/A
	HS-07	T	N/A	N/A	N/A	N/A
	JMM-46	T	S	D	N/A	N/A
	HS-08	T	N/A	N/A	N/A	N/A
	HS-06	T	N/A	N/A	N/A	N/A

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A); Source/Tail (S/T)

MAROS Site Results

Project: DDHU OU4

User Name: PARSONS

Location: OGDEN

State: Utah

Recommendation Basis:

Monitoring System Category from Compliance Monitoring Analysis Moderate

Number of Source Wells: 6 Number of Tail Wells: 13

Hydrogeology and Plume Information:

Main Constituents: Chlorinated Solvent Groundwater Seepage Velocity: 1000 ft/yr Current Plume Length: 3000 ft
Current Plume Width: 1000 ft

Source Information:

Source Treatment: No Current Site Treatment NAPL is not present at this site.

Down-gradient Information:

Distance from Source to Nearest:		Distance from Edge of Tail to Nearest:	
Down-gradient receptor:	4000 ft	Down-gradient receptor:	1000 ft
Down-gradient property:	3500 ft	Down-gradient property:	500 ft

Compliance Monitoring/Remediation Optimization Results:

Preliminary Monitoring System Optimization Results: Based on site classification, source treatment and Monitoring System Category the following suggestions are made for site Sampling Frequency, Duration of Sampling, and Well Density. These criteria take into consideration: Plume Stability, Type of Plume, and Groundwater Velocity.

COC	Tail Stability	Source Stability	Design Category	Sampling Duration	Sampling Frequency	Sampling Density
BENZENE	N/A	D	N/A	Insufficient Data, continue sampling	Insufficient Data	40
cis-1,2-DICHLOROETHYLENE	S	D	M	Sample 4 more years	Biannually (6 months)	40
TRICHLOROETHYLENE (TCE)	N/A	PD	N/A	Insufficient Data, continue sampling	Insufficient Data	40
VINYL CHLORIDE	PD	PD	L	Sample 2 more years	Biannually (6 months)	40

Note:

Plume Status: (I) Increasing; (PI) Probably Increasing; (S) Stable; (NT) No Trend; (PD) Probably Decreasing; (D) Decreasing
Design Categories: (E) Extensive; (M) Moderate; (L) Limited (N/A) Not Applicable, Insufficient Data Available

MAROS Linear Regression Statistics

Project: DDHU OU4

User Name: PARSONS

Location: OGDEN

State: Utah

Constituent	Well	Source/ Tail	Average	Standard Deviation	Ln Slope	Coefficient of Variation	Confidence in Trend	Concentration Trend
BENZENE								
	JMM-08	S	2.9E-03	3.4E-03	0.0E+00	0.0E+00	0.0%	N/A
	JMM-7R	S	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	JMM-09	S	1.5E-03	1.7E-03	-1.0E-03	1.1E+00	100.0%	D
	JMM-56	S	5.6E-04	1.3E-04	-1.3E-04	2.2E-01	100.0%	D
	JMM-52	S	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	JMM-57	S	6.1E-04	2.1E-04	-2.7E-04	3.5E-01	100.0%	D
	JMM-14	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	JMM-33	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	HS-07	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	JMM-44	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	JMM-15	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	JMM-46	T	5.0E-04	7.3E-12	0.0E+00	0.0E+00	0.0%	N/A
	JMM-30	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	HS-05	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	JMM-64	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	HS-10	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	HS-06	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	JMM-65	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	HS-08	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
cis-1,2-DICHLOROETHYLENE								
	JMM-57	S	1.7E-02	9.8E-03	-5.5E-04	5.8E-01	100.0%	D
	JMM-7R	S	1.2E-03	4.1E-04	0.0E+00	0.0E+00	0.0%	N/A
	JMM-09	S	1.8E-01	5.3E-01	-1.6E-03	2.9E+00	100.0%	D
	JMM-06	S	9.5E-02	1.1E-01	-1.4E-04	1.1E+00	100.0%	D
	JMM-56	S	1.4E-02	1.9E-02	-1.1E-03	1.3E+00	100.0%	D
	HS-07	T	4.4E-03	3.0E-03	0.0E+00	0.0E+00	0.0%	N/A
	HS-06	T	1.5E-03	1.4E-03	0.0E+00	0.0E+00	0.0%	N/A
	JMM-65	T	4.2E-03	1.2E-02	-9.1E-04	2.9E+00	100.0%	D
	JMM-64	T	3.1E-02	1.2E-02	-6.0E-04	3.9E-01	100.0%	D
	HS-10	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	JMM-30	T	5.0E-04	1.5E-11	0.0E+00	2.9E-08	100.0%	S
	HS-05	T	2.6E-03	7.1E-05	0.0E+00	0.0E+00	0.0%	N/A
	HS-08	T	1.7E-03	1.4E-04	0.0E+00	0.0E+00	0.0%	N/A
	JMM-14	T	4.7E-04	4.9E-05	0.0E+00	0.0E+00	0.0%	N/A
	JMM-46	T	1.6E-02	9.7E-03	-3.1E-04	6.0E-01	100.0%	D
	JMM-44	T	7.4E-04	3.5E-04	6.2E-04	4.7E-01	100.0%	I
	JMM-15	T	3.4E-03	1.1E-03	5.7E-06	3.3E-01	100.0%	I
	JMM-33	T	5.0E-04	1.5E-11	0.0E+00	2.9E-08	100.0%	S
TRICHLOROETHYLENE (TCE)								
	JMM-7R	S	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	JMM-06	S	4.1E-04	1.3E-04	0.0E+00	0.0E+00	0.0%	N/A
	JMM-57	S	5.2E-04	7.2E-05	-4.8E-05	1.4E-01	100.0%	D

Project: DDHU OU4

User Name: PARSONS

Location: OGDEN

State: Utah

Constituent	Well	Source/ Tail	Average	Standard Deviation	Ln Slope	Coefficient of Variation	Confidence in Trend	Concentration Trend
TRICHLOROETHYLENE (TCE)								
	JMM-56	S	3.1E-03	3.0E-03	-1.5E-03	9.7E-01	100.0%	D
	JMM-09	S	6.0E-04	1.9E-04	-2.2E-04	3.2E-01	100.0%	D
	HS-05	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	HS-06	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	JMM-30	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	HS-07	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	JMM-65	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	HS-08	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	JMM-64	T	4.2E-04	1.2E-04	0.0E+00	0.0E+00	0.0%	N/A
	HS-10	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	JMM-46	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	JMM-14	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	JMM-15	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	JMM-44	T	6.2E-04	2.1E-05	0.0E+00	0.0E+00	0.0%	N/A
	JMM-33	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
VINYL CHLORIDE								
	JMM-08	S	3.4E-02	2.6E-02	-1.3E-04	7.5E-01	100.0%	D
	JMM-09	S	5.9E-02	9.9E-02	-1.2E-03	1.7E+00	100.0%	D
	JMM-52	S	3.1E-02	6.6E-02	-2.6E-03	2.1E+00	100.0%	D
	JMM-56	S	6.7E-03	1.4E-02	-9.3E-04	2.0E+00	100.0%	D
	JMM-57	S	1.1E-02	9.9E-03	-6.9E-04	9.2E-01	100.0%	D
	JMM-7R	S	7.3E-03	1.2E-02	0.0E+00	0.0E+00	0.0%	N/A
	HS-06	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	HS-08	T	2.7E-03	1.6E-03	0.0E+00	0.0E+00	0.0%	N/A
	JMM-15	T	5.4E-04	1.3E-04	-1.6E-04	2.5E-01	100.0%	D
	JMM-33	T	5.4E-04	1.3E-04	-1.6E-04	2.5E-01	100.0%	D
	JMM-14	T	5.0E-04	7.8E-12	0.0E+00	1.6E-08	100.0%	S
	JMM-44	T	5.0E-04	1.5E-11	0.0E+00	3.0E-08	100.0%	S
	HS-10	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	JMM-46	T	6.6E-03	4.5E-03	-3.7E-04	6.8E-01	100.0%	D
	JMM-65	T	5.0E-04	1.5E-11	0.0E+00	2.9E-08	100.0%	S
	HS-05	T	1.9E-03	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	JMM-64	T	1.1E-02	6.3E-03	-7.7E-04	5.6E-01	100.0%	D
	HS-07	T	5.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0%	N/A
	JMM-30	T	5.0E-04	1.5E-11	0.0E+00	2.9E-08	100.0%	S

MAROS Sampling Location Optimization Results

Project: DDHU OU4

User Name: PARSONS

Location: OGDEN

State: Utah

Analysis by DeLauney Method

Sampling Events Analyzed: From Sample Event 1 4/1/91
To Sample Event 14 4/11/00

Constituent	Well Name	Average Slope Factor	Eliminated?
BENZENE	JMM-65	0.000	<input checked="" type="checkbox"/>
	HS-05	0.000	<input checked="" type="checkbox"/>
	JMM-7R	0.029	<input type="checkbox"/>
	JMM-64	0.000	<input type="checkbox"/>
	JMM-57	0.000	<input type="checkbox"/>
	JMM-56	0.780	<input type="checkbox"/>
	JMM-52	0.000	<input type="checkbox"/>
	JMM-46	0.000	<input type="checkbox"/>
	JMM-44	1.023	<input type="checkbox"/>
	JMM-33	0.000	<input type="checkbox"/>
	HS-06	0.000	<input type="checkbox"/>
	JMM-30	0.000	<input type="checkbox"/>
	HS-07	0.000	<input checked="" type="checkbox"/>
	HS-08	0.000	<input checked="" type="checkbox"/>
	HS-10	0.000	<input type="checkbox"/>
	JMM-08	1.400	<input type="checkbox"/>
JMM-09	0.650	<input type="checkbox"/>	
JMM-14	0.000	<input checked="" type="checkbox"/>	
JMM-15	0.335	<input type="checkbox"/>	
cis-1,2-DICHLOROETHYLENE	HS-08	0.170	<input checked="" type="checkbox"/>
	JMM-30	1.098	<input type="checkbox"/>
	JMM-57	0.559	<input type="checkbox"/>
	JMM-56	0.524	<input type="checkbox"/>
	JMM-46	0.817	<input type="checkbox"/>
	JMM-44	1.013	<input type="checkbox"/>

Project: DDHU OU4

User Name: PARSONS

Location: OGDEN

State: Utah

	JMM-33	1.380	<input type="checkbox"/>
	JMM-64	1.046	<input type="checkbox"/>
	JMM-15	0.175	<input checked="" type="checkbox"/>
	JMM-14	0.988	<input type="checkbox"/>
	JMM-09	0.241	<input checked="" type="checkbox"/>
	HS-05	0.626	<input type="checkbox"/>
	HS-10	0.850	<input type="checkbox"/>
	HS-07	0.378	<input checked="" type="checkbox"/>
	HS-06	0.549	<input type="checkbox"/>
	JMM-65	1.297	<input type="checkbox"/>
	JMM-7R	0.295	<input checked="" type="checkbox"/>
	JMM-08	1.005	<input type="checkbox"/>

TRICHLOROETHYLENE (TCE)

JMM-46	0.131	<input type="checkbox"/>
HS-05	0.000	<input checked="" type="checkbox"/>
JMM-65	0.153	<input type="checkbox"/>
JMM-64	0.576	<input type="checkbox"/>
JMM-56	0.232	<input type="checkbox"/>
JMM-7R	0.040	<input type="checkbox"/>
JMM-44	0.723	<input type="checkbox"/>
JMM-33	0.003	<input checked="" type="checkbox"/>
JMM-30	0.204	<input type="checkbox"/>
HS-06	0.000	<input checked="" type="checkbox"/>
JMM-14	0.000	<input checked="" type="checkbox"/>
JMM-09	0.181	<input type="checkbox"/>
JMM-08	0.710	<input type="checkbox"/>
HS-10	0.056	<input type="checkbox"/>
HS-08	0.043	<input type="checkbox"/>
HS-07	0.045	<input type="checkbox"/>
JMM-15	0.073	<input type="checkbox"/>
JMM-57	0.003	<input type="checkbox"/>

VINYL CHLORIDE

JMM-33	0.968	<input type="checkbox"/>
JMM-44	1.156	<input type="checkbox"/>
JMM-46	0.857	<input type="checkbox"/>
JMM-52	0.105	<input checked="" type="checkbox"/>

Project: DDHU OU4

User Name: PARSONS

Location: OGDEN

State: Utah

JMM-56	0.632	<input type="checkbox"/>
JMM-57	0.238	<input checked="" type="checkbox"/>
JMM-65	1.063	<input type="checkbox"/>
JMM-30	0.850	<input type="checkbox"/>
JMM-64	0.932	<input type="checkbox"/>
JMM-15	1.024	<input type="checkbox"/>
JMM-14	0.561	<input type="checkbox"/>
JMM-09	0.359	<input checked="" type="checkbox"/>
JMM-08	1.073	<input type="checkbox"/>
HS-10	0.752	<input type="checkbox"/>
HS-08	0.554	<input type="checkbox"/>
HS-07	0.559	<input type="checkbox"/>
HS-05	0.370	<input type="checkbox"/>
JMM-7R	0.323	<input checked="" type="checkbox"/>
HS-06	0.491	<input type="checkbox"/>

Note: The Delauney method results tell how important a well is in a given sampling event. The larger the SF value of a well, the more important it is.

Abandoned Sampling Locations by considering all COCs

Well Name	East Coord.	North Coord.	Abandoned?
HS-05	1860355.250	341184.844	<input type="checkbox"/>
HS-06	1860368.000	341442.125	<input type="checkbox"/>
HS-07	1860490.625	341447.281	<input type="checkbox"/>
HS-08	1860499.125	341260.719	<input type="checkbox"/>
HS-10	1860395.000	341062.000	<input type="checkbox"/>
JMM-08	1862100.000	343438.063	<input type="checkbox"/>
JMM-09	1862227.000	342899.844	<input type="checkbox"/>
JMM-14	1860984.000	341858.031	<input type="checkbox"/>
JMM-15	1861408.000	342463.406	<input type="checkbox"/>
JMM-30	1860475.875	340609.938	<input type="checkbox"/>
JMM-33	1862457.875	341970.188	<input type="checkbox"/>
JMM-44	1862164.250	344532.813	<input type="checkbox"/>
JMM-46	1861379.000	341384.000	<input type="checkbox"/>
JMM-52	1862336.000	343857.000	<input type="checkbox"/>
JMM-56	1862629.000	343408.000	<input type="checkbox"/>

Project: DDHU OU4

User Name: PARSONS

Location: OGDEN

State: Utah

JMM-57	1862426.500	342517.188	<input type="checkbox"/>
JMM-64	1861030.375	340957.125	<input type="checkbox"/>
JMM-65	1861970.625	341253.000	<input type="checkbox"/>
JMM-7R	1862375.000	343831.000	<input type="checkbox"/>

To be conservative, a location is abandoned only when it is eliminated from all COCs.

MAROS Sampling Frequency Optimization Results

Project: DDHU OU4

User Name: PARSONS

Location: OGDEN

State: Utah

Analysis by Modified CES Method

Number of Sampling Events Analyzed 14

Recent Sampling Events: From Sample Event 8 4/1/97
To Sample Event 14 4/11/00

Constituent	Well Name	Sampling Frequency	Frequency based on current period	Frequency based on overall period
BENZENE	HS-05	Quarterly	Quarterly	Quarterly
	HS-06	Quarterly	Quarterly	Quarterly
	HS-07	Quarterly	Quarterly	Quarterly
	HS-08	Quarterly	Quarterly	Quarterly
	HS-10	Quarterly	Quarterly	Quarterly
	JMM-08	Quarterly	Quarterly	Quarterly
	JMM-09	Annual	Annual	Annual
	JMM-14	Quarterly	Quarterly	Quarterly
	JMM-15	Quarterly	Quarterly	Quarterly
	JMM-30	Quarterly	Quarterly	Quarterly
	JMM-33	Quarterly	Quarterly	Quarterly
	JMM-44	Quarterly	Quarterly	Quarterly
	JMM-46	Quarterly	Quarterly	Quarterly
	JMM-52	Quarterly	Quarterly	Quarterly
	JMM-56	Quarterly	Quarterly	Quarterly
	JMM-57	Annual	Annual	Annual
	JMM-64	Quarterly	Quarterly	Quarterly
JMM-65	Quarterly	Quarterly	Quarterly	
JMM-7R	Quarterly	Quarterly	Quarterly	
cis-1,2-DICHLOROETHYLENE	HS-05	Annual	Annual	Annual
	HS-06	Annual	Annual	Annual
	HS-07	Annual	Annual	Annual
	HS-08	Annual	Annual	Annual
	HS-10	Annual	Annual	Annual

	JMM-08	Annual	Annual	Annual
	JMM-09	Biennial	Annual	Annual
	JMM-14	Annual	Annual	Annual
	JMM-15	Annual	Annual	Annual
	JMM-30	Biennial	Annual	Annual
	JMM-33	Biennial	Annual	Annual
	JMM-44	Annual	Annual	Annual
	JMM-46	Biennial	Annual	Annual
	JMM-56	Biennial	Annual	Annual
	JMM-57	Biennial	Annual	Annual
	JMM-64	Annual	Annual	Annual
	JMM-65	Biennial	Annual	Annual
	JMM-7R	Annual	Annual	Annual
TRICHLOROETHYLENE (TCE)	HS-05	Annual	Annual	Annual
	HS-06	Annual	Annual	Annual
	HS-07	Annual	Annual	Annual
	HS-08	Annual	Annual	Annual
	HS-10	Annual	Annual	Annual
	JMM-08	Annual	Annual	Annual
	JMM-09	Biennial	Annual	Annual
	JMM-14	Annual	Annual	Annual
	JMM-15	Annual	Annual	Annual
	JMM-30	Annual	Annual	Annual
	JMM-33	Annual	Annual	Annual
	JMM-44	Annual	Annual	Annual
	JMM-46	Annual	Annual	Annual
	JMM-56	Annual	Annual	Annual
	JMM-57	Biennial	Annual	Annual
	JMM-64	Annual	Annual	Annual
	JMM-65	Annual	Annual	Annual
	JMM-7R	Annual	Annual	Annual
VINYL CHLORIDE	HS-05	Quarterly	Quarterly	Quarterly
	HS-06	Quarterly	Quarterly	Quarterly
	HS-07	Quarterly	Quarterly	Quarterly

HS-08	Quarterly	Quarterly	Quarterly
HS-10	Quarterly	Quarterly	Quarterly
JMM-08	SemiAnnual	Annual	Quarterly
JMM-09	Annual	Annual	Annual
JMM-14	Annual	Annual	Annual
JMM-15	Annual	Annual	Annual
JMM-30	Annual	Annual	Annual
JMM-33	Annual	Annual	Annual
JMM-44	Annual	Annual	Annual
JMM-46	Annual	Annual	Annual
JMM-52	Quarterly	Quarterly	Quarterly
JMM-56	Annual	Annual	Annual
JMM-57	Annual	Annual	Annual
JMM-64	Annual	Annual	Annual
JMM-65	Annual	Annual	Annual
JMM-7R	Quarterly	Quarterly	Quarterly

Note: Modified CES (LLNL) method results in a recommended sampling interval for each well. This is based on analysis of concentration trend, so looks at specified sampling interval.

Summary - Final Recommendation for Sampling Frequency

Well Name	Sampling Frequency
HS-05	Quarterly
HS-06	Quarterly
HS-07	Quarterly
HS-08	Quarterly
HS-10	Quarterly
JMM-08	Quarterly
JMM-09	Annual
JMM-14	Quarterly
JMM-15	Quarterly
JMM-30	Quarterly
JMM-33	Quarterly
JMM-44	Quarterly
JMM-46	Quarterly
JMM-52	Quarterly

Project: DDHU OU4

User Name: PARSONS

Location: OGDEN

State: Utah

JMM-56	Quarterly
JMM-57	Annual
JMM-64	Quarterly
JMM-65	Quarterly
JMM-7R	Quarterly

Note: the most stringent sampling frequency was chosen among all COCs.

APPENDIX E

**ADDENDUM TO DRAFT REMEDIAL PROCESS OPTIMIZATION
REPORT**

ADDENDUM TO DRAFT REMEDIAL PROCESS OPTIMIZATION REPORT DEFENSE DEPOT HILL, UTAH

This addendum to the November 2000 draft remedial process optimization (RPO) Phase II evaluation report for Defense Depot Hill, Utah (DDHU) (Parsons Engineering Science, Inc. [Parsons], 2000a) was prepared to address concerns raised by the U.S. Army Corps of Engineers (USACE), Sacramento District and to incorporate additional groundwater monitoring data provided by DDHU and USACE. This addendum addresses the following issues:

- Evaluation of the Operable Unit 1 (OU1) extraction, treatment, and injection (ETI) system optimization plan and the revised groundwater monitoring and sampling plan, approved by the regulators on December 2, 2000;
- Evaluation of additional data for OU4 extraction wells and “hot-spot” monitoring wells, including:
 - Calculation of mass removal of chemicals of concern (COCs) over time based on extraction-well COC concentrations and pumping rates,
 - Generation of bar graphs showing annual COC mass-removal rates by well based on the data available for review, and
 - A temporal trend analysis for COC concentrations at the hot-spot monitoring wells;
- Revision of cost analyses for OU1 and OU4 based on the revised operations, maintenance, and monitoring (OM&M) costs provided by DDHU; and
- Revision of recommendations based upon the evaluation of the additional data provided by DDHU and USACE.

Figures and tables presented in this addendum have been assigned reference designations that correlate with related figures and tables presented in the draft RPO report (Parsons, 2000a). Letters have been added to the draft report designations to indicate revision of the original figures and tables based on the supplemental information and data provided by DDHU and/or USACE.

E1.0 EVALUATION OF OPTIMIZED OU1 EXTRACTION, TREATMENT, AND INJECTION SYSTEM

The original groundwater ETI system at OU1 had 16 operating extraction wells. On December 2, 2000, regulators approved a new extraction-well plan for OU1. The new plan removes nine existing extraction wells (EW-1, EW-6, EW-7, EW-10, EW-11, EW-12, EW-13, EW-14, and EW-15) from the extraction network, and adds one well (1EW-NEW) in the vicinity of JMM-22. The optimized OU1 extraction system includes seven original extraction wells (1EW-2, 1EW-3, 1EW-4, 1EW-5, 1EW-8, 1EW-9, and 1EW-

16) and the new 1EW-NEW. The original- and optimized-system wells are shown on Figure 6.9A. Since December 2, 2000, two new extraction wells (EW-17 and EW-18) have been installed in the plume area at OU1 (Ron Smith, June, 2001). The following capture zone analysis is based on the original optimized system since the revisions were not known until the completion of this addendum.

Figure 6.9A also presents the results of a capture-zone analysis performed on the optimized extraction system at OU1. Table 6.5A lists the optimized pumping rates and parameters used for the capture-zone analysis. The evaluation was performed using the analytical modeling software WINFLOW, provided by Scientific Software Group (2000).

The optimized extraction system approved for implementation at OU1 is very similar to the optimized system recommended in Section 6 of the draft RPO report. The results of the capture-zone analysis (Figure 6.9A) for the approved optimized system show that four of the extraction wells (1EW-4, 1EW-5, 1EW-16, and 1EW-NEW) effectively capture the vinyl chloride (VC) plume. The seven injection wells located downgradient from this plume (Figure 6.9A and Table 6.5A) also create an effective barrier to further migration of dissolved contaminants. The analysis results also suggest that groundwater extraction at wells 1EW-2, 1EW-3, 1EW-8, and 1EW-9 could be reduced or eliminated without adversely affecting capture of the VC plume.

E2.0 EVALUATION OF THE REVISED OU1 GROUNDWATER MONITORING PROGRAM

The original 15-well groundwater monitoring program at OU1 was evaluated in the draft RPO report using hydrogeologic information (qualitative evaluation) and temporal-trend and spatial statistical analyses. Monitoring points that provided relatively greater amounts of information regarding the occurrence and distribution of VOCs in groundwater were distinguished from those wells that provide relatively lesser amounts of information. The results of the qualitative, temporal, and spatial evaluations are summarized in Table 6.11 of the draft RPO report (Parsons, 2000a). Addendum Table 6.11A compares the revised OU1 groundwater monitoring plan approved by the regulators with the optimized groundwater monitoring plan recommended in the draft report. The regulator-approved plan eliminates JMM-20 and JMM-48 from the monitoring program, primarily because COCs have not been detected in these wells for several years. The draft RPO report recommended that sampling at five wells (JMM-6, JMM-29, JMM-48, JMM-62, and JMM-63) be eliminated. Based on the recent regulatory approval of an optimized monitoring program, no further evaluation of the groundwater-monitoring program at OU1 is warranted at this time.

E3.0 COST EVALUATION OF OU1 SYSTEM

Operation of the original OU1 groundwater extraction system, consisting of 16 extraction wells, a single air-stripping tower, and 16 injection wells, began in December 1994. In 1992, the present-worth capital and O&M cost from system installation through attainment of remediation goals was projected to be \$1,155,000 (James M. Montgomery

Figure 6.9A Modeled Potentiometric Surface and Flowlines: Optimized Extraction System – OU1

Table 6.5A Optimized Groundwater Extraction/Injection System – OU1

Table 6.11A Summary of Evaluation of Groundwater Monitoring Program

[JMM], 1992a). The actual capital cost for installation of the OU1 system was estimated to be \$340,000 (in 1994 dollars) (Parsons, 2000b), and the actual annual lump-sum OM&M cost as of November 2000, according to DDHU, is \$340,000 (in 2000 dollars). The estimated cumulative cost through December 2000, calculated by accruing capital expenditures and annual OM&M costs from 1994 through 2000, is approximately \$2,380,000 (Table 6.12A). As of December 2000, a total estimated mass of about 3 pounds of VC has been removed from groundwater at OU1 (Section 6.2.2.1 of the draft RPO report). Based on the cumulative total capital and OM&M cost estimated through December 2000, the cost per pound to remove VC from OU1 groundwater is approximately \$793,000.

TABLE 6.12A
SUMMARY OF CAPITAL, OPERATIONS, MAINTENANCE,
AND MONITORING COSTS
OPERABLE UNIT 1
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Item	Cost
Capital Costs ^{a/}	\$340,000
Total Annual OM&M Costs ^{b/}	\$340,000
Total Cost to Date ^{c/}	\$2,380,000
Cost Per Pound of Vinyl Chloride Removed	
Mass of vinyl chloride removed to date (pounds)	~ 3
Cost per pound of vinyl chloride removed ^{b/}	\$793,000
Current rate of vinyl chloride mass removal (pound per year)	0.2
Cumulative total mass of vinyl chloride removed by end of year 2003 at current removal rate (pounds)	3.6
Cost per pound of vinyl chloride removed by end of year 2003 ^{b/}	\$944,000

^{a/} In 1994 dollars.

^{b/} Estimated cumulative operation, maintenance, and monitoring costs through December 2000 in 2000 dollars, based on information provided during November 30, 2000 RPO briefing.

In the OU1 ROD (JMM, 1992a), the time required to achieve the remedial action objectives (RAOs) for groundwater (i.e., the federal maximum contaminant levels [MCLs]) was estimated to be approximately 5 years. Based on this estimate, VC remediation to its MCL of 2 micrograms per liter ($\mu\text{g/L}$) should have been completed by the end of 1999. Trend analyses of available data (Parsons, 2000a) indicated that the concentrations of VC throughout most of the ROD-specified OU1 attainment area may be reduced below 2 $\mu\text{g/L}$ by the end of 2003 under then-current system operating conditions (Section 6.2.2; Figure 6.2 of draft RPO report). If the rate of VC removal (less than 0.2 pound per year) estimated in the draft RPO report is maintained through that period, a

cumulative total of less than 4 pounds of VC will have been removed from groundwater at OU1 by the end of 2003. If the annual OU1 OM&M costs remain constant at about \$340,000 (in constant 2000 dollars), and no additional capital expenditures are incurred, the removal of 3.6 pounds of VC from OU1 groundwater will have been accomplished at a cost of \$944,000 per pound (in 2000 dollars (Table 6.12a). The impact of the recently approved extraction-system optimization on the mass-removal rate has not been evaluated. However, the reduced volume of groundwater to be extracted by the optimized seven-well system, which includes a new well extracting groundwater from the center of the VC plume, and the expected enhanced mass-removal rate, may result in a reduced cost per pound to remove VC from OU1 groundwater.

E4.0 EVALUATION OF OU4 REMEDIAL SYSTEMS

Following submittal of the draft RPO report in November 2000, DDHU provided analytical data for the OU4 hot-spot monitoring wells collected during nine sampling events, and analytical data for OU4 extraction wells collected during six sampling events conducted over a 6-year period. The following discussion evaluates the trends in VC concentrations in the groundwater samples from the OU4 hot-spot wells, and the concentration trends and VC and *cis*-1,2-dichloroethene (DCE) mass-removal efficiencies of the OU4 extraction wells.

E4.1 Vinyl Chloride Concentrations in OU4 Hot-Spot Monitoring Wells

Table E.1 presents the VC concentrations detected from April 1999 through September 2000 in groundwater samples from OU4 hot-spot monitoring wells. Hot-spot monitoring wells HS-2, HS-3, HS-4, HS-7, HS-8, and HS-10 are located upgradient from the OU4 hot-spot groundwater extraction trench, which is located along the western DDHU property boundary, just north of the west gate (refer to Figure 6.23 of the draft RPO report [Parsons, 2000a]). Monitoring wells HS-5 and HS-6 are located downgradient from the extraction trench. Analysis of the VC data for samples from HS-5 indicates that VC concentrations at this location have been decreasing since March 2000. The concentrations of VC detected at HS-5 through March 2000 indicate that the VC plume migrated off-Depot prior to installation and startup of the extraction trench in April 1999. The decreases in VC concentrations since installation of the extraction trench suggest that the extraction trench is controlling continued migration of the VC plume beyond the DDHU boundary, and suggest that the VC mass present in the groundwater downgradient from the extraction trench is attenuating. However, monitoring data for a 1-year period are not sufficient to fully evaluate the impact of the extraction trench on VC concentrations in groundwater downgradient from the OU4 hot spot. Groundwater monitoring and operation of the trench in this area should continue.

TABLE E.1
CONCENTRATIONS OF VINYL CHLORIDE
IN OU4 HOT-SPOT MONITORING WELLS
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Sampling Date	Vinyl Chloride Concentrations at Hot-Spot Wells (µg/L) ^{a/}							
	HS-2	HS-3	HS-4	HS-5	HS-6	HS-7	HS-8	HS-10
Apr-99	NA ^{b/}	NA	NA	1.6	ND ^{c/}	ND	9.6	ND
Oct-99	NA	NA	NA	1.9	ND	ND	3.8	ND
Jan-00	NA	NA	NA	2.4	ND	ND	3.8	ND
Mar-00	NA	NA	NA	2.2	ND	ND	3.4	ND
Mar-00	NA	NA	NA	1.5	ND	ND	2.5	ND
Apr-00	NA	NA	NA	1.9	ND	ND	1.6	ND
May-00	NA	NA	NA	1.3	ND	ND	1.0	ND
Jun-00	NA	NA	NA	1.2	ND	ND	1.7	ND
Sep-00	4.2	7.8	3.5	ND	ND	ND	3.3	ND

^{a/} µg/L = micrograms per liter.

^{b/} NA = not analyzed or data not available.

^{c/} ND = not detected.

E4.2 Evaluation of Mass Removal by the OU4 Extraction System

DDHU provided analytical data for *cis*-1,2-DCE and VC concentrations in groundwater samples from OU4 extraction wells for six sampling events from July 1995 through August 2000. Figures 6.17A, 6.17B, and 6.17C present bar graphs showing the calculated annual, well-specific *cis*-1,2-DCE mass-removal rates for the years 1995, 1996, and 1999, respectively. Figures 6.18A, 6.18B, and 6.18C present bar graphs for VC mass removal during 1995, 1996, and 1999, respectively. Figures 6.17 and 6.18 in the draft RPO report presented the well-specific *cis*-1,2-DCE and VC mass-removal rates, respectively, for the year 2000. These figures show that the COC mass-removal efficiencies of many of the extraction wells have declined since OU4 extraction-system operation began in 1995. Five wells, EW-1, EW-2, EW-6, EW-7, and EW-8, are removing more COC mass than the remaining extraction wells combined.

Although the OU4 extraction system is containing the COC plume, the data indicate that most of the extraction wells are not effectively removing contaminant mass from the groundwater plume. Further evaluation of the contaminant plume and the remediation system is needed to optimize the OU4 remedy for attainment of ROD objectives.

E5.0 COST EVALUATION FOR OU4

The OU4 groundwater ETI system for the main CAH plume, completed in July 1995, consists of 31 extraction wells, two air-stripping towers, and 25 injection wells. The treatment system for the OU4 hot spot, which began operation in April 1999, consists of a 300-foot-long interceptor trench, ozone and hydrogen peroxide reactors, and a discharge hookup to the Central Weber Sewer Improvement District (CWSID) sanitary

sewer system. In the 1992 ROD for OU4 (JMM, 1992b), the present-worth capital and OM&M cost for the OU4 main plume pump-and-treat system through a 5-year life cycle was projected to be \$3,022,000. The present-worth capital and OM&M costs for the OU4 hot-spot interceptor-trench system was projected to be \$1,104,000 over a 5-year operating period (Montgomery Watson, 2000).

The actual capital cost for installation of the OU4 main plume extraction and treatment system was \$1,057,000 (in 1995 dollars), and the actual capital cost for the hot-spot interceptor-trench system was \$507,000 (in 1999 dollars) (Montgomery Watson, 2000). The annual lump-sum OM&M cost for both systems is \$614,000 for 2000 (Parsons, 2000a). The cumulative costs through December 2000, calculated by accruing capital expenditures and annual OM&M from 1995 through the end of the year 2000 (December 2000), are approximately \$4,634,000 (Table 6.23A). Through the end of the year 2000, about 57 pounds of VC (50 pounds during the period from 1995 through 1999, and 7 pounds from 1999 through December 2000) has been removed from OU4 groundwater (Section 6.3.2.1 of the draft RPO report). Based on the cumulative capital and OM&M costs through December 2000, the cost per pound to remove VC from groundwater at OU4 is approximately \$81,300.

TABLE 6.23A
SUMMARY OF CAPITAL, OPERATION, MAINTENANCE,
AND MONITORING COSTS GROUNDWATER EXTRACTION/TREATMENT
SYSTEMS
OPERABLE UNIT 4
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Item	Cost
Capital Costs	
OU4 "Main Plume" System ^{a/}	\$1,057,000
OU4 Hot-Spot System ^{b/}	\$507,000
Annual OM&M Costs ^{b/}	\$614,000
Total Cost to Date^{b/}	\$4,634,000
Cost Per Pound of Vinyl Chloride Removed	
Mass of vinyl chloride removed to date (pounds)	~ 57
Cost ^{b/} per pound of vinyl chloride removed	\$81,300
Current rate of vinyl chloride mass removal (pounds per year)	7
Cumulative mass of vinyl chloride removed by end of 2003 at current removal rate (pounds)	78
Cost per pound of vinyl chloride removed by end of 2003 ^{b/}	\$83,000

^{a/} In 1995 dollars.

^{b/} Costs for operations, maintenance, and monitoring through December 2000 in 2000 dollars, based on information provided during November 30, 2000 RPO briefing.

In the OU4 ROD (JMM, 1992b), the time required to achieve the RAOs was estimated to be approximately 5 years. Based on this estimate, VC removal should have been completed by year-end 2000. Trend analyses of available data suggest that VC concentrations throughout much of the ROD-specified OU4 attainment area may be reduced below the 2- $\mu\text{g/L}$ MCL by the end of 2003 under current operating conditions (Section 6.3.2; Figure 6.16, draft RPO report [Parsons, 2000a]).

However, it is unlikely that MCLs for groundwater will have been achieved at all locations throughout the OU4 area of attainment by the end of 2003. If the current VC removal rate (about 7 pounds per year) is maintained through that period, then by the end of the year 2003, a total of about 78 pounds of VC will have been removed from OU4 groundwater (Figure 6.26). If the annual OM&M costs remain constant at about \$614,000 per year (in 2000 dollars), and no additional capital expenditures are incurred, the removal of 78 pounds of VC from OU4 groundwater will have been accomplished for a cost of about \$83,000 per pound (in 2000 dollars) (Table 6.23a). If, as is likely, continuation of groundwater ETI and discharge for a significantly longer period of time is necessary to achieve RAOs at OU4, cumulative system OM&M costs will be correspondingly greater.

E6.0 REVISED RPO RECOMMENDATIONS

This section incorporates the evaluation of additional data provided by DDHU and USACE in December 2000 into the recommendations made in Section 7 of the Draft RPO Phase II Evaluation Report submitted in November 2000 (Parsons, 2000a). The additional information provided included regulator-approved optimizations of the OU1 ETI system and groundwater monitoring program; supplemental analytical data for COCs in OU4 hot-spot monitoring wells located downgradient from the extraction trench; extraction well COC analytical data for OU4; and OM&M costs for OU1 and OU4. Evaluation of the additional information relative to the conclusions and optimization recommendations presented in the draft RPO report has provided additional support for those RPO conclusions and recommendations. This section reviews the draft RPO report recommendations and incorporates changes that reflect the remediation system and monitoring plan modifications recently implemented at DDHU.

E6.1 Short-Term Recommendations

E6.1.1 System Improvements

Reductive dechlorination of *cis*-1,2-DCE in groundwater continues to generate VC at both OU1 and OU4. The prevailing reducing conditions in the shallow aquifer are not conducive to biodegradation of VC, which occurs most efficiently under oxidizing (aerobic) conditions. Thus, VC persists in both plume areas.

DDHU is currently proceeding with optimization of the extraction system at OU1. The regulatory project managers have approved OU1 modifications that add one new extraction well within the plume area, and eliminate pumping at nine of the original 16 extraction wells required to attain MCLs. The optimized system has been revised to include the installation of two new extraction wells in the plume area (Ron Smith, June 2001). These improvements are similar to the recommendations made in the Draft RPO

Phase II Evaluation Report (Parsons, 2000a). Parsons evaluated the plume-containment effectiveness of recently approved OU1 system modifications using the WINFLOW analytical model (Figure 6.9A). This evaluation determined that operation of the extraction and injection wells in the core and upgradient portions of the VC plume is adequate for plume capture/containment. Operation of additional extraction wells located downgradient from the VC plume may not be necessary for the containment and capture of the COC plume.

Based on evaluation of historical and recent mass-removal rates using new data for the OU4 extraction wells provided by DDHU, Parsons maintains that the existing system is inefficient for removing dissolved VC and *cis*-1,2-DCE mass. The extraction and treatment system at OU4 is more than adequate to contain the CAH plume; however, only a few of the wells are effectively removing a significant amount of CAH mass from groundwater. Based on the evaluations presented in this addendum and the draft RPO report (Parsons, 2000a), the following recommendations are made to improve the remedies for addressing CAH contamination in OU1 and OU4 groundwater.

Recommendation 1: Turn off the existing ETI system at OU1 and monitor quarterly for chlorinated aliphatic hydrocarbons (CAHs) and natural attenuation parameters in groundwater for 1 year.

Rationale:

The optimized ETI system recently approved for OU1 (see Table 6.11A) will be more efficient than the original system at removing VC from groundwater. However, based on the mass of VC removed to date, the relatively low mass that likely remains in OU1 groundwater, and the likelihood that little TCE/DCE source mass remains, active remediation may not be necessary to reduce remaining VC concentrations to the 2- μ g/L ROD cleanup goal. Suspension of pumping at OU1 would allow the following to occur:

- Observe if VC concentrations in groundwater rebound when the ETI system is not operating. Such rebounding commonly occurs after pumping ceases, as residual COC mass partitions from sorbed or gas phases to re-establish equilibrium in the groundwater.
- Reduce the volume of water requiring treatment and disposal by 100 percent.
- Reduce O&M for extraction and injection wells.
- Reduce the overall system OM&M cost by lowering labor, utility, and analytical expenses, although groundwater monitoring at extraction well locations should continue during the 1-year shutdown.
- Monitoring CAH concentrations and natural attenuation parameters in groundwater for 1 year after system shutdown

will allow assessment of CAH plume stability under natural (non-pumping) conditions, and will provide information to support additional remedy-optimization evaluations.

Based on the concerns of DDHU, appropriate maintenance measures should be implemented to protect the ETI system from damage during the 1-year period of suspended operations. Should significant rebound of CAH concentrations or migration of contamination be observed during the monitoring period, the system could be restarted.

Recommendation 2: Continue to operate the ETI system at OU4, and evaluate the potential for optimizing the current system for more efficient removal of CAH mass from groundwater. Operation of the ETI systems should continue until, at a minimum, concentrations of *cis*-1,2-DCE are reduced below the MCL.

Rationale:

The additional data provided by DDHU and USACE (Sacramento), combined with the data evaluated in the draft RPO report, indicate that VC is still being generated in the OU4 plume. Therefore, operation of the ETI system should continue. Capture-zone analysis of the OU4 extraction wells indicates that the system can be optimized by reducing the number of extraction wells from 31 to 16, and reducing the number of injection wells from 26 to 10. Optimization of the ETI system at OU4 would allow the following to occur:

- Reduce the volume of water requiring treatment and disposal by 40 to 50 percent.
- Reduce O&M for extraction and injection wells.
- Reduce the overall system OM&M cost by lowering labor, utility, and analytical expenses for extraction and injection wells.

Recommendation 3: Analyze untreated groundwater from the OU4 hot-spot extraction trench for CAHs, and other parameters that may be listed in the CWSID discharge permit, prior to delivery of the water to the treatment system. If CAH concentrations exceed ROD cleanup objectives, the groundwater would be directed to the treatment system before disposal to the sewer system. If CAH concentrations do not exceed MCLs, and the water quality requirements of the sewer discharge permit are met, the groundwater could be discharged directly from the trench to the sewer system.

Rationale: As discussed in Section 6 of the draft RPO report (Parsons, 2000a), the concentrations of VC in groundwater samples collected from the OU4 hot-spot extraction trench effluent upstream from the treatment system are consistently below the 2- $\mu\text{g/L}$ cleanup goal. Monitoring of pretreated

water from the extraction trench, and direct discharge to the sewer of pretreated groundwater that meets CAH MCLs, would result in a reduction in treatment costs. Maintenance of the current treatment system would be required in the event that VC or other CAH concentrations in extracted groundwater exceeded MCLs, requiring treatment of the extracted water before discharge to the sewer system. Implementation of this recommendation would allow the following to occur:

- Reduce the volume of water requiring treatment.
- Reduce treatment system O&M.
- Provide analytical data to support eventual shutdown of the treatment plant.

To address concerns raised by DDHU, it is recommended that the appropriate measures are taken to maintain operation integrity of the OU4 hot-spot extraction and treatment system during implementation of the current monitoring program. As noted above, the treatment system would have to remain on line in the event that trench water does not meet CWSID discharge requirements.

A6.1.2 Monitoring Program Improvements at OU1

The groundwater-monitoring program at OU1 has recently been modified and approved by regulators. The revised monitoring program is similar to the optimized monitoring program recommended in the draft RPO report. No further recommendations for optimization of the OU1 monitoring program are necessary.

E6.1.3 Monitoring Program Improvements at OU4

It was estimated that annual costs associated with the original groundwater LTM program at OU4 was approximately \$77,000 (Draft RPO Report). The total cost of monitoring at OU4 for a 10-year period of current system operation that might be required before VC concentrations decrease to levels below the MCL of 2 µg/L could range to \$768,000. The number of wells currently sampled during each semi-annual monitoring event, the frequency of sampling, and sampling procedures, were reviewed as part of the RPO evaluation. Considering that the size of the VC plume has not increased since startup of the groundwater ETI system, recommendations have been made to reduce the number of monitoring wells required to monitor conditions in the plume. A short-term opportunity exists to optimize the groundwater monitoring program while providing sufficient data to monitor conditions at OU4.

Recommendation 4: Maintain the current frequency of groundwater monitoring during operation of the OU4 ETI system, and reduce the number of wells sampled during long-term groundwater monitoring.

Rationale:

The spatial distribution of the current sampling points was reviewed, recognizing that it may not be appropriate or necessary to conduct LTM at all wells that were installed during site

characterization activities. Using a screening-level evaluation, it was determined that sampling fewer wells could provide sufficient data to monitor plume migration, configuration, and concentration trends. At a minimum, two wells could be removed from the monitoring program. JMM-41D and JMM-43D are screened in the artesian aquifer, located below the confining clay layer at the base of the shallow water table aquifer, where CAH contamination is present. CAHs were detected in small amounts at these wells (JMM-410 [October 1998: DCE 0.8 µg/L and October 1995: TCE 4.8 µg/L] and JMM-430 [October 1995: TCE 1.4 µg/L]. CAHs are currently not detected in either well. Because these wells are not completed in the shallow aquifer, and are outside the OU4 plume, it is recommended that these wells be removed from the monitoring program, thereby reducing the number of wells sampled in the monitoring program at OU4, from 17 to 15.

E6.1.4 Cost Impact

Traditionally, long-term costs have been estimated and reported as net-present-value (NPV) costs, in which the lump-sum value that must be invested at the present time was calculated using an adjustment rate that accounts for inflation and the cost of funds (i.e., interest) in order to meet future expenditures to be paid over time. However, federal funding for specific projects is obtained via annual appropriations that must be authorized by Congress for each fiscal year. Therefore, NPV cost estimates are not appropriate for federal remediation projects such as the cleanup of groundwater at DDHU. The option of investing the NPV value of long-term OM&M costs, to be drawn on as necessary to meet expenditures throughout the full OM&M period, is simply not available for federally funded projects. Rather, estimates of OM&M costs through the duration of remediation activities were generated by projecting the annual OM&M costs, in 2000 dollars, through the remaining project life cycle (a “constant-dollar” analysis). The remaining project life cycle is determined by the amount of contaminant that currently remains in the plume and the estimated time required to reduce contaminant concentrations to below the cleanup level.

E6.1.4.1 Remediation Systems

The source contaminants in the plumes at both OU1 and OU4 are undergoing biodegradation through reductive dechlorination (Section 6). The 2000 ETI systems are no longer optimized for effective removal of VC and *cis*-1,2-DCE mass at either site. At OU1, an optimized ETI system has been developed and approved by the regulators. The optimized ETI system for OU1 reduces the number of extraction wells needed to capture and contain the VC plume, and is similar to the optimized system proposed in the draft RPO report. However, active groundwater treatment at OU1 may not be necessary, because there is not a significant amount of VC mass remaining in groundwater.

At OU4, VC is still being generated in the plume, and parent compounds, such as *cis*-1,2-DCE, are still present in the groundwater, with concentrations exceeding MCLs at specific locations. The current data indicate that operation of the ETI system at OU4

should continue until, at a minimum, the concentrations of *cis*-1,2-DCE in groundwater drop below MCLs. The current ETI system at OU4 can be optimized to fully capture and contain the VC plume, and more effectively remove CAH mass from groundwater at the site, with fewer extraction and injection wells.

Suspending operation of the ETI system at OU1, and optimizing the ETI system at OU4 can result in significant savings (Table 7.1A). At OU1, the lump-sum annual OM&M cost is \$340,000. It is estimated that the annual cost of the current program for monitoring groundwater and treatment plant effluent is approximately \$72,000 (Table 6.7, draft RPO report), which leaves approximately \$268,000 for ETI system O&M. At OU4, the annual OM&M cost is \$614,000 for both the ETI system and the hot-spot extraction trench and treatment system. It is estimated that the annual cost of the current program for monitoring groundwater and treatment plant effluent for the ETI system is approximately \$77,000 (Table 6.18, draft RPO report). The annual cost for monitoring groundwater and treatment plant effluent at the OU4 hot-spot extraction trench is approximately \$57,000. This estimate assumes that eight monitoring wells are sampled quarterly, and one treatment plant effluent sample is collected monthly. The sampling cost per monitoring well per sampling event is approximately \$1,500, based upon the data provided in Table 6.18 of the draft RPO report, and the cost per treatment plant effluent sample is approximately \$700. Total annual monitoring costs for OU4 and the OU4 hot spot are approximately \$134,000, which leaves approximately \$480,000 for annual O&M costs at OU4.

Shutting down the OU1 ETI system, but maintaining semiannual monitoring, can result in an annual savings of approximately \$268,000. Optimizing the OU4 ETI system by eliminating 14 extraction wells and 16 injection wells could result in an annual savings of \$200,000 in O&M costs. This estimate assumes that annual O&M costs for the OU4 ETI treatment plant and hot-spot extraction trench and treatment plant are approximately \$100,000 per year, leaving approximately \$380,000 for annual O&M costs for the extraction and injection wells. With 57 operational extraction and injection wells, the annual O&M cost per well is approximately \$6,500. Since the short-term recommendation for the OU4 hot-spot extraction trench requires that the system remain operational, short-term optimization savings have not been estimated for this system. The annual savings to optimize the systems at OU1 and OU4 could amount to approximately \$268,000 at OU1 and \$200,000 at OU4 (in year 2000 dollars), or a total of \$468,000 annually. Over a period of 10 years, potential savings could total approximately \$4.7 million if the short-term RPO recommendations for OU1 and OU4 are implemented.

E6.1.4.2 Monitoring Programs

Revising the long-term monitoring (LTM) programs by decreasing the number of wells sampled and the sampling frequency produces estimated cost savings of about \$6,000 per year each for OU1 and OU4. This estimate assumes two sampling events per year at a cost of \$1,500 per well per sampling event. The new monitoring plan at OU1 reduces the number of wells sampled by two, and the proposed monitoring plan for OU4 eliminates two monitoring wells. Over a 10-year period this would amount to a total savings of \$60,000 (in constant year 2000 dollars) for compliance monitoring costs at both OU1 and OU4.

E6.2 Long-Term Opportunities

The long-term RPO opportunities presented here are dependent upon the results of 1 year of rebound and natural attenuation monitoring during shutdown of the ETI system at OU1, and the successful reduction of CAHs in groundwater at OU4. Monitored natural attenuation is the recommended remedy for OU1. The recommended remedy for OU4 is optimization and continued operation of the existing ETI system, and monitoring of pretreated groundwater at the hot-spot extraction trench, until concentrations of *cis*-1,2-DCE in groundwater are below the MCL. Section 6 of the Draft RPO Phase II Evaluation Report presents an evaluation of other remediation technologies that could be considered for DDHU groundwater if monitored natural attenuation is determined to be inadequate, insufficient, or otherwise unacceptable to the regulators.

This long-term opportunity essentially consists of replacing active pump-and-treat with monitored natural attenuation as the remedy for treatment of CAHs in groundwater. The parent CAH (primarily TCE) at OU1 and OU4 has been degraded to DCE and VC through reductive dechlorination. Presently, VC persists in the groundwater for two reasons:

Opportunity 1: Implement monitored natural attenuation at OU1. Implement monitored natural attenuation at OU4 when *cis*-1,2-DCE concentrations in groundwater are below MCLs.

- *cis*-1,2-DCE continues to be reductively dechlorinated to VC; and
- VC is biologically recalcitrant under the reducing conditions predominate throughout much of the CAH plume.

Although VC is still being generated and biological decay is limited by prevailing geochemical conditions, concentrations are gradually decreasing through dilution and, at the edges of the plumes, aerobic degradation, and also as a consequence of declining

TABLE 7.1A
SHORT-TERM RECOMMENDATIONS
OPERABLE UNITS 1 AND 4
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH

Recommendation	Annual Cost Savings	Cost Savings Over 10-Year Period^{a/}	Reduction in Time to Meet Cleanup Goals	Difficulty of Implementation	Cost to Implement
Recommendation No. 1 – Turn off the existing pump-and-treat system at OU1 and monitor CAHs and natural attenuation parameters in groundwater for 1 year.	\$268 K	\$2.7 M	None	Moderate – Requires regulatory approval.	\$25K
Recommendation No. 2 - Maintain operation of the ETI system at OU4 until <i>cis</i> -1,2-DCE concentrations fall below the MCL and optimize the system by eliminating 14 extraction wells and 16 injection wells.	\$200 K	\$2.0 M	None	Moderate – Requires regulatory approval.	\$25K
Recommendations No. 3 Monitor untreated groundwater from the OU4 hot-spot trench for CAHs Bypass the treatment system if CAH concentrations are below MCLs and discharge directly to the sewer.	\$0 ^{b/}	TBD	None	Low – Requires regulatory concurrence.	\$0
Recommendation No. 4 Maintain the current monitoring frequency and reduce the number of wells sampled by two during long-term groundwater monitoring at OU4.	\$6 K	\$60 K	None	Low – Requires regulatory approval.	\$5K
TOTAL	\$474K	\$4.7 M			\$60K

^{a/} Estimated costs in 2000 constant dollars. Estimated time remaining for reduction of vinyl chloride below 2 micrograms per liter under monitored natural attenuation remedy is 10 years.

^{b/} No short-term savings are estimated for bypassing the treatment system at the extraction trench, because this recommendation requires keeping the treatment system operational in the event that CAH concentrations in pretreated water are above MCLs.

source mass of *cis*-1,2-DCE in the plume. By suspending operation of the extraction and treatment system at OU1, and at OU4 when CAH concentrations are below MCLs, it can be determined if natural attenuation processes will be sufficient to contain and remove the remaining mass of VC from groundwater.

Opportunity 2: Monitor groundwater quality at the OU4 extraction trench and terminate operation when upgradient COC concentrations meet ROD cleanup criteria.

Operation of the extraction trench located at the western boundary of DDHU should continue in order to remove CAHs that otherwise could migrate off-facility during monitored natural attenuation at OU4. Short-term recommendations allow for continued monitoring of CAHs in the groundwater extracted from the trench before it enters the treatment plant. If CAH concentrations exceed MCLs (2 µg/L for VC and 70 µg/L for *cis*-1,2-DCE), then extracted groundwater can be sent through the treatment system before discharge to the CWSID sewer system. If CAH concentrations are below MCLs (and all other CWSID discharge requirements are met), the groundwater can be disposed directly into the sanitary sewer. Continued monitoring of pretreated groundwater from the extraction trench allows for the creation of a database which will support the eventual shutdown of the treatment plant should detected CAH concentrations in the pretreated groundwater remain below MCLs

This opportunity takes advantage of the current groundwater monitoring program at the extraction trench, and adds potential cost savings by utilizing the treatment system only when necessary. Use of the extraction trench to capture CAHs that could migrate off-Depot during monitored natural attenuation could delay or eliminate the need to resume ETI system operation if CAH concentrations in the upgradient portions of the OU4 plume increase during monitored natural attenuation.

Opportunity 3: If CAH concentrations in the groundwater show significant rebound and potential for off-Depot migration, then operate a modified ETI system as recommended in Section 6 of the Draft RPO Phase II Evaluation Report. This long-term opportunity is recommended only in the event that natural attenuation mechanisms are not sufficient to prevent off-Depot migration of CAHs in groundwater.

E6.2.1 Costs

Table 7.2A presents the long-term opportunities and the associated estimated cost savings. The cost savings for Opportunity No. 1 are essentially the cost savings realized by implementing the short-term recommendations. A total savings of \$474,000 per year could be realized by shutting down the ETI system at OU1 and conducting quarterly groundwater monitoring for 1 year, and optimizing the current ETI system at OU4 and continuing groundwater monitoring.

The cost savings for modifying operation of the OU4 extraction trench are minimal, and are realized by bypassing the treatment system when CAH concentrations are below MCLs. O&M costs for the extraction trench are included in the total O&M costs for OU4, and were not provided to Parsons separately. However, for purposes of the draft

RPO report and this addendum, Parsons estimated the annual O&M cost for the extraction trench and treatment system to be approximately \$50,000.

If it is apparent that operation of the OU1 and OU4 ETI systems is necessary to contain the CAH plumes, then operating the optimized ETI system at OU1 could result in annual O&M savings of \$135,000, and operating the optimized ETI system at OU4 could result in annual O&M savings of \$200,000. This would produce annual cost savings of \$335,000 if Opportunity No. 3 is implemented (Table 7.2A).

E7.0 REVISED RPO IMPLEMENTATION PLAN

E7.1 Short-Term Recommendations

The following section is a summary of what is required for implementation of the RPO recommendations. Based on a review of the available data collected, the short-term recommendations provided in this addendum could be implemented by the Depot's environmental and/or O&M contractors.

Recommendations 1 and 2: Discontinue pumping at all extraction wells in OU1 and monitor groundwater quality quarterly. Implement optimization of the ETI system at OU4, and continue to operate the system until CAH concentrations in groundwater are below MCLs.

- Well shutdown at OU1 should be planned to coincide with a scheduled groundwater monitoring event (e.g., March 2002). Prior to cessation of pumping, collect water-level measurements and groundwater samples from each of the operating extraction wells. Water levels and analytical results will be used to confirm historical concentrations in extraction-well discharge, and to establish initial conditions against which potential future plume migration or changes in concentrations can be evaluated.
- Prepare the ETI system for a 12-month shutdown period to prevent damage to the system, and shut down the ETI system at OU1.

**TABLE 7.2A
LONG-TERM RPO OPPORTUNITIES
OPERABLE UNITS 1 AND 4
REMEDIAL PROCESS OPTIMIZATION
DEFENSE DEPOT HILL, UTAH**

Opportunity	Annual Cost Savings	Cost Savings Over 10-Year Period ^{a/}	Reduction in Time to Meet Cleanup Goals	Difficulty of Implementation	Cost to Implement
Opportunity No. 1 – Implement monitored natural attenuation at OU1 and optimize the ETI system at OU4.	\$474K	\$4.7 M	None	Moderate – Requires regulatory approval	\$50K
Opportunity No. 2 – Monitor groundwater quality at the OU4 hot-spot extraction trench, and, when appropriate, terminate operations.	\$50 K ^{b/}	\$500 K	None	Moderate – Requires regulatory approval	\$25K
Opportunity No. 3 – Implement modified ETI system operations if monitoring of CAHs in groundwater shows both rebound and continued migration offsite.	\$335 K	\$3.4 M	None	Moderate – Requires regulatory approval	\$50K

^{a/} Estimated costs in 2000 constant dollars. Estimated time remaining for reduction of vinyl chloride below MCL of 2 µg/L under monitored natural attenuation is 10 years.

^{b/} O&M costs for the extraction trench are included in the total O&M costs for OU4, and were not provided to Parsons separately. However, for purposes of this report, Parsons estimated the O&M cost for the extraction trench to be \$50,000.

- Quarterly groundwater monitoring for CAH concentrations and natural attenuation parameters should continue following shutdown of the OU1 ETI system to evaluate temporal changes in chemical concentrations, potential changes in plume configuration, and the possible effects of natural attenuation. As noted in Section 6 of the draft RPO report, monitored natural attenuation cannot be fully evaluated during active groundwater extraction because the effects of pumping can mask some natural-attenuation indicators.
- At the end of the 12-month rebound period, conduct a scheduled groundwater monitoring event, including collection of water-level measurements . The results of this monitoring event can be compared with the results of the initial and quarterly monitoring events to evaluate changes in chemical concentrations and plume configuration, and also can be used in a detailed evaluation of natural attenuation.
- At OU4, once CAH concentrations in groundwater are below MCLs, a rebound test, as recommended for OU1, can be performed, following the implementation procedures as described above.

Recommendation 3: Bypass the treatment system at the OU4 hot-spot extraction trench, and monitor untreated groundwater from the trench for CAHs (and other discharge permit parameters).

- Collect groundwater from the trench before it enters the treatment system.
- Analyze untreated groundwater samples for VC, *cis*-1,2-DCE, and other CWSID discharge permit parameters.
- If concentrations of VC and *cis*-1,2-DCE remain within acceptable treatment system effluent limits established in the ROD (Section 5 of draft RPO report), and other discharge requirements are met, discharge the water directly to the sanitary sewer.
- If concentrations of VC and *cis*-1,2-DCE (or other parameters) are above the acceptable treatment system effluent limits, direct the water through the treatment system prior to discharge to the sanitary sewer.
- If CAH concentrations in the extracted groundwater are consistently below the MCLs for VC and *cis*-1,2-DCE, then the treatment system at the OU4 extraction trench can be bypassed.

Recommendation 4: Reduce the number of wells sampled during long-term groundwater monitoring at OU1 and OU4.

The monitoring program at OU1 has already been optimized. The monitoring program at OU4 can be evaluated and optimized at anytime during the operation of the ETI system.

E7.2 LONG-TERM OPPORTUNITIES

Opportunity 1: Implement monitored natural attenuation for CAHs in groundwater at OU1, and optimize the ETI system at OU4.

Monitored natural attenuation at OU1 should be evaluated during the 1-year rebound test before proceeding to full-scale implementation. A detailed assessment of the potential for MNA can be conducted using the monitoring data to be collected immediately prior to shutdown of the ETI system, during the 1-year test, and at the conclusion of the 12-month test. Detailed instructions for conducting MNA evaluations are provided in existing protocol documents (e.g., USEPA, 1998).

Extraction well data indicate that only five of the OU4 extraction well remove a significant amount of CAH mass from the groundwater plume. Optimization of the ETI system at OU4 should be evaluated in order to improve the efficiency of the system and to reduce O&M costs. Monitored natural attenuation at OU4 should be evaluated only after operation of the ETI system has reduced CAH concentrations in the groundwater to levels below MCLs.

Opportunity 2: Monitor groundwater quality at the OU4 extraction trench and, when appropriate, terminate operation.

The long-term opportunity at the OU4 extraction trench is two-fold:

- Monitoring CAH concentrations in extracted groundwater before the water is directed to the treatment system can assist in evaluating whether treatment of the water is necessary prior to disposal in the sanitary sewer. If the monitoring results indicate that groundwater does not require treatment after extraction, then cost savings could be realized by taking the dedicated trench treatment system off line .
- Monitoring extracted groundwater quality at the extraction trench concurrently with the rebound test/monitored natural attenuation evaluation at OU4 may assist in evaluating the role of the extraction trench in capturing CAHs that would otherwise have been contained by the ETI system. If necessary, the extraction trench can remain in operation as a low-cost alternative to operation of a modified pump-and-treat system.

Opportunity 3: If CAH concentrations in the groundwater show significant rebound, together with potential for off-site migration, then a modified ETI system could be operated, as recommended in Section 6 of the draft RPO report.

This long-term opportunity should be considered only if natural attenuation processes are not sufficient to prevent CAH from migrating off the Depot. At OU1, the size of the CAH plume and the current concentrations of VC and *cis*-1,2-DCE suggest that off-site migration of the plume will not occur. At OU4, CAH concentrations in the groundwater plume should be reduced below MCLs before the ETI system is shut down for a 1-year rebound test and evaluation of monitored natural attenuation. Until the results of the 1-year rebound test are evaluated, it should be assumed that the CAH plume has the

potential to migrate off site. As a contingency measure, the OU4 extraction trench can be used to intercept CAHs that might otherwise migrate off-site.

REFERENCES
(EXTRACTED FROM DRAFT RPO REPORT)

- JMM. 1991a. *Draft Final Remedial Investigation/Feasibility Study Report for Operable Unit 1*. July.
- JMM. 1991b. *Draft Final Remedial Investigation/Feasibility Study Report for Operable Unit 4*. September.
- JMM, 1992a. *Record of Decision, OUI, Defense Depot Hill, Utah*.
- JMM. 1993a. *Ground-Water Monitoring Plan for Operable Unit 1, Defense Distribution Depot, Ogden, Utah*. February.
- JMM. 1993b. *Ground-Water Monitoring Plan for Operable Unit 4, Defense Distribution Depot, Ogden, Utah*. May.
- Klienfelder Inc. 1999. *Groundwater Treatment System Evaluation Report, Defense Depot, Hill, Utah, Operable Unit #1, Fourth Year*. April.
- Montgomery Watson. 2000. *Final Record of Decision Amendment for Operable Unit 4*. Prepared for U.S. Army Corps of Engineers. March.
- OHM Remediation Services Corporation (OHM). 1999. *Fourth Year Report O&M of Groundwater Pump and Treat Systems, Operable Unit 4 and Operable Unit 4 Hotspot, Defense Distribution Depot Hill, Utah-Ogden Site*. November.
- OHM. 2000. *Year 5 Second Quarter Operations Report, Operable Unit 4 and Operable Unit 4 Hot Spot, Defense Distribution Depot Hill, Utah-Ogden Site*. February.
- Parsons Engineering Science, Inc. (Parsons). 2000a. *Draft Remedial Process Optimization Report for Defense Depot Hill, Utah*. November 2000.
- Parsons ES. 2000b. Meeting minutes for the RPO briefing at Defense Depot Hill, Utah. November 30, 2000.
- Scientific Software Group, 2000. *Winflow Analytical Groundwater Model*. December.
- Smith, Ron. 2001. *Comments on Addendum to Draft Remedial Process Optimization Report, Defense Depot Hill, Utah*. June.

APPENDIX F
RESPONSE TO COMMENTS

**RESPONSE TO DDHU COMMENTS ON THE ADDENDUM THE DRAFT REMEDIAL
PROCESS OPTIMIZATION REPORT FOR DEFENSE DEPOT HILL, UTAH**

Item No.	Page	Line/Para/Table	Comment	Response
1.	A-2	Section A1.0	In this section you talk about the new extraction-well plan for OU1. We installed two new extraction wells (EW -17 and EW -18) instead of only one. Request you change this section to incorporate this comment.	Comment noted. Our evaluation was based upon the revised and regulator-approved pump and treat system as provided to us by DDHU in their comments on the Draft RPO report (December 20, 2000). Text will be added to acknowledge that additional revisions have since been made to the pump and treat system. However, evaluation of the revised pump and treat system is not necessary, because our evaluation of the new pump and treat system indicated that it would perform adequately at capturing the remaining vinyl chloride plume.
2.	A-13	Section A6.1.1 Lines 8 & 9	Need to change to show we added two new extraction wells (EW -17 and EW -18) instead of only one.	See response to comment 1.
3.	A-18	Lines 6 & 7	You stated that CAHs have not been detected in JMM-41D and JMM-43D. This is not a true statement. We did have small amounts of CAHs detected in JMM-41D (Oct 98, DCE 0.8 and Oct 95, TCE 4.8) and JMM-43D (Oct 95, TCE 1.4).	We appreciate the additional data incorporated into the text.