

FINAL

**Remedial Process Optimization Report for
Operable Unit 1
Northeast Disposal Area**



**George Air Force Base
California**

Prepared For

**Air Force Center for Environmental Excellence
Technology Transfer Division
Brooks Air Force Base
San Antonio, Texas**

and

**AFBCA/OL-C
George Air Force Base, California**

November 2000

**FINAL
REMEDIAL PROCESS OPTIMIZATION REPORT
FOR
OPERABLE UNIT 1 – NORTHEAST DISPOSAL AREA
GEORGE AIR FORCE BASE, CALIFORNIA**

Prepared for the:

**AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE
TECHNOLOGY TRANSFER DIVISION
BROOKS AIR FORCE BASE, TEXAS**

and

**AFBCA/OL-C
GEORGE AIR FORCE BASE, CALIFORNIA**

November 2000

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13. ABSTRACT (<i>Maximum 200 words</i>) Parsons Engineering Science, Inc. (Parsons ES) prepared a draft remedial process optimization (RPO) handbook for the Air Force Center for Environmental Excellence Technology Transfer Division (AFCEE/ERT), to be used by 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 Air Force facilities. Parsons ES is field-testing the approach described in the draft handbook at multiple Air Force sites, including Operable Unit 1 (OU1) groundwater associated with the Northeast Disposal Area (NEDA) at George Air Force Base (GAFB), California. At GAFB, the Air Force is operating a groundwater extraction and treatment (pump-and-treat) system to contain a plume of dissolved trichloroethene (TCE), and eventually remove sufficient contaminant mass to reduce TCE concentrations below the cleanup goals established for groundwater at GAFB OU1. TCE in groundwater is thought to have originated at the NEDA; and the plume has migrated off-Base to the north, across a distance of several thousand feet. The RPO evaluation determined that the existing groundwater pump-and-treat system has been neither efficient nor effective in removing TCE mass from groundwater. The likelihood of the pump-and-treat system achieving the cleanup goals or effectively meeting performance criteria within a reasonable timeframe is questionable. Short-term recommendations and long-term opportunities were identified to immediately affect system performance and provide a framework for the future direction of site remediation. Recommendations for short-term system modifications include removing 11 of the existing 18 wells in the extraction network from service and evaluating alternate treatment and disposal options for extracted groundwater. Recommended changes to the monitoring program include reducing the frequency of sampling from semiannual to annual, and reducing the number of groundwater monitoring wells sampled. If implemented, these short-term recommendations would result in more than \$170,000 in annual cost savings. Long-term opportunities include pursuing alternate, risk-based cleanup goals for groundwater at GAFB OU1 and fully evaluating other potential remedial measures. Long-term cost savings could be in the millions of dollars.			
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LIST OF ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AFBCA	Air Force Base Closure and Realignment
AFCEE	Air Force Center for Environmental Excellence
AMC	Air Mobility Command
ASCE	American Society for Chemical Engineers
amsl	above mean sea level
ARAR	applicable or relevant and appropriate requirement
ASTM	American Society for Testing and Materials
bgs	below ground surface
CaCO ₃	calcium carbonate
CAH	chlorinated aliphatic hydrocarbon
CalEPA	California Environmental Protection Agency
CCR	California Code of Regulations
CERCLA	Comprehensive Environmental Restoration, Compensation, and Liability Act
CFR	Code of Federal Regulations
CLGB	contaminant level greater than background
CSM	conceptual site model
DO	dissolved oxygen
DOD	Department of Defense
ERPIMS	Environmental Resources Program Information Management System
ERT	Technology Transfer Division
ESA	Endangered Species Act
FFA	Federal Facilities Agreement
FS	feasibility study
ft/day	feet per day
ft/ft	foot per foot
GAFB	George Air Force Base
gpm	gallon(s) per minute
IRP	Installation Restoration Program
lbs	pounds
LTM	long-term monitoring
µg/L	microgram(s) per liter
MCL	maximum contaminant level
mg/L	milligram(s) per liter
MNA	monitored natural attenuation
mol/L	mole(s) per liter
mV	millivolt(s)
NCP	National Hazardous Substances Pollution Contingency Plan
NEDA	Northeast Disposal Area
NPL	National Priorities List
OM&M	operation, maintenance, and monitoring
OPS	operating properly and successfully

ORP	oxidation/reduction potential
OSWER	Office of Solid Waste and Emergency Response
OU	operable unit
Parsons ES	Parsons Engineering Science, Inc.
PCE	tetrachloroethene
POTW	publicly owned treatment works
PRL	project reporting limit
ppbv	parts per billion, volume per volume
Radian	Radian International LLC
RAO	remedial action objective
RBCA	risk-based corrective action
RBSL	risk-based screening level
RCRA	Resource Conservation and Recovery Act
RI	remedial investigation
RNA	remediation by natural attenuation
ROD	record of decision
RPO	remedial process optimization
RWQCB	Regional Water Quality Control Board
SAIC	Science Applications International Corporation
SAP	sampling and analysis plan
STP	sewage treatment plant
TBC	to-be-considered criteria
TCA	trichloroethane
TCE	trichloroethene
TI	technical impracticability
TOC	total organic carbon
US	United States
USC	United States Code
USEPA	United States Environmental Protection Agency
VVWRA	Victor Valley Water Reclamation Authority
VOC	volatile organic compound

EXECUTIVE SUMMARY

Parsons Engineering Science, Inc. (Parsons ES) prepared a draft remedial process optimization (RPO) handbook for the Air Force Center for Environmental Excellence Technology Transfer Division (AFCEE/ERT). The handbook will be used by 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 Air Force facilities. Parsons ES is field-testing the approach described in the draft handbook at multiple Air Force sites, including Operable Unit 1 (OU1) groundwater associated with the Northeast Disposal Area (NEDA) at George Air Force Base (GAFB), California. Lessons learned from the RPO field tests will be incorporated into the final RPO handbook. The Air Force 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.

At GAFB, the Air Force is operating a groundwater extraction and treatment (pump-and-treat) system in accordance with the requirements of a ROD established in compliance with the Comprehensive Environmental Restoration, Compensation, and Liability Act (Sections 1 and 3). The system is intended to contain a plume of dissolved trichloroethene (TCE), and eventually remove sufficient contaminant mass to reduce TCE concentrations below the cleanup goals established for groundwater at GAFB OU1 (i.e., the federal maximum contaminant level of 5 micrograms per liter [$\mu\text{g/L}$] for TCE). TCE in groundwater is thought to have originated at the NEDA; however, during numerous investigations through a period of more than 15 years, no discrete source of TCE has been identified. The plume has migrated off-Base to the north, across a distance of several thousand feet. The maximum concentrations of TCE in groundwater (about 300 to 400 $\mu\text{g/L}$) have been detected in samples from wells near the northern Base boundary (Section 2).

The groundwater extraction and treatment system currently operating at GAFB OU1 was installed in two phases in 1991 and 1996. The pump-and-treat system consists of 18 groundwater extraction wells; an influent wet-well; twin-packed, counterflow air stripping towers that remove volatile organic compounds from the influent water; an effluent wet-well; associated piping, electrical service, and ancillary equipment. When the system was installed in 1991, extracted and treated groundwater was discharged to the arroyo immediately east of the treatment plant. Later, treated water was discharged to the sewage treatment plant percolation ponds, near the eastern boundary of the Base. After the three new infiltration ponds, located approximately 3,000 feet south of the treatment system, were constructed in 1997, all discharge from the treatment plant has been directed to these ponds. The average extraction and treatment rate reported for the first quarter of 1999 was about 580 gallons per minute (gpm). The mean influent TCE concentration detected in water samples from the influent wet-well is generally less than 10 $\mu\text{g/L}$. The TCE concentrations in the effluent stream transferred to the infiltration ponds are below detection limits.

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

- Review existing data to evaluate previously completed site characterization activities;
- Prepare a site-specific work plan and a site-specific addendum to the project health and safety plan;
- Evaluate the remedial decision process leading to the current system design, in accordance with the draft RPO handbook;
- Conduct a site visit to further evaluate the effectiveness and efficiency of the existing and currently operating system in accordance with the draft RPO handbook;
- Collect analytical data to support the RPO evaluation;
- Evaluate the currently operating groundwater extraction/treatment system in accordance with the draft RPO handbook;
- Recommend short-term modifications to the future OM&M of the remediation system that will result in future cost savings;
- Identify long-term opportunities for the direction of remedial decision making;
- Provide an implementation plan for appropriate short-term recommendation and long-term opportunities; and
- Prepare a site-specific RPO report presenting Parsons ES's conclusions regarding the groundwater remediation system evaluation, and recommendations for RPO at GAFB OU1.

The RPO evaluation determined that the existing groundwater pump-and-treat system has been neither efficient nor effective in removing TCE mass from groundwater. Through April 1999, the groundwater pump-and-treat system had recovered approximately 120 pounds of TCE, or about 13 percent of the estimated total mass of TCE in groundwater at GAFB OU1, at an average cost per pound of about \$46,000. Several of the extraction wells may be effective in limiting the further migration of the TCE plume; however, many of the existing extraction wells are ineffective at plume containment, and/or removal of TCE mass. The likelihood of the pump-and-treat system achieving the cleanup goals or effectively meeting performance criteria within a reasonable timeframe is questionable.

Under current land-use conditions, no completed exposure pathways to human receptors exist. Furthermore, if institutional controls restricting the use of groundwater beneath OU1 remain in place, the possibility of future human or ecological exposure to TCE in groundwater is remote. In some areas of OU1, natural attenuation processes may be assisting in reducing the concentrations of TCE, in containing the migration of TCE,

or both; however, the aerobic and toxic conditions in OU1 groundwater suggest that if TCE biodegradation is occurring, such processes are proceeding relatively slowly via aerobic degradation mechanisms.

Based on the review of the remedial decision process and system performance to date, short-term recommendations and long-term opportunities were identified to immediately affect system performance and provide a framework for the future direction of site remediation. Recommendations for short-term system modifications include removing 11 of the existing 18 wells in the extraction network from service, thereby reducing the system flow rate by as much as 50 percent, and evaluating alternate treatment and disposal options for extracted groundwater. Recommended changes to the monitoring program include reducing the frequency of sampling from semi-annual to annual, and at a minimum reducing the number of groundwater monitoring wells sampled from 47 to 34. If implemented, these short-term recommendations could result in more than \$170,000 in annual cost savings, which is equivalent to more than 50 percent of the current annual OM&M budget for the system. Long-term opportunities include pursuing alternate, risk-based cleanup goals for groundwater at GAFB OU1, that would be protective of future human and ecological receptors; and fully evaluating other potential remedial measures (e.g., monitored natural attenuation and phytoremediation). Long-term cost savings could be in the millions of dollars.

Tables ES.1 and ES.2 provide a summary of the potential cost savings associated with the short-term recommendations and long-term opportunities identified as a result of the RPO evaluation of the OU1 pump-and-treat system at GAFB. An RPO implementation plan and schedule is included as Section 6 of this document. If so directed by the Contracting Officer, Parsons ES will advise the Base OM&M contractor on implementing the recommendations provided in Section 5 of this document.

TABLE ES.1
RPO SUMMARY: SHORT-TERM RECOMMENDATIONS AND POTENTIAL COST SAVINGS
REMEDIAL PROCESS OPTIMIZATION, OU1
GEORGE AIR FORCE BASE, CALIFORNIA

Current System				Short-Term Optimization Recommendations	Optimized System				Difficulty of Implementation
System Component	Estimated Annual Cost ^{a/}	Estimated Total Remaining Cost ^{a/}			Estimated Annual Cost Savings	Cost Savings Over Remaining 33-Year Project Life Cycle ^{b/}	Cost Savings Over Remaining 100-Year Project Life Cycle ^{c/}	Reduction in Time to Meet Cleanup Goals	
		33-Year Period of Operation Remaining ^{b/}	100-Year Period of Operation Remaining ^{c/}						
18 groundwater extraction wells	\$60,000	\$2.0 million	\$6.0 million	Remove 11 of 18 existing extraction wells from service.	\$30,000	\$990,000	\$3.0 million	None	Moderate - Requires regulatory approval.
Air-stripping treatment system	\$40,000	\$1.3 million	\$4.0 million	Terminate air-stripping treatment of extracted groundwater.	\$40,000	\$1.3 million	\$4.0 million	None	Moderate - Requires demonstration that TCE in discharge would not exceed acceptable limits, with subsequent regulatory approval.
Groundwater monitoring program	\$150,000	\$5.0 million	\$15.0 million	Optimize long-term monitoring.	\$100,000 ^{d/} \$113,000 ^{e/}	\$3.3 million ^{d/} \$3.7 million ^{e/}	\$10.0 million ^{d/} \$11.3 million ^{e/}	None	Low - Requires regulatory approval.

^{a/} Estimated costs given in constant 1999 dollars (see Section 4).

^{b/} Assumes that remediation objectives are achieved in year 2033.

^{c/} Assumes that remediation objectives are achieved in year 2100.

^{d/} Monitoring costs using conventional or micropurge techniques.

^{e/} Monitoring costs using diffusion sampling techniques.

TABLE ES.2
RPO SUMMARY: LONG-TERM OPPORTUNITIES AND POTENTIAL COST SAVINGS
REMEDIAL PROCESS OPTIMIZATION, OU1
GEORGE AIR FORCE BASE, CALIFORNIA

Long-Term Optimization Opportunities	Annual Cost Savings	Cost Savings Over Remaining 33-Year Project Life Cycle ^{a/}	Cost Savings Over Remaining 100-Year Project Life Cycle ^{a/}	Reduction in Time to Meet Cleanup Goals	Difficulty of Implementation
Develop proposal for establishing site-specific, risk-based goals in accordance with requirements of Lahontan Basin Plan. Terminate operation of OU1 pump-and-treat system.	\$170,000	\$5.6 million	\$17 million	> 30 years	High - Requires regulatory approval and negotiation of site-specific, risk-based cleanup goals.
Evaluate monitored natural attenuation option in detail by shutting down system for 12-month period and observing plume migration. If appropriate, terminate operation of OU1 pump-and-treat system.	\$170,000	\$5.6 million	\$17 million	TBD ^{b/}	Moderate - Requires regulatory approval, long-term monitoring, and negotiation of site-specific, risk-based cleanup goals.
Refine conceptual hydrogeologic model, and use to evaluate phytoremediation option. If appropriate, terminate operation of all or part of OU1 pump-and-treat system.	\$150,000	\$5 million	\$15 million	TBD	Moderate – Requires regulatory approval, treatability study, and negotiation of site-specific, risk-based cleanup goals.

^{a/} Costs given in constant 1999 dollars (see Section 4).

^{b/} TBD = to be determined.

SECTION 1

INTRODUCTION

Parsons Engineering Science, Inc. (Parsons ES) was awarded a delivery order under the Air Mobility Command (AMC) contract (F11623-94-D0024, RL 72) on 18 September 1998, to prepare a guidance document for remedial process optimization (RPO) for the Air Force Center Environmental Excellence, Technology Transfer Division (AFCEE/ERT). The Air Force goals for the RPO program are to :

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

The guidance document will be used by AFCEE during the design of new remediation systems, and while implementing performance enhancements for existing systems, performing 5-year record-of-decision (ROD) reviews, and preparing documentation for "operating properly and successfully" (OPS) certification. A draft RPO handbook has been prepared for AFCEE by Parsons ES (1999).

The approach described in the draft RPO handbook (Parsons ES, 1999a) was field-tested at several Air Force sites, including the Northeast Disposal Area (NEDA) in Operable Unit 1 (OU1) at George Air Force Base (GAFB) in southern California. The primary objective of this RPO evaluation for the NEDA at GAFB was to use the methods described in the draft RPO handbook to evaluate the performance of a groundwater extraction and treatment (i.e., pump-and-treat) system installed to treat a dissolved solvent plume.

1.1 DESCRIPTION OF THE RPO PROCESS

RPO can be broadly defined as a systematic approach to evaluating and improving the effectiveness and efficiency of site remediation so that maximum risk reduction is achieved for each dollar spent. The overall objective of RPO is to protect human health and the environment using technical and management solutions that represent current "best practice" methods. Although RPO frequently is associated with the optimization of remediation systems (the technical means by which cleanup will be accomplished), application of RPO is equally important in reviewing why certain cleanup goals have been established, and updating those decisions based on new regulatory options. Just as the technical approach to remediation should be reviewed and revised to take advantage of scientific advances and evolving standard practice, changes in regulatory framework, such as risk-based cleanup goals and the growing acceptance

of monitored natural attenuation, should be considered in the optimization process. An effective RPO program will evaluate a wide range of optimization opportunities.

1.2 SITE-SPECIFIC SCOPE AND OBJECTIVES

The work plan for the RPO evaluation at the NEDA, OU1, GAFB (Parsons ES, 1999b) outlined the objectives and activities to be conducted to implement the procedures described in the draft RPO handbook (Parsons ES, 1999a). The objectives of the RPO project at the NEDA included:

- Reviewing and updating the existing conceptual site model (Section 2);
- Evaluating the cleanup goals established for this site (Section 3);
- Examine the effectiveness of the existing remediation system using the performance criteria (Section 4);
- Evaluating monitored natural attenuation (MNA) as an alternative remedial method (Sections 2 and 4);
- Recommending short-term modifications to the future operation, maintenance, and monitoring (OM&M) of the remediation system that will result in future cost savings (Section 5);
- Identifying long-term opportunities for the direction of remedial decision making (Section 5); and
- Providing an implementation plan for appropriate short-term recommendations and long-term opportunities (Section 6).

The following activities were completed to accomplish these objectives:

- Data review to evaluate previously completed site characterization activities;
- Preparation of the site-specific work plan and a site-specific addendum to the project health and safety plan;
- Evaluation of the remedial decision process leading to the current system design, in accordance with the draft RPO handbook;
- Evaluation of the existing and currently operating groundwater extraction/treatment system in accordance with the draft RPO handbook; and
- Preparation of this site-specific RPO report presenting Parsons ES's conclusions regarding the groundwater remediation system evaluation, and recommendations for RPO at GAFB OU1.

This report is organized into six sections, including this introduction, and three appendices. A review of the conceptual site model is presented in Section 2, together with a discussion of the available hydrologic and chemical data. Section 3 provides an evaluation of the site cleanup goals. Section 4 presents an evaluation of the remedial system's effectiveness. Section 5

presents recommendations for short- and long-term RPO opportunities, and Section 6 provides an RPO implementation plan. Site specific chemical data, collected in support of this RPO evaluation, are provided on a compact disk in Environmental Resources Program Information Management System (ERPIMS) format, in Appendix A, together with field sampling forms. A brief discussion of chemical properties and natural attenuation processes, and their effects on chemical fate in the environment is provided in Appendix B. Appendix C provides details regarding the calculation of risk-based cleanup standards. Appendix D provides responses to the United States Environmental Protection Agency (USEPA) comments on the draft final RPO report.

1.3 SITE INFORMATION

1.3.1 Site Description and Operational History

GAFB is located in southern California, northwest of the city of Victorville (Figure 1.1). The Base was initially activated in 1941 as Victorville Army Airfield, and served as a training facility for pilots and bombardiers. In 1945, flying operations were discontinued, and the Base was assigned to the Air Tactical Services Command as an aircraft storage facility. In 1948, the Base was transferred to the Sacramento Air Material Command, and all stored aircraft were removed from the site. In 1950, the Base was reopened as GAFB. During the Korean War, the Base was home to the 1st Fighter Interceptor Wing and the 131st and 146th Fighter Bomber Wings. After the Korean War, GAFB remained active as a fighter training base. In 1989, the realignment and closure of GAFB was approved by the Secretary of Defense and Congress, and closure began in 1992. Currently, GAFB is not occupied by Air Force personnel, and is being converted for civilian use (airport and aircraft maintenance, and an industrial park).

Operations at GAFB required the storage, use, and disposal of hazardous materials. Active environmental cleanup has been under way at GAFB since 1981, in accordance with the Comprehensive Environmental Restoration, Compensation, and Liability Act (CERCLA) guidance and regulations as part of the Air Force Installation Restoration Program (IRP). During the IRP Phase I Records Search (CH2M Hill, 1982), 54 sites that were known or suspected to have received hazardous materials were identified at GAFB. Six additional sites were identified during the IRP Phase II Confirmation/Quantification Study (Science Applications International Corporation [SAIC], 1987). Sites judged to warrant further investigation were grouped into three OUs (Figure 1.2). OU1 includes Department of Defense (DOD) Site SD-25 (IRP Site S-20), the Industrial/Storm Drain; DOD Site WP-26 (IRP Site S-21), the Sewage Treatment Plant (STP) Percolation Ponds; and a dissolved trichloroethene (TCE) plume in groundwater beneath the NEDA in the northeastern part of the Base and adjacent, downgradient off-Base areas. The NEDA groundwater plume and associated remedial system are the focus of this RPO evaluation.

1.3.2 Previous Investigations

Characterization and monitoring of contamination at the NEDA began in 1985. Reports generated during previous investigations include:

- IRP Phase II Confirmation/Quantification Stage 1 report (SAIC, 1985);
- IRP Phase II Confirmation/Quantification Stage 2 report (SAIC, 1987);
- NEDA March 1988 water quality report (James M. Montgomery [JMM], 1988a);

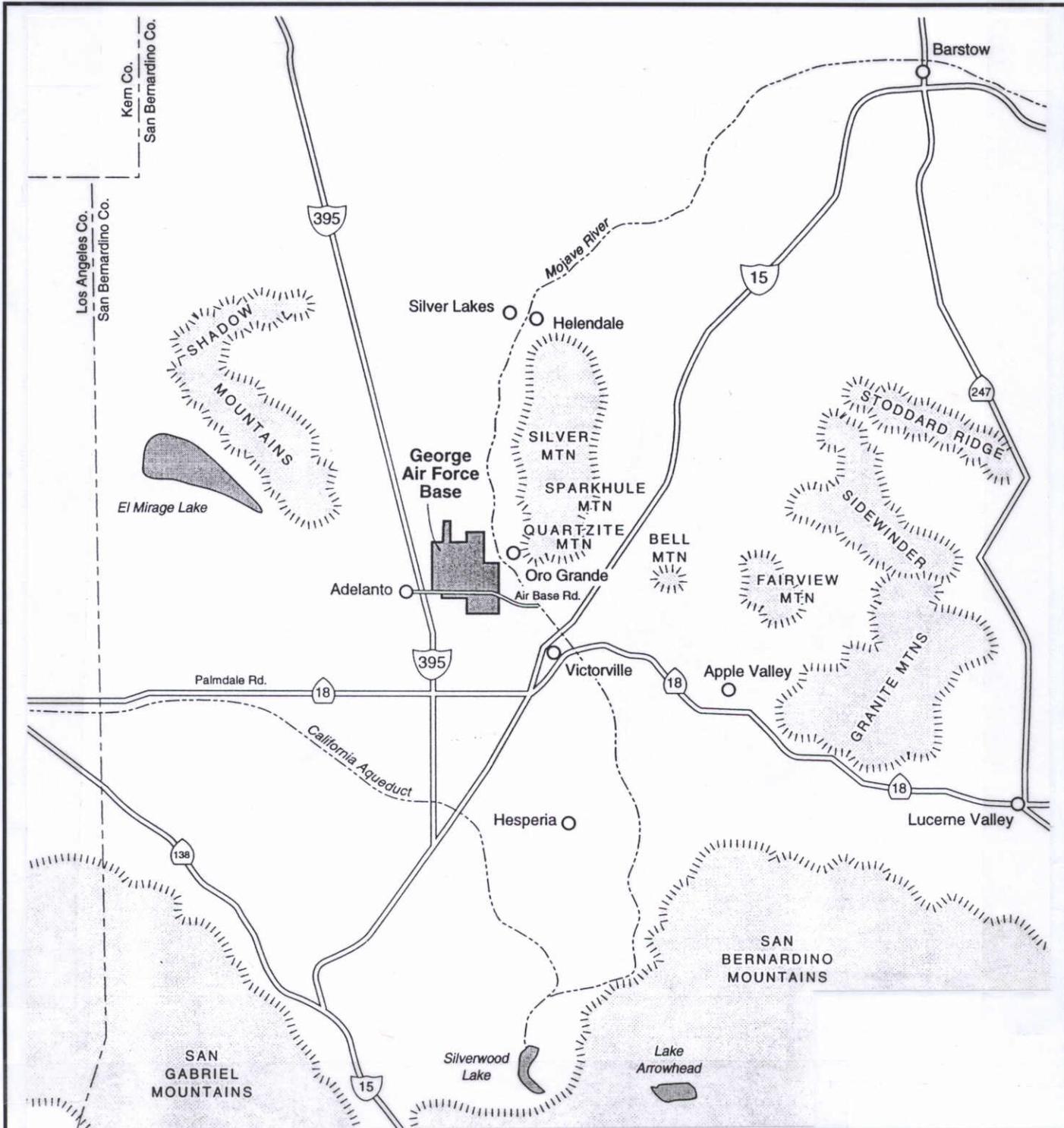


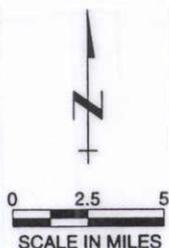
FIGURE 1.1

VICINITY MAP

Remedial Process Optimization
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Source: The Thomas Guide (1992).

- IRP Phase IV-A NEDA upper aquifer feasibility study (FS)/site investigation report; (JMM, 1988b);
- GAFB remedial investigation (RI) report (JMM, 1988c);
- Hydrological studies in support of jurisdictional determination for Application No. 29163, George Air Force Base (Radian International, LLC [Radian], 1989);
- Final technical memorandum for Site S-20, Site S-26, and the NEDA (JMM, 1990);
- Final RI report for OU1 (JMM, 1992);
- Final FS for OU1 (JMM, 1993);
- ROD for OU1 (Montgomery Watson, 1994);
- October 1997 Basewide groundwater monitoring report (Montgomery Watson, 1998a);
- Final remedial action report for the OU1 groundwater extraction/treatment system (Montgomery Watson, 1998b);
- Second-quarter 1998 process monitoring report, OU1 groundwater extraction/treatment system (Montgomery Watson, 1998c);
- October 1998 Basewide groundwater monitoring report (Montgomery Watson, 1998d);
- Fourth-quarter 1998 process monitoring report, OU1 groundwater extraction/treatment system (Montgomery Watson, 1999a);
- Final proposal for modifications to OU1 groundwater extraction and treatment system (Montgomery Watson, 1999b); and
- Second-quarter 1999 process monitoring report, OU1 groundwater extraction/treatment system (Montgomery Watson, 1999c).

1.3.3 Site Geology and Hydrogeology

1.3.3.1 Geology

GAFB is located within the Victor Valley, San Bernardino County, California, approximately 70 miles northeast of the Los Angeles (Figure 1.1). The valley is within the southwestern margin of the Mojave Desert Physiographic Province, and is bounded by the Shadow Mountains on the northwest, the Mojave River on the east, and the San Gabriel Mountains on the southwest. The valley occupies the southeastern corner of a triangular-shaped crustal block bounded by the Garlock fault zone on the northwest, the Lockhart and Helendale faults on the northeast, and the San Andreas Fault on the southwest.

GAFB is situated along high bluffs overlooking the western edge of the Mojave River floodplain (Figure 1.1). Topographic relief across most of the base is low, and is flat to gently sloping. However, there is an elevation difference of about 300 feet along the escarpment

between the bluffs and the Mojave River to the east and northeast, and topographic relief is pronounced. The nearly flat desert pavement west of the bluffs on which the Base is located is incised by the dry washes of a number of small, ephemeral streams (“arroyos”). These trend generally from southwest to north or northeast, and have cut steep channels in the bluffs along the Mojave River. The largest of the arroyos originates near the NEDA in the northern part of the Base, trends nearly due north for about 3,000 feet, and turns abruptly east, debouching from the escarpment along the bluffs just south of the Victor Valley Water Reclamation Authority (VWVRA) treatment plant.

Victor Valley is an alluvium-filled basin containing unconsolidated deposits derived from the surrounding mountains and recent deposits of the Mojave River. Several geological units have been formally characterized and mapped on a regional basis, including:

- Alluvial-fan deposits (a common feature in arid climates formed by the rapid deposition of sediments transported by fluvial and debris-flow processes, including stream deposition and flash flooding, producing compositionally and spatially heterogeneous and anisotropic deposits);
- Alluvial-plain deposits (typically areally extensive, low-permeability, fine sands, silts, and clays);
- Fluvial deposits (well-graded, unconsolidated sands, silts, and gravels deposited by the Mojave River);
- Playa and lacustrine deposits (low-permeability clays and silts, and evaporite minerals); and
- Bedrock (Paleozoic marine metasedimentary rocks, Mesozoic igneous intrusive and extrusive suites, and Tertiary terrigenous clastic sediments).

Three primary geologic units have been encountered during the subsurface investigation activities at OU1. The stratigraphically highest unit (Upper Alluvial Unit) consists of distal alluvial fan deposit of the Victorville Fan, and is composed of sands derived from a granitic provenance (“source area”). Within the Upper Alluvial Unit there also are intercalated finer-grained (silts) alluvial-fan deposits, strata of sand and silt deposited by an antecedent Mojave River, fine-grained lacustrine deposits, and locally, gravel and caliche horizons.

The Upper Alluvial Unit overlies a silt and clay unit that may have been deposited in a lake-filled basin during Pleistocene time. The unit is thickest in the western part of the Base, where 38.5 feet of silty clay was encountered in the borehole for well RZ-03 (JMM, 1992). The unit averages 25 feet in thickness across the Base, thinning to the east until it apparently pinches out near the bluffs that form the northeastern boundary of the Base.

The third primary unit, the Lower Alluvial Unit, consists of heterogeneous deposits of interbedded granitic sands with a minor volcanic component. The coarser sediments of the Lower Alluvial Unit appear to be associated with the distal edge of an alluvial fan, which originated in the mountains east of GAFB. The Lower Alluvial Unit may extend to a depth of at least 425 feet below ground surface (bgs) (Montgomery Watson, 1998a).

GAFB is located within the George Sub-Basin of the Upper Mojave River Groundwater Basin, which is bounded on the east and west by Mesozoic and Paleozoic bedrock. The George Sub-Basin is a structural trough filled with over 3,000 feet of Tertiary and Quaternary sediments.

Three primary hydrogeologic units, corresponding with the three primary geologic units described in Section 1.3.3.1 and shown in the conceptual hydrogeologic model (Figure 1.3) developed by Montgomery Watson (1998a), are present in the subsurface beneath GAFB. The Upper Aquifer is contained within the interbedded sand and silty sand of the Upper Alluvial Unit at a depth of approximately 150 to 200 feet bgs (2,620 to 2,670 feet above mean sea level [amsl]). The Upper Aquifer is perched above the silt and clay lacustrine deposits that comprise an aquitard at approximately 130 to 200 feet bgs. The groundwater potentiometric surface ("water table") within the Upper Aquifer occurs within an elevation range of approximately 2,680 to 2,760 feet amsl (Montgomery Watson, 1995). In the absence of hydraulic stresses (e.g., pumping), groundwater within the Upper Aquifer beneath GAFB flows from the south and west to the north, northeast, and northwest (Figure 1.4), with a gradient of approximately 0.003 foot per foot (ft/ft). The gradient steepens as groundwater elevations drop rapidly toward the east and northeast along the edge of the bluffs where the Upper Aquifer pinches out. The hydraulic conductivity of the unit ranges from approximately .01 feet per day (ft/day) to 48 ft/day (Montgomery Watson, 1995). Groundwater velocity within the Upper Aquifer ranges from about 0.0025 to 1.2 ft/day.

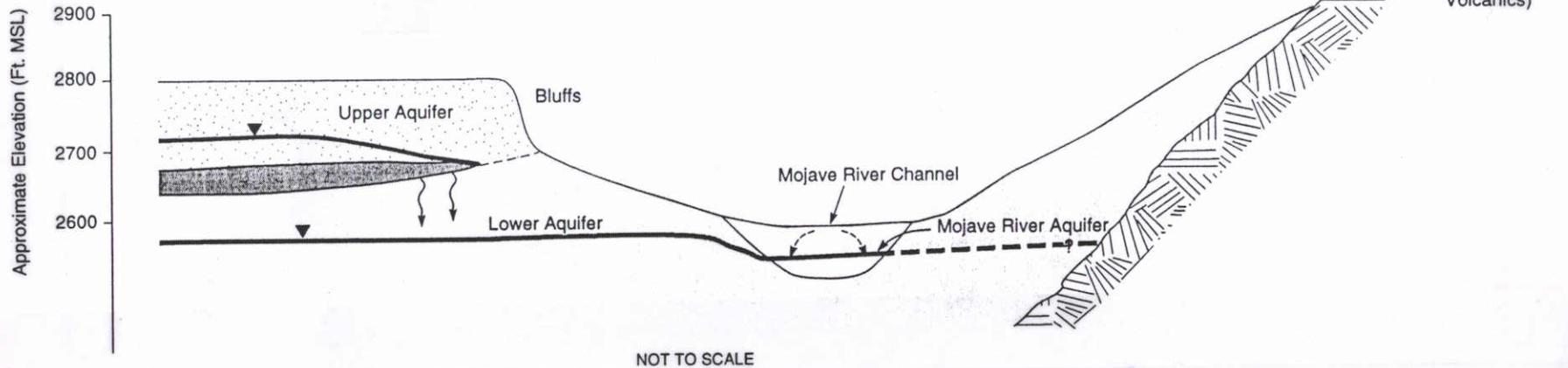
The aquitard below the Upper Aquifer is composed of brown, fine-grained sandy clay to olive, plastic silty clay, which is believed to have been deposited in a playa, or lacustrine basin that once occupied the area. The aquitard occurs between elevations of 2,650 to 2,740 feet amsl (130 to 200 feet bgs), and functions as a hydrologic barrier, restricting the vertical movement of groundwater between the Upper Aquifer and the Lower (formerly called the Regional) Aquifer. However, near the bluffs along the eastern boundary of the Base, the aquitard apparently pinches out, and the Upper Aquifer and Lower Aquifer merge, forming a single hydrostratigraphic unit (Figure 1.3).

The Lower Aquifer, the deepest hydrostratigraphic unit identified beneath GAFB, consists of interbedded sands, gravelly sands, silty sands, silts, and clays of the Lower Alluvial Unit, and is present beneath the entire Base at a depth of approximately 210 to 250 feet bgs. The groundwater potentiometric surface within the Lower Aquifer occurs within the elevation range of approximately 2,575 to 2,590 feet amsl (Montgomery Watson, 1995); therefore, a potential difference ("head") of about 100 feet exists between the Upper and Lower Aquifer systems. Groundwater within the Lower Aquifer beneath GAFB flows from southwest to northeast. The hydraulic gradient is approximately 0.0002 ft/ft in the central and western portions of the Base, and increases eastward to approximately 0.007 ft/ft as groundwater elevations drop rapidly toward the Mojave River (Figure 1.5). The hydraulic conductivity of the Lower Aquifer ranges from about 3.8 to 88 ft/day (Montgomery Watson, 1995). The rates of groundwater movement in the Lower Aquifer are estimated to range from 0.025 ft/day to 0.53 ft/day.

Based on similarities in groundwater elevations, the Lower Aquifer appears to be in hydraulic communication with the Mojave River aquifer that occupies the river channel sediments east of the Base. Historical pump-test data (Radian, 1989) indicate a hydraulic conductivity of 573 ft/day for the Mojave River sediments. The relationship between the Lower Aquifer and regional groundwater to the north, west, and south of GAFB is not well understood. However, groundwater elevation data suggest that the Lower Aquifer may be hydraulically related to the regional groundwater system southwest of the Base.

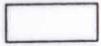
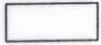
EAST

WEST



6-1

LEGEND

-  Upper Alluvial Unit
-  The Aquitard
-  Lower Alluvial Unit
-  Mojave River Channel Deposits
-  Potentiometric Surface
-  Bedrock

Approximate Location of Cross Section

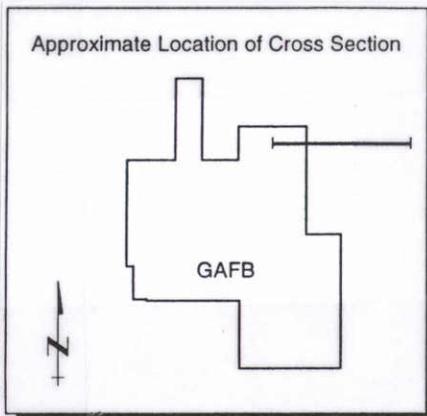


FIGURE 1.3

SIMPLIFIED CONCEPTUAL HYDROGEOLOGIC CROSS-SECTION

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Source: Montgomery Watson (1998a).

1.3.4 Nature and Extent of Contamination

The primary chemicals of concern in groundwater at GAFB OU1 are volatile organic compounds (VOCs). The results of previous investigations indicate that tetrachloroethene (PCE), TCE, 1,1,1-trichloroethane (1,1,1-TCA), chloroform, and methylene chloride are present in groundwater within the Upper and Lower Aquifer systems at concentrations that exceed currently established regulatory levels (Figures 1.6 and 1.7). Possible sources of these VOCs include the former Base landfill, Site LF-14 (IRP Site L-13) (Figure 1.2); the pesticide and paint burial site, Site DP-02 (IRP Site B-8); the old fire training area, Site FT-20 (IRP Site S-6); and the new fire training area, Site FT-19 (IRP Site S-5). A plausible (though undocumented) source of solvents in the subsurface may be releases that occurred during the cleaning of aircraft canopies during periods when aircraft were stored at GAFB (Cass, 1998).

TCE is the most widespread contaminant of concern. Other chemicals, some of which occur in groundwater at concentrations above regulatory levels, do not extend significant distances downgradient from possible source areas. TCE has been detected in groundwater in the Upper Aquifer beneath the NEDA, and in the Lower Aquifer northeast of the probable edge of the aquitard, where the two water-bearing units are thought to merge (Figures 1.6 and 1.7). TCE was detected in groundwater samples collected from the Upper Aquifer in October 1998 at concentrations ranging from below detection limits in wells near the new percolation ponds, to 381 micrograms per liter ($\mu\text{g/L}$) in the sample from well NZ-11, located approximately 3,500 feet northeast of the new percolation ponds and near extraction well EW-13 (Figure 1.8). Northeast of the boundary of GAFB near the edge of the bluff, the aquitard is thought to thin and pinch out, and groundwater of the Upper and Lower Aquifer systems commingles (Figure 1.3). Groundwater moving northeast in the Upper Aquifer, past the edge of the aquitard, is thought to mix with water in the deeper, regional system. TCE dissolved in groundwater of the Upper Aquifer thereby migrates into the Lower Aquifer (Figures 1.8 and 1.9). The highest concentration of TCE in groundwater from the Lower Aquifer ($23 \mu\text{g/L}$) was detected in samples collected in October 1998 at the northern end of the plume near monitoring well NZ-73 (Montgomery Watson, 1998d). Thus, VOCs originating at on-Base sources have migrated in groundwater past the northern Base boundary into saturated alluvial deposits that border the Mojave River northeast of GAFB.

1.3.5 Description of the Current Remediation System

The groundwater extraction and treatment system currently operating at OU1 was installed in 1991 and 1996 (Montgomery Watson, 1998a). The pump-and-treat system consists of 18 groundwater extraction wells (Figure 1.10); an influent wet-well; twin-packed, counterflow air stripping towers that remove VOCs from the influent groundwater; an effluent wet-well; associated piping, electrical power, and ancillary equipment. When the system was originally installed in 1991, extracted and treated groundwater was discharged to the arroyo immediately east of the treatment plant. Later, treated water was discharged to the STP percolation ponds, near the eastern boundary of the Base. After the three new infiltration ponds, located approximately 3,000 feet south of the treatment system, were constructed in 1997, all discharge from the treatment plant has been directed to these ponds, which are used to infiltrate the treated water back into the groundwater system. In addition to the counterflow towers, the existing treatment system includes the following components:

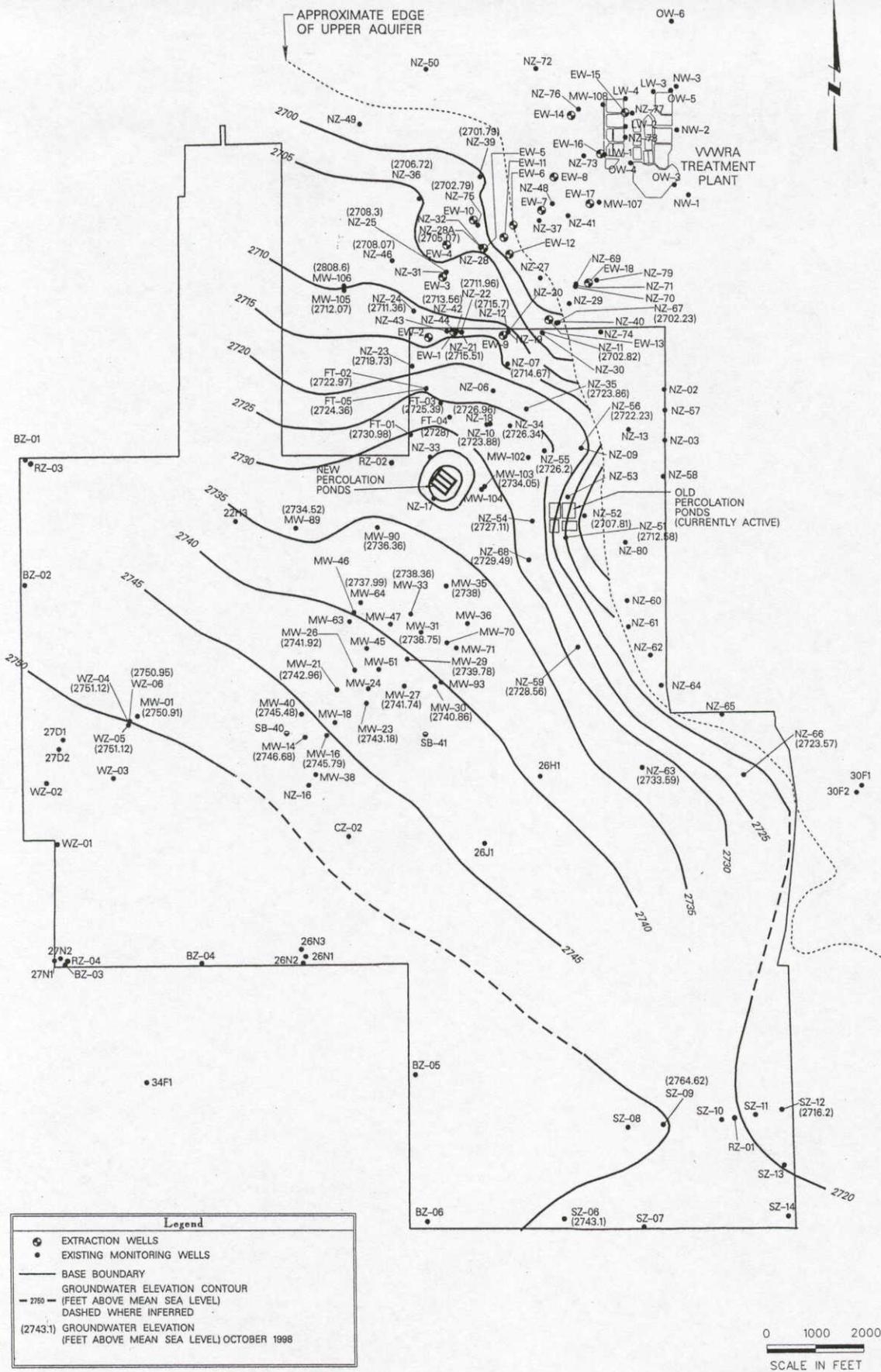


FIGURE 1.4
GROUNDWATER POTENTIOMETRIC ELEVATIONS IN THE UPPER AQUIFER AT OU1 (OCTOBER 1998)
 Remedial Process Optimization
 George AFB, California
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PARSONS ENGINEERING SCIENCE, INC.
 Denver, Colorado

Source: Montgomery Watson 1999.

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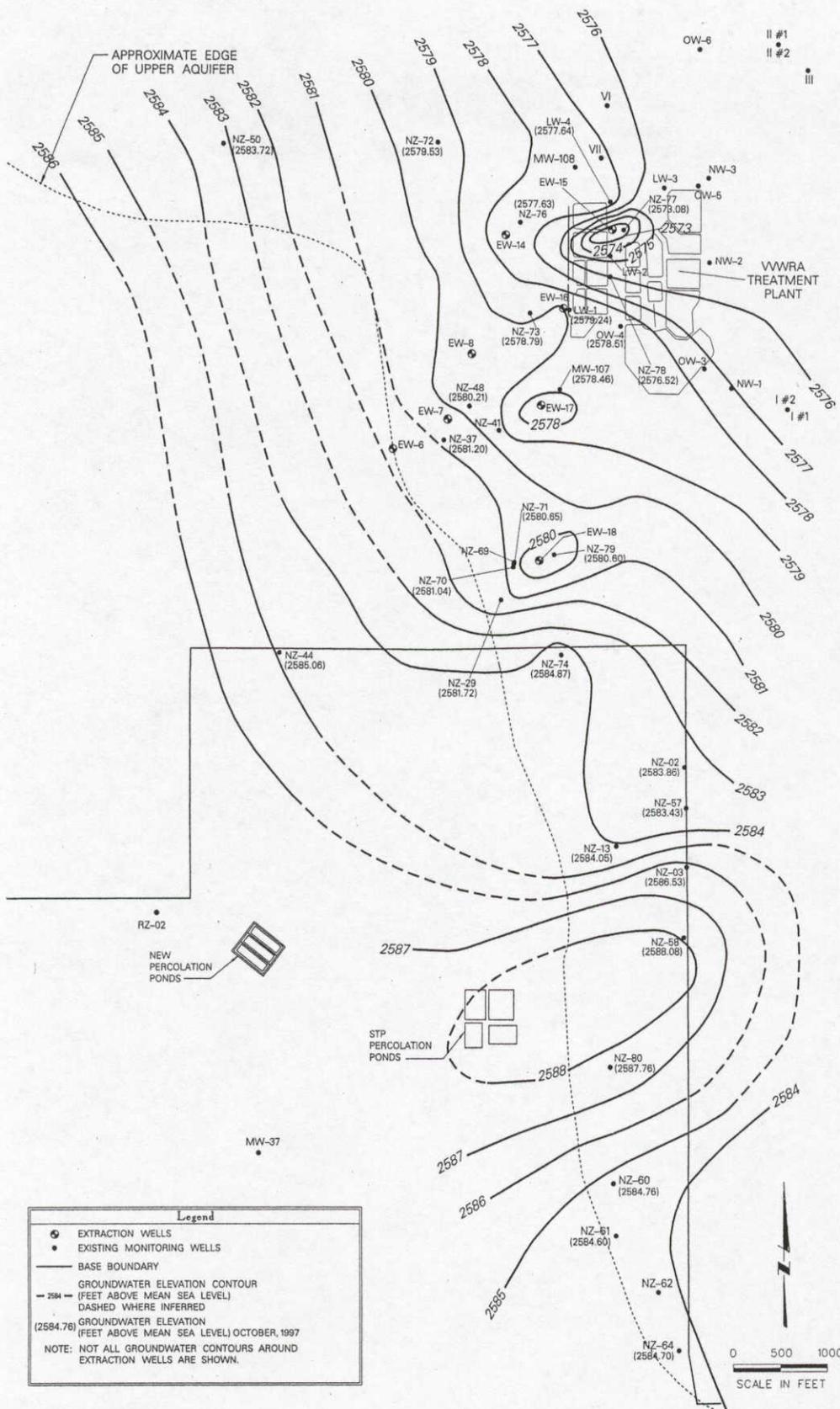


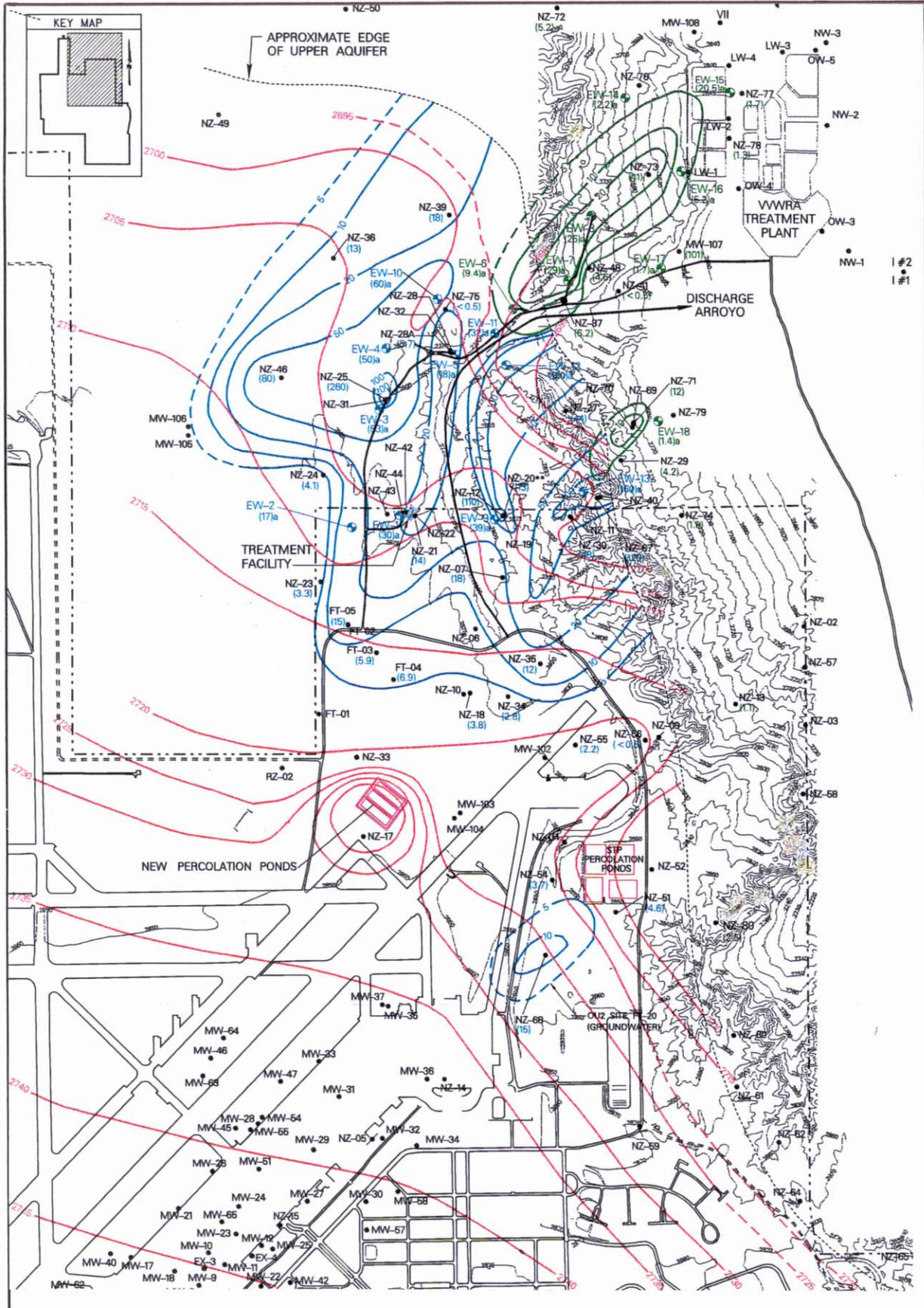
FIGURE 1.5
GROUNDWATER POTENTIOMETRIC ELEVATIONS IN THE LOWER AQUIFER AT OU1 (OCTOBER 1998)

Remedial Process Optimization
 George AFB, California

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Denver, Colorado

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0 500 1000
SCALE IN FEET

- Legend**
- (18) MONITORING WELL (TCE VALUE) ^b
 - ABANDONED WELL
 - ⊕ UPPER AQUIFER EXTRACTION WELL
 - ⊖ LOWER AQUIFER EXTRACTION WELL
 - BASE BOUNDARY
 - TCE CONCENTRATION CONTOUR (ug/L) Upper Aquifer (1097)
 - TCE CONCENTRATION CONTOUR (ug/L) Lower Aquifer (1097)
 - GROUNDWATER ELEVATION CONTOUR (FEET MSL)
- ^a EXTRACTION WELL ANALYTICAL RESULTS ARE NOT FULLY COMPARABLE TO MONITORING WELL RESULTS DUE TO LONGER EXTRACTION WELL SCREENS.
- ^b DATA QUALIFIERS APPEAR IN APPENDIX C

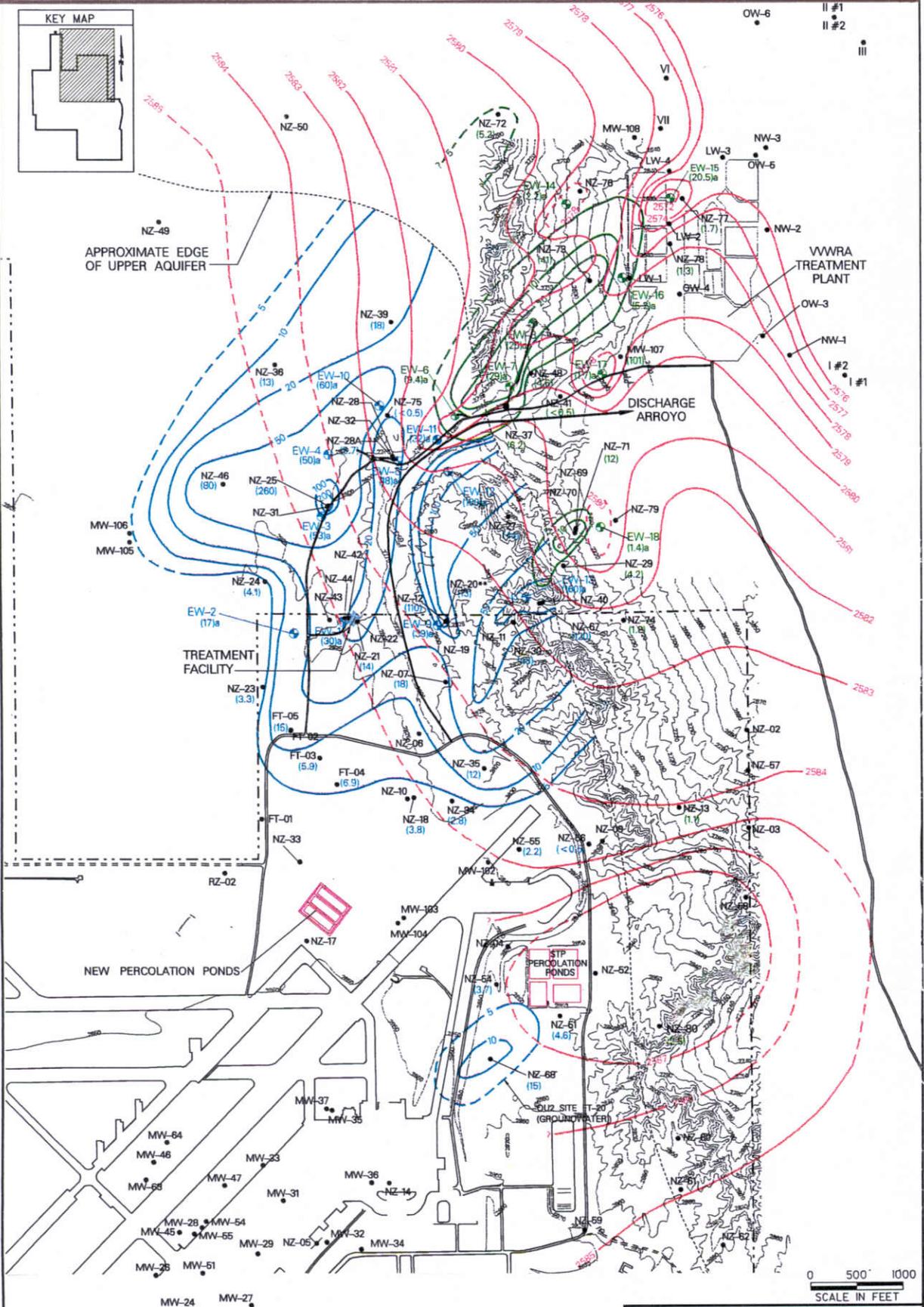
FIGURE 1.6
TCE CONCENTRATIONS AND
GROUNDWATER ELEVATIONS
IN UPPER AQUIFER AT OU1
OCTOBER 1997

Remedial Process Optimization
 George AFB, California

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 Denver, Colorado

Source: Montgomery Watson (1998a).

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0 500' 1000
SCALE IN FEET

FIGURE 1.7
TCE CONCENTRATIONS AND
GROUNDWATER ELEVATIONS
IN LOWER AQUIFER AT OU1
OCTOBER 1997
 Remedial Process Optimization
 George AFB, California
PARSONS
PARSONS ENGINEERING SCIENCE, INC.
 Denver, Colorado

- Legend**
- (16) MONITORING WELL (TCE VALUE) b
 - ABANDONED WELL
 - UPPER AQUIFER EXTRACTION WELL
 - LOWER AQUIFER EXTRACTION WELL
 - BASE BOUNDARY
 - 5 TCE CONCENTRATION CONTOUR (ug/L) Upper Aquifer (1097)
 - 5 TCE CONCENTRATION CONTOUR (ug/L) Lower Aquifer (1097)
 - GROUNDWATER ELEVATION CONTOUR (FEET MSL)
- a EXTRACTION WELL ANALYTICAL RESULTS ARE NOT FULLY COMPARABLE TO MONITORING WELL RESULTS DUE TO LONGER EXTRACTION WELL SCREENS.
 b DATA QUALIFIERS APPEAR IN APPENDIX C

Source: Montgomery Watson (1998a).

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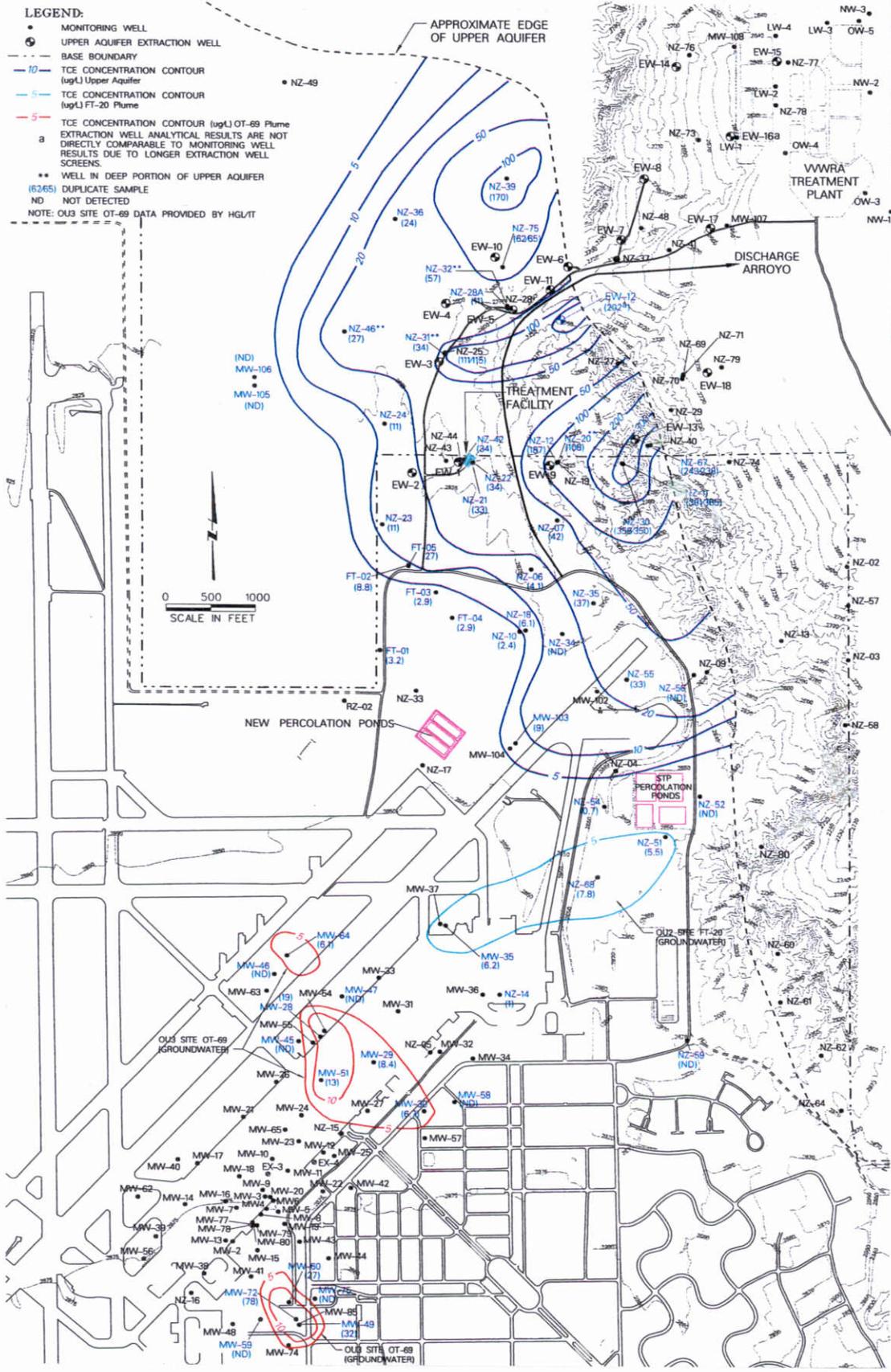


FIGURE 1.8
**TCE CONCENTRATIONS
 IN UPPER AQUIFER
 AT OU1 (OCTOBER 1998)**

Remedial Process Optimization
 George AFB, California

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 Denver, Colorado

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LEGEND

- EW-6 OU 1 EXTRACTION WELL
- - - - BASE BOUNDARY
- - - - PIPELINE
- ROAD

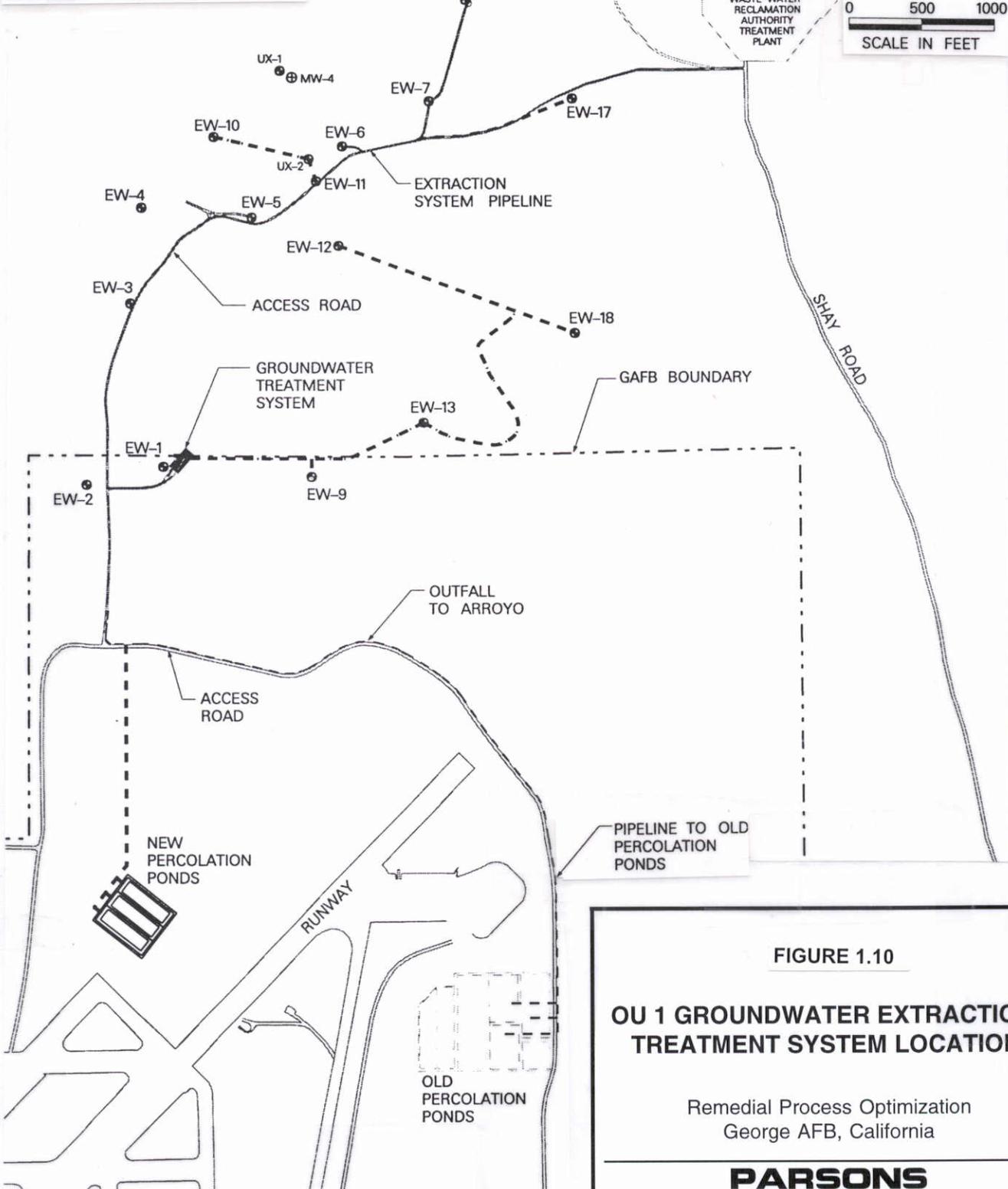


FIGURE 1.10

**OU 1 GROUNDWATER EXTRACTION/
TREATMENT SYSTEM LOCATION**

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Denver, Colorado

Source: The Thomas Guide, (1998c).

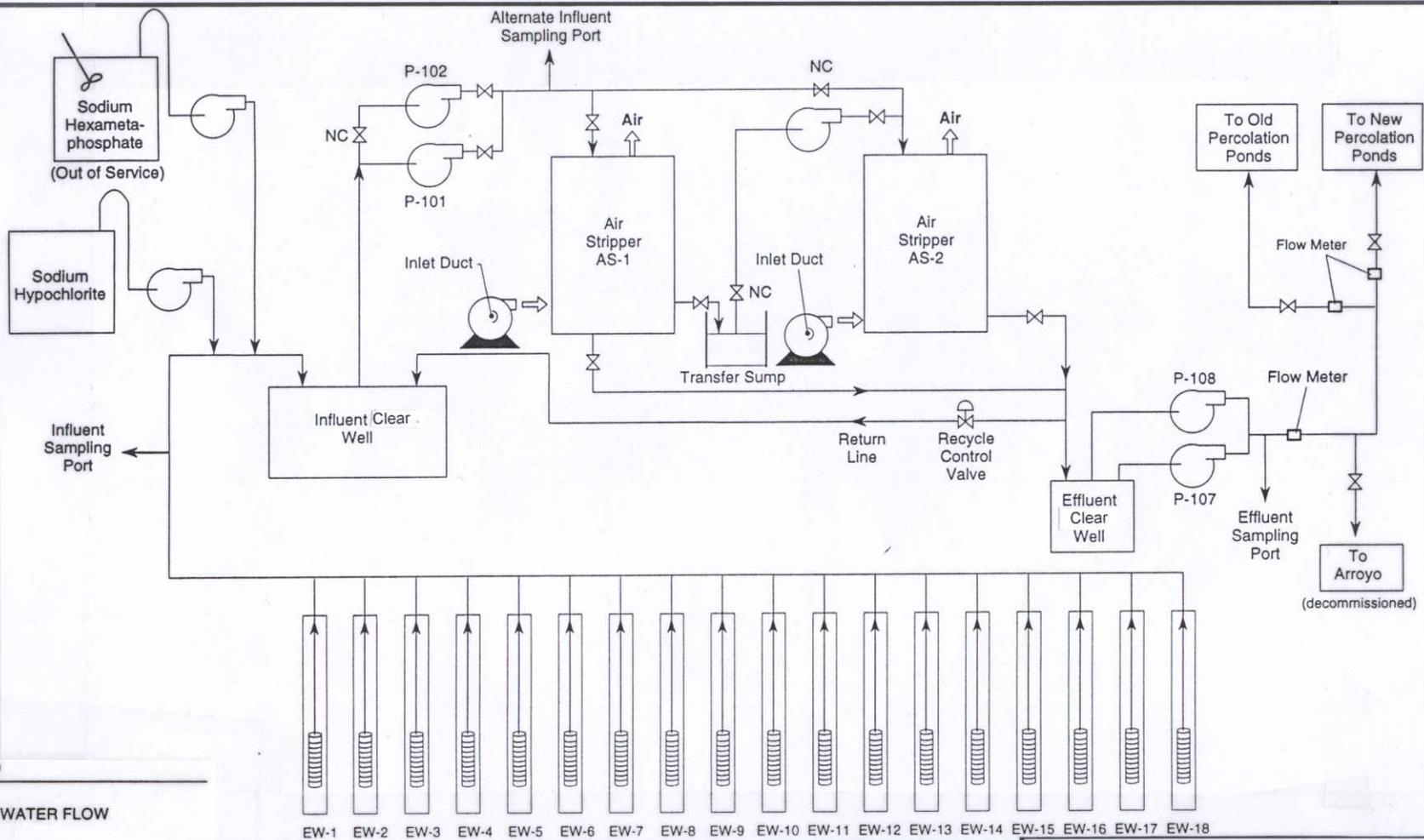
- Pretreatment sodium hypochlorite to control biofouling in the air strippers;
- Transfer sumps;
- Blowers;
- Booster pumps; and
- Pressure conduits.

The system is designed to remediate VOC-contaminated groundwater. The current (April 1999) average extraction and treatment rate is about 860 gallons per minute (gpm) (Montgomery Watson, 1999c). The mean influent TCE concentration detected in water samples from the influent wet-well is generally less than about 10 µg/L. The TCE concentrations in the effluent stream directed to the infiltration ponds are below detection limits (Montgomery Watson, 1998c). The existing groundwater extraction and treatment system and process flows are shown schematically on Figure 1.11. Of the 18 wells comprising the current groundwater extraction system, 10 wells completed in the Upper Aquifer are intended to accomplish removal of TCE mass, and 8 wells completed in the Lower Aquifer are intended to contain plume migration (Montgomery Watson, 1999c).

The system was constructed in two phases. The first phase (nine wells, an air stripper, and discharge to the old STP percolation ponds and/or an arroyo) was completed in 1991; the second phase (an additional nine wells, an expanded treatment system, and discharge to new percolation ponds) was begun in 1996 (Montgomery Watson, 1999c). In October 1998, six of the Regional (Lower) Aquifer extraction wells were in operation, and the total groundwater extraction rate at that time was about 525 gpm. In April 1999, the final two extraction wells in the Lower Aquifer (wells EW-8 and EW-16) were placed on-line, increasing the maximum system extraction rate capacity to about 860 gpm.

The design production rates for the 18 wells in the current system range from 2 gpm to 160 gpm; the actual production rates of wells completed in the Upper Aquifer (2 to about 50 gpm) are generally much lower than the rates of wells completed in the Lower Aquifer (20 to 200 gpm). The average groundwater extraction and treatment rate reported for the first quarter of 1999 was about 580 gpm (Montgomery Watson, 1999c); and an instantaneous extraction and treatment rate of 748 gpm was reported for the monitoring event of April 1999 (Montgomery Watson, 1999e). Recently-reported average extraction and treatment rates have ranged from 540 gpm (Montgomery Watson, 1999a) to over 700 gpm (Montgomery Watson, 1999d). Extracted groundwater is pumped through a pipeline that generally parallels the northern arroyo to the treatment plant, at an elevation of about 2,825 feet amsl, near the northern boundary of the Base (Figure 1.10). Treated water is pumped through another pipeline to the infiltration ponds, 3,000 feet south of the treatment plant, at an elevation of about 2,850 feet amsl. The total elevation difference between the infiltration ponds and the extraction well at lowest elevation (well EW-15, west of the VVWRA treatment plant, at an elevation of about 2,640 feet amsl) is about 210 feet. This represents a substantial gravitational potential difference (“head”) that must be overcome by pumping extracted groundwater uphill for treatment and disposal.

In May 1999, after reviewing the results of the October 1998 groundwater monitoring report (Montgomery Watson, 1998d), USEPA requested that extraction wells EW-14, EW-15, EW-16, EW-17, and EW-18, completed in the Lower Aquifer northeast of the Base boundary, be shut



LEGEND

- WATER FLOW
- ↻ AIR FLOW
- PUMP
- BLOWER
- EW EXTRACTION WELL
- SUBMERSIBLE PUMP
- VALVE
- CONTROL VALVE
- NC NORMALLY CLOSED

EW-1 EW-2 EW-3 EW-4 EW-5 EW-6 EW-7 EW-8 EW-9 EW-10 EW-11 EW-12 EW-13 EW-14 EW-15 EW-16 EW-17 EW-18

FIGURE 1.11

OU 1 EXTRACTION/TREATMENT SYSTEM SCHEMATIC

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down (Montgomery Watson, 1999b). Two general reasons were provided by USEPA for requesting cessation of pumping in these wells:

- The concentrations of TCE in the effluent streams from the five wells have been below the 5- $\mu\text{g/L}$ TCE cleanup objective specified in the ROD.
- The quantities of discharge from the treatment plant to the infiltration ponds have increased substantially since the five Lower Aquifer extraction wells were put into production in 1996 through 1999. The increased discharge has caused problems associated with steadily increasing groundwater potentiometric elevations (a groundwater “mound”) beneath the infiltration ponds, notably partial flooding of a nearby soil-vapor-extraction system, and changes in local hydraulic gradients that could cause TCE to migrate into previously uncontaminated parts of the Upper Aquifer.

In June 1999, the Remedial Project Management Group for GAFB concurred that pumping would temporarily be discontinued in Lower Aquifer extraction wells EW-6, EW-14, EW-15, EW-16, and EW-17, and a revised monitoring program was instituted to more thoroughly evaluate trends in plume migration and containment in the Lower Aquifer in detail (Montgomery Watson, 1999b). Because the shutdown is described as “temporary”, these wells could be placed back in service at any time. Therefore, these wells were included in the RPO evaluation of the system.

1.3.6 Current Monitoring Program

Groundwater monitoring at GAFB OU1 of the TCE plume is conducted semiannually, to provide information regarding chemical and hydraulic (gradient) conditions within, and down-gradient of the plume. The groundwater-monitoring program is intended to provide water level and analytical data for use in ensuring compliance with requirements of the ROD, and for evaluating the overall effectiveness of the extraction system. Key components of the groundwater extraction and treatment system are monitored monthly, enabling evaluation of overall system performance.

Currently, approximately 50 monitoring wells at GAFB OU1 are sampled during semiannual monitoring events conducted in April and October (Table 1.1, based on information provided by Montgomery Watson on March 15, 1999). Groundwater samples were collected by Montgomery Watson during the April 1999 monitoring event from a total of 47 monitoring wells associated with OU 1. These wells were selected by Montgomery Watson, GAFB, and regulatory agency staff representing the USEPA and the Lahontan Regional Water Quality Control Board (RWQCB) during discussions regarding modifications to the sampling and analytical protocols for GAFB OU1, conducted to update the Basewide sampling and analysis plan (SAP). Water-level measurements and groundwater samples are collected from these wells during each monitoring event, and samples are analyzed for VOCs by USEPA Method SW8260B (Montgomery Watson, 1998d).

Groundwater samples also are collected from most of the groundwater extraction wells during each semiannual monitoring event. During the October 1998 event, samples were collected from 16 of the 18 extraction wells; and in the April 1999 sampling event, samples were collected from 2 of the extraction wells (Montgomery Watson, 1999a and 1999c). Samples also are collected from sampling ports in the influent and effluent lines of the treatment system (Figure 1.11).

TABLE 1.1
CURRENT GROUNDWATER MONITORING PROGRAM AT OU1
Monitoring Event of April - May 1999
REMEDIAL PROCESS OPTIMIZATION, OU-1
GEORGE AIR FORCE BASE, CALIFORNIA

Sampling Location	Operable Unit(s)	Site / Area	Aquifer Monitored	Purge Method	Laboratory Analyses	
					VOCs ^{a/}	Metal Landfill Surrogate ^{b/}
EW-12*	OU 1	-	U	MSP ^{c/}	✓	
FT-01	OU 1	-	U	MSP	✓	
FT-02	OU 1	-	U	MSP	✓	
FT-03	OU 1	-	U	MSP	✓	
FT-05	OU 1	-	U	MSP	✓	
FT-06	OU 1	-	U	MSP	✓	
LW-1	OU 1	-	L	MSP	✓	
MW-103	OU 1	-	U	MSP	✓	
MW-35	OU 1	-	U	MSP	✓	
MW-37b	OU 2	Background	L	MSP	✓	✓
NZ-07	OU 1	-	U	MSP	✓	
NZ-10	OU 1	-	U	MSP	✓	
NZ-11	OU 1	-	U	MSP	✓	
NZ-12	OU 1	-	U	MSP	✓	
NZ-13	OU 1	-	U	MSP	✓	
NZ-18	OU 1	-	U	MSP	✓	
NZ-20	OU 1	-	U	MSP	✓	
NZ-21	OU 1	-	U	MSP	✓	
NZ-24	OU 1	-	U	MSP	✓	
NZ-25	OU 1	-	U	MSP	✓	
NZ-27**	OU 1	-	U	MSP	✓	
NZ-29	OU 1	-	L	MSP	✓	
NZ-31	OU 1	-	U	MSP	✓	
NZ-32	OU 1	-	U	MSP	✓	
NZ-34	OU 1	-	U	MSP	✓	
NZ-35	OU 1	-	U	MSP	✓	
NZ-36	OU 1	-	U	MSP	✓	
NZ-37	OU 1	-	L	MSP	✓	
NZ-39	OU 1	-	U	MSP	✓	
NZ-46	OU 1	-	U	MSP	✓	
NZ-48	OU 1	-	L	MSP	✓	
NZ-51	OU 1	-	U	MSP	✓	

TABLE 1.1 (continued)
CURRENT GROUNDWATER MONITORING PROGRAM AT OU1
Monitoring Event of April - May 1999
REMEDIAL PROCESS OPTIMIZATION, OU-1
GEORGE AFB, CALIFORNIA

Sampling Location	Operable Unit(s)	Site / Area	Aquifer Monitored	Purge Method	Laboratory Analyses	
					VOCs	Metal Landfill Surrogates
NZ-52	OU 1	-	U	MSP	✓	
NZ-54	OU 1	-	U	MSP	✓	
NZ-55	OU 1	-	U	MSP	✓	
NZ-56	OU 1	-	U	MSP	✓	
NZ-58	OU 1/OU 3	LF-14	L	MSP	✓	✓
NZ-67	OU 1	-	U	MSP	✓	
NZ-68	OU 1	-	U	MSP	✓	
NZ-70	OU 1	-	L	MSP	✓	
NZ-72	OU 1	-	L	MSP	✓	
NZ-73	OU 1	-	L	MSP	✓	
NZ-74	OU 1	-	L	MSP	✓	
NZ-75	OU 1	-	U	MSP	✓	
NZ-76	OU 1	-	L	MSP	✓	
NZ-77	OU 1	-	L	MSP	✓	
NZ-79	OU 1	-	L	MSP	✓	
RZ-02	-	Background	L	MSP	✓	✓

^aVOCs - Volatile Organic Compounds analyzed by SW8260B

^bLandfill metal surrogates include nitrate, sulfate, chloride, and total dissolved solids (TDS)

Nitrate, sulfate, and chloride analyzed by SW9056

TDS analyzed by EPA Method 160.1

^cMSP - Modified Slow Purge

Source: Montgomery Watson, 1999

SECTION 2

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 model provides the basis for understanding the occurrence and movement of water and contaminants at the site, and incorporates the geologic and hydrologic information necessary to guide 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, no subsequent activities or level of effort will generate conclusions that can be used with any confidence. At a minimum, the conceptual hydrogeologic model 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 elevation and configuration of the groundwater potentiometric surface(s);
- Surface drainage configuration, 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; and
- Source(s) of contaminants, and the direction(s) and rate(s) of contaminant migration.

The conceptual hydrogeologic model of GAFB OU1 (Figure 3.1) developed by JMM (1992) and revised by Montgomery Watson (1994), and subsequently referred to as the ROD conceptual hydrogeologic model, presumably represents the framework within which the current remediation system was conceived, evaluated, and designed. Examination and, if necessary, refinement of the conceptual hydrogeologic model presented in the ROD is therefore a critical element of the RPO evaluation.

2.1 CONCEPTUAL HYDROGEOLOGIC MODEL OF GAFB OU1 AS PRESENTED IN THE ROD

The conceptual hydrogeologic model of GAFB OU1 (Figure 1.3), as presented in the RI report (JMM, 1992) and ROD (Montgomery Watson, 1994) incorporates the following principal features:

- The groundwater system beneath GAFB OU1 consists of an Upper Aquifer and a Lower Aquifer, which are hydrologically distinct water-bearing units (Figure 1.3).
- The Upper Aquifer is a zone of saturated, moderately permeable interbedded silts, clays, and poorly sorted sands (Figures 2.1 through 2.4). The potentiometric surface in the Upper Aquifer is about 100 feet bgs across much of the Base; potentiometric elevations range from about 2,750 feet amsl, in the southwestern part of the Base, to about 2,700 feet amsl along the bluffs that border the Mojave River floodplain (Figure 1.4). The saturated thickness of the Upper Aquifer ranges from about 20 to 40 feet. Groundwater in the Upper Aquifer moves from south to north or northeast, down a gradient of about 0.003 ft/ft.
- The Lower, or "Regional" Aquifer is a saturated zone of permeable, interbedded sands, gravelly sands, and silts at some depth beneath the Upper Aquifer (Figures 2.1 through 2.4). The Lower Aquifer is areally extensive, and is in hydraulic communication with saturated alluvial deposits along the Mojave River. Groundwater potentiometric elevations within the Lower Aquifer are generally about 120 to 150 feet lower than potentiometric elevations in the Upper Aquifer, and range from 2,590 feet amsl in the southwestern part of the Base, to about 2,580 feet amsl beneath the bluffs (Figure 1.5). The saturated thickness of the Lower Aquifer is probably greater than several hundred feet. Groundwater in the Lower Aquifer beneath GAFB moves from southwest to northeast, down a gradient of about 0.001 ft/ft.
- The Upper and Lower Aquifers are separated by a clay/silt aquitard, a low-permeability stratum (or series of interbedded or intercalated strata) that is present in the hydrostratigraphic column between the upper and lower saturated units (Figures 1.3, 2.1 through 2.4). The total thickness of the aquitard ranges from about 20 to 40 feet; south and west of GAFB, the aquitard appears to be regionally extensive, and prevents hydraulic communication between the Upper and Lower Aquifers. Near the bluffs along the Mojave River floodplain, north and northeast of the NEDA, the aquitard pinches out, and the upper and lower saturated units are in hydraulic communication.
- Recharge to the Upper Aquifer may occur from the gullies and arroyos that function as channels of intermittent streams that collect water during the sporadic, but intense precipitation events characteristic of the Mojave Desert. The Upper Aquifer discharges to the Lower Aquifer beneath the bluffs along the Mojave River, where groundwater "cascades" over the edge of the aquitard from the Upper Aquifer into the Lower Aquifer (Figure 1.3).
- With the exception of groundwater moving from the Upper Aquifer, the source(s) of recharge to the Lower Aquifer are not specified. Groundwater from the Lower Aquifer eventually discharges to the Mojave River, which gains flow near GAFB.

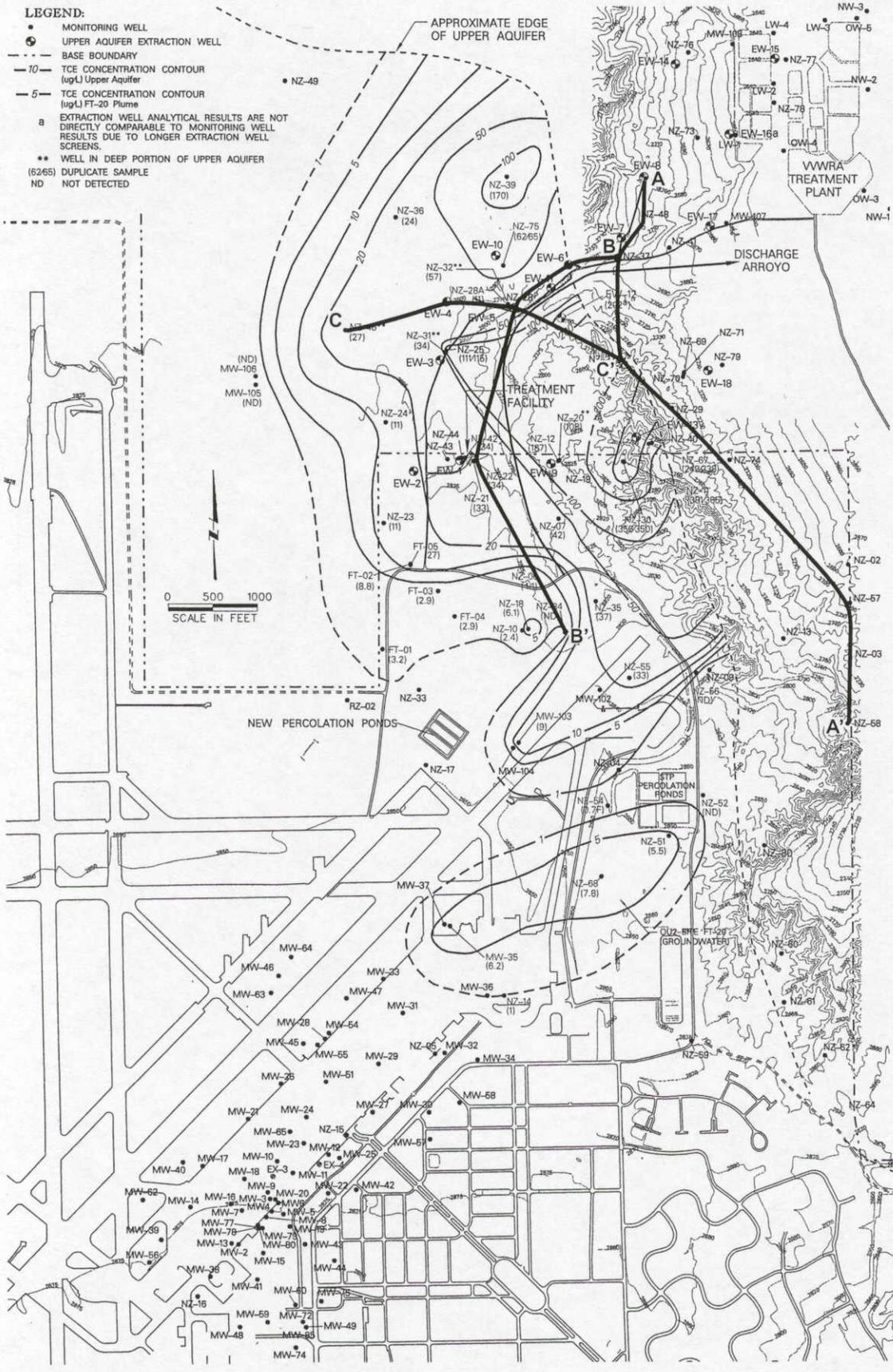
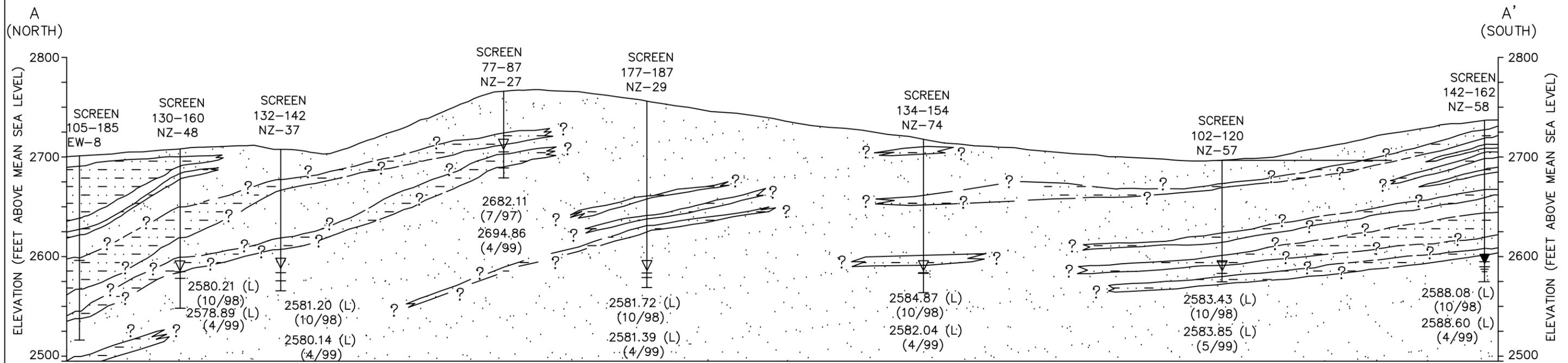


FIGURE 2.1
LOCATIONS OF HYDROGEOLOGIC CROSS-SECTION TRACES
 Remedial Process Optimization
 George AFB, California
PARSONS
 PARSONS ENGINEERING SCIENCE, INC.
 Denver, Colorado

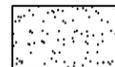
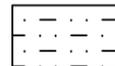
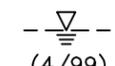
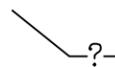
Source: Montgomery Watson 1999d.

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LEGEND

-  SAND OR SILTY SAND
-  SILTY CLAY
-  GROUNDWATER POTENTIOMETRIC SURFACE ELEVATION IN UPPER AQUIFER (DATE)
-  (L) GROUNDWATER POTENTIOMETRIC SURFACE ELEVATION IN LOWER AQUIFER (DATE)
-  MONITORING OR EXTRACTION WELL WITH SCREENED INTERVAL
-  LITHOLOGIC CONTACT DASHED WHERE INFERRED; QUERIED WHERE UNCERTAIN

NOTE:
ALL ELEVATIONS SHOWN ARE IN NGVD 29. TO CONVERT TO NAVD 88 ADD 3.32 FEET.

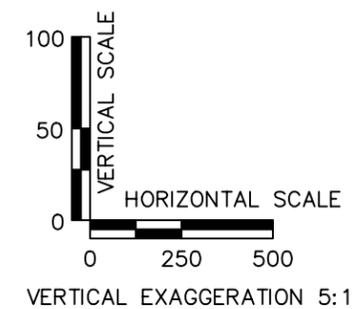


FIGURE 2.2

GENERALIZED CROSS-SECTION A-A'

Remedial Process Optimization
George Air Force Base, California

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Denver, Colorado

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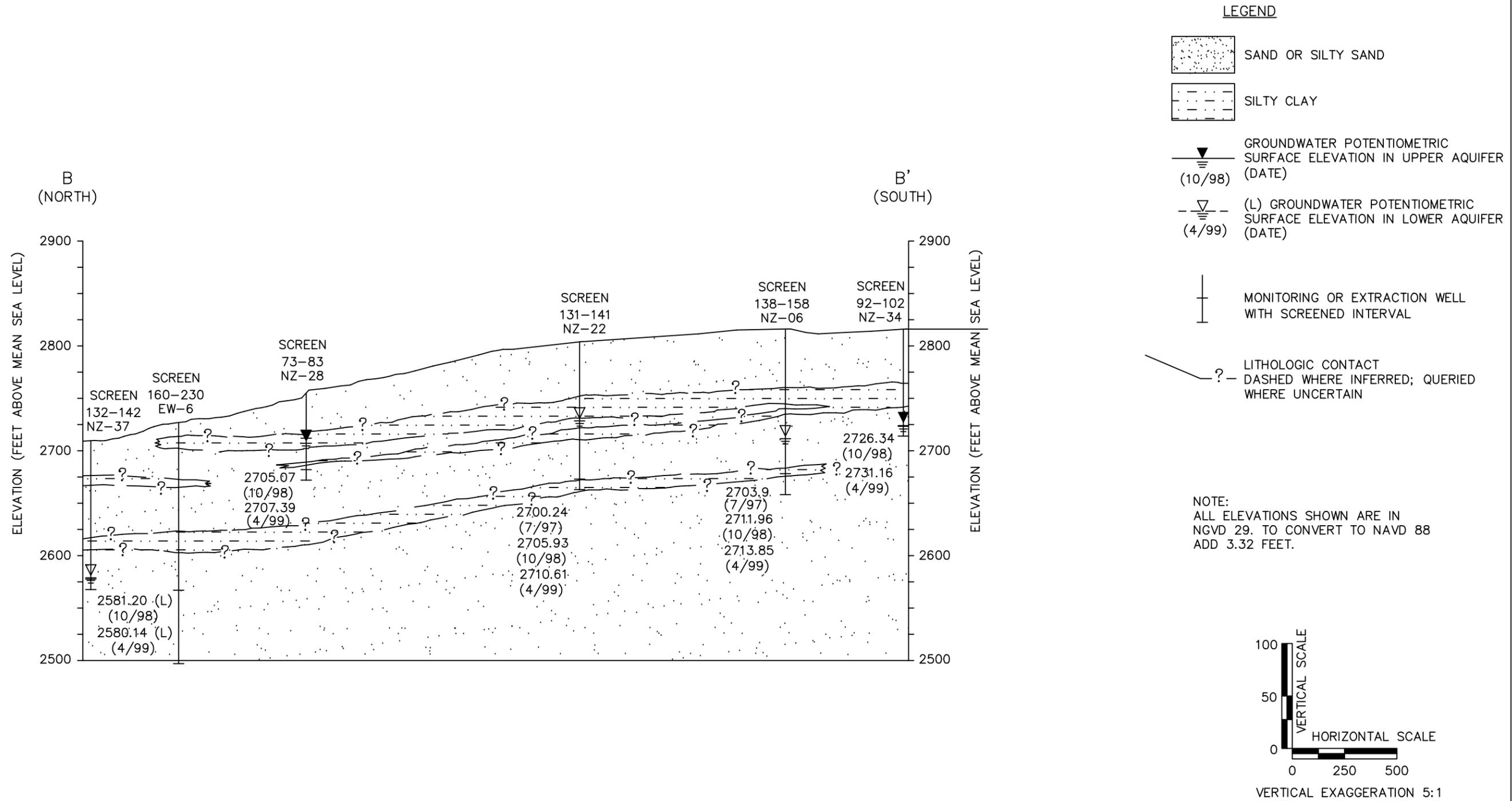


FIGURE 2.3

GENERALIZED CROSS-SECTION B-B'

Remedial Process Optimization
George Air Force Base, California

PARSONS ENGINEERING SCIENCE, INC.

Denver, Colorado

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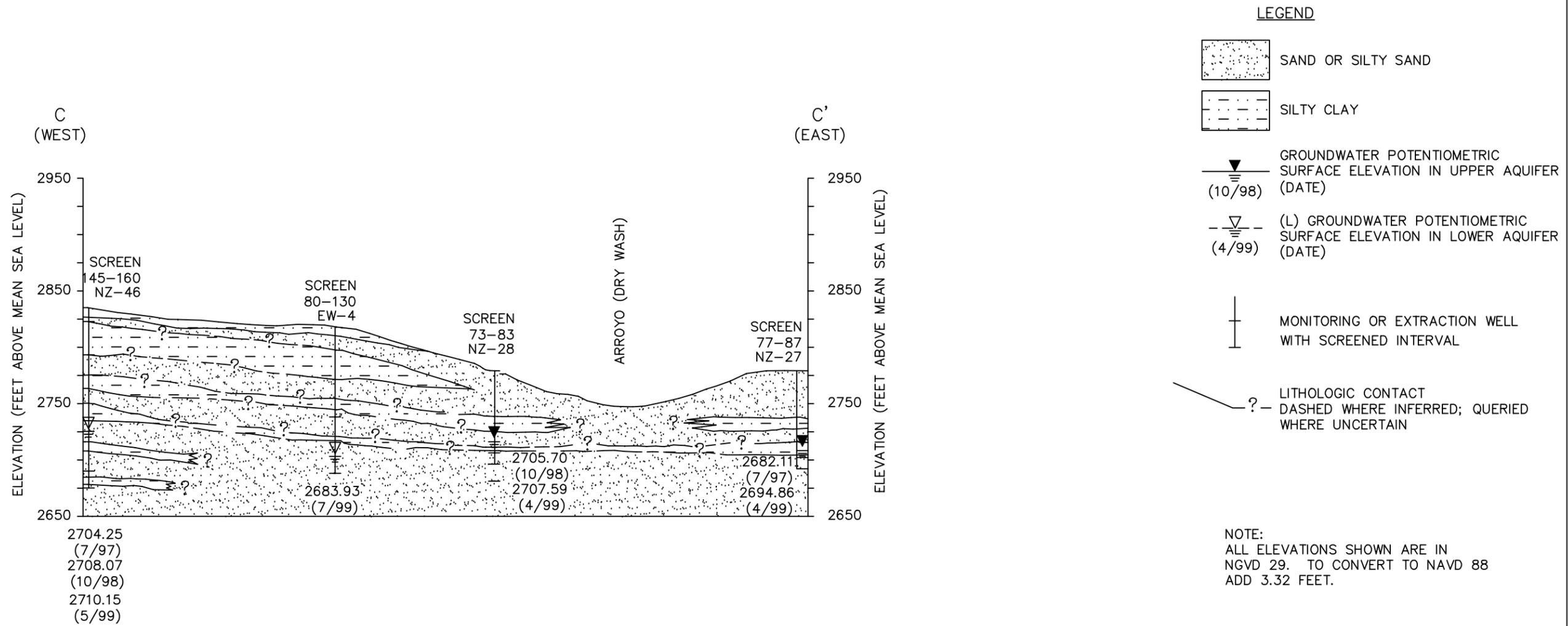


FIGURE 2.4
GENERALIZED CROSS-SECTION C-C'
Remedial Process Optimization
George Air Force Base, California
PARSONS ENGINEERING SCIENCE, INC.
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- The source of TCE in groundwater of the Upper Aquifer is not currently known. However, several former waste-disposal sites within the NEDA are suspected to be potential source areas.

Several inconsistencies are apparent in the interpretation of the available hydrogeologic and chemical information, suggesting that refinement of the ROD conceptual hydrogeologic model may be appropriate. The nature of the hydrologic interactions between the groundwater systems in the Upper and Lower Aquifers, and the occurrence and migration of VOCs, are the issues of primary concern.

Interpretation of the ROD conceptual model indicates that the aquitard separating the Upper and Lower Aquifers does not extend in the subsurface to the bluffs northeast and east of GAFB OU1 (Figure 2.5). In the absence of recharge, the potentiometric surface of the Upper Aquifer near the terminus of the aquitard will develop a convex profile, typical of “perched” groundwater systems (Freeze and Cherry, 1979). Recent information obtained from carbon-dating of groundwater (Izbicki *et al.*, 1995) indicates that groundwater in the Upper Aquifer is greater than 10,000 years old; while groundwater in the Lower Aquifer was recharged less than 2,400 years before the present. The results of other investigations (Radian, 1989; Martin, 1994), including examination of chloride profiles in the unsaturated zone near GAFB (Izbicki *et al.*, in press) indicate that virtually no precipitation recharge to the Upper Aquifer system is occurring at the present time. Cumulatively, several observations suggest that groundwater in the Upper Aquifer is probably “perched”, with an upper potentiometric surface as conceptually represented in Figure 2.5:

- Potentiometric elevations in the Upper Aquifer are generally about 100 feet higher than potentiometric elevations in the Lower Aquifer.
- Groundwater in the Upper Aquifer is at least 8,000 years older than groundwater in the Lower Aquifer (Izbicki *et al.*, 1995).
- Chloride profiles in the unsaturated zone (Izbicki *et al.*, in press) indicate that little or no recharge to the Upper Aquifer is occurring under current climatic conditions. Limited recharge to the Upper Aquifer may occur as water infiltrates through the beds of intermittent streams, discharging through washes or arroyos during intense precipitation events.
- If the Upper and Lower Aquifers were in good hydraulic communication along the edge of the aquitard, all the groundwater in the Upper Aquifer would eventually drain into the Lower Aquifer, in the absence of recharge to the Upper Aquifer. This has not occurred, through a period of at least 10,000 years. Because little or no recharge to the Upper Aquifer is occurring, the hydraulic communication between the Upper and Lower Aquifers must therefore be limited.

Groundwater movement in the Upper Aquifer occurs in accordance with the Dupuit-Forchheimer theory of flow in an unconfined system bounded by a free surface (Freeze and Cherry, 1979):

$$Q = K \times h(l) \times \frac{dh}{dl}$$

where

Q = discharge through a unit cross-section of aquifer (L^3/T),

K = hydraulic conductivity of aquifer material (L/T),

$h(l)$ = the elevation of the phreatic surface above the aquitard at point l (L), and

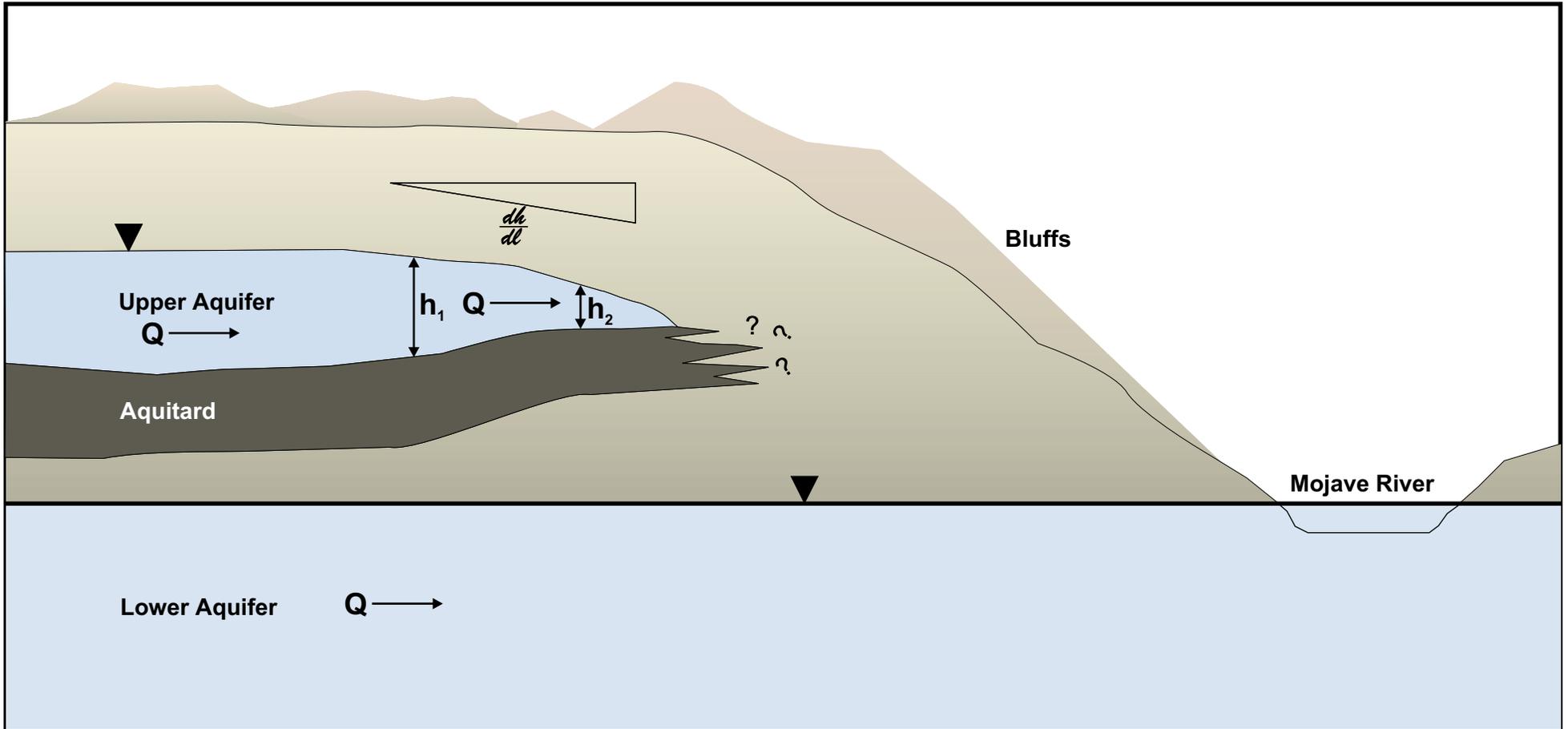
dh/dl = the groundwater hydraulic gradient at point l (L/L).

The phreatic surface of a perched groundwater system develops a convex profile near its edge, because sufficient groundwater moves out of the perched system to reduce the cross-sectional area of the saturated section near the edge. This process continues until the hydraulic gradient of the saturated zone, and the matric potential of the adjacent unsaturated zone, are in equilibrium (Freeze and Cherry, 1979). This produces a situation in which the elevation of the phreatic surface above the aquitard becomes progressively lower as the edge is approached (h_1 is greater than h_2 , and so on; Figure 2.5), eventually becoming zero. Groundwater discharge through a cross-section of zero area is not possible; therefore, groundwater flow over the “edge” of the aquitard, given the apparent configuration of the phreatic surface in the Upper Aquifer, probably does not occur in the manner portrayed in the conceptual model presented in the ROD (Figure 1.3). However, because the number of groundwater monitoring wells completed in the Upper Aquifer near the bluffs is limited, the actual configuration of the potentiometric surface in the Upper Aquifer near the edge of the perched system is not known.

The configuration of the groundwater potentiometric surface in the Upper Aquifer displays significant hydraulic gradients, (Figure 1.4) indicating that some groundwater movement is occurring; and the detection of TCE in groundwater of the Lower Aquifer (Figures 1.8 and 1.9) supports the hypothesis that the Upper and Lower Aquifer systems are in hydraulic communication, at least locally. However, if groundwater containing TCE could in fact “cascade” over the “edge” of the aquitard at many points, TCE should be present in groundwater of the Lower Aquifer at a number of locations downgradient from the “edge” of the aquitard. This is not the case – TCE has been detected only in groundwater within restricted areas of the Lower Aquifer, primarily in that part of the Lower Aquifer beneath the mouth of the north-trending arroyo, near the VVWRA treatment facility (Figure 1.9). Therefore, the nature of the connection between the two systems is not adequately explained by the conceptual model presented in the ROD (1994).

The distribution of TCE in groundwater of the Upper and Lower Aquifer systems (Figures 1.8 and 1.9) is not typical of the distribution of a contaminant that originated at a discrete source area and migrated as a non-conservative (“retarded”) constituent via advective transport mechanisms (Gillham and Cherry, 1982; Reilly *et al.*, 1987; USEPA, 1989). A “reactive” constituent can sorb to the aquifer matrix (Appendix B), and is dispersed during migration in groundwater. This causes the concentrations of a contaminant to change with transport distance from a contaminant source area. Usually, concentrations are highest near the contaminant source, and decrease with increasing migration distance downgradient from the source area. The history of chemical discharge also can affect the distribution of contaminant concentrations, so that in some situations it is possible for concentrations to be higher at downgradient locations than at the source area. This can indicate that the source area has become relatively depleted in contaminant mass through time, as a result of leaching and migration of chemicals. This process could explain the distribution of chemicals along flowpaths originating at the NEDA (an area of

2-13



Not To Scale

FIGURE 2.5
CONCEPTUAL
HYDROGEOLOGIC MODEL OF
UPPER AND LOWER AQUIFERS
(DETAIL)

Remedial Process Optimization
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relatively low TCE concentrations) and proceeding north-northeast to an area of relatively higher TCE concentrations, approximately along a line connecting monitoring wells NZ-18, NZ-07, NZ-30, NZ-11, and NZ-67 (Figures 1.4, 1.6, and 1.8). However, a second area within which groundwater contains TCE at relatively elevated concentrations is present in the vicinity of well NZ-39, near the edge of the bluffs north of the Base boundary (Figure 1.8). The configuration of the potentiometric surface in the Upper Aquifer (Figure 1.4) indicates that groundwater flowpaths originating at the NEDA, or at other known or suspected sources of TCE, do not pass through this area. The source of TCE in groundwater of the Upper Aquifer north of the arroyo is therefore unknown.

Wells NZ-27 and EW-12 are completed in the Upper Aquifer, near the presumed “edge” of the aquitard (Figure 1.8). Elevated concentrations of TCE (44 µg/L to over 200 µg/L) have historically been detected in groundwater samples from these wells (Table 2.1). If groundwater, containing TCE, were “cascading” from the Upper Aquifer into the Lower Aquifer near these points, the concentrations of TCE in groundwater within the Lower Aquifer should be relatively elevated beneath the bluffs, decreasing with distance away from the bluffs. In fact, the concentrations of TCE detected in groundwater samples collected from wells NZ-37 and NZ-48 in October 1998 (Figure 1.9 and Table 2.1) were relatively low (8.9 µg/L and 2 µg/L, respectively). The concentration of TCE in the sample from downgradient well NZ-73 was somewhat higher (23 µg/L). Well NZ-73 is about 2,000 feet downgradient from well NZ-37, and is about 400 feet west of the VVWRA infiltration ponds. The distribution of TCE in Lower Aquifer groundwater downgradient from the “edge” of the aquitard, is therefore not in accordance with the chemical distribution that should result from the hydraulic connection described in the conceptual model as presented in the ROD (Figure 1.3).

These observations indicated that the available information should be thoroughly reviewed and used to refine the conceptual hydrogeologic model for GAFB OU1. As necessary, additional information required for the RPO evaluation was identified and collected.

2.2 AVAILABLE DATA

Investigation activities have been conducted at GAFB OU1 since 1986 (JMM, 1992). Groundwater samples have been collected and analyzed for VOCs, SVOCs, fuel constituents, metals, and other inorganic constituents/parameters. The results of groundwater sample and analyses from 1994 through 1998 were provided by Montgomery Watson to Parsons ES in electronic format, for use in the RPO evaluation.

After reviewing the available information for GAFB OU1, 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, in the work plan for the GAFB OU1 RPO investigation, Parsons ES (1998) proposed to conduct a field program to collect the information necessary for further evaluation of the geochemistry and extent of groundwater contamination at GAFB OU1. In conjunction with the scheduled April 1999 monitoring event, and in cooperation with Montgomery Watson, groundwater samples were collected from a subset of the existing monitoring wells. The resulting data were integrated

TABLE 2.1
VOLATILE ORGANIC CHEMICALS IN GROUNDWATER (mg/L)
REMEDIAL PROCESS OPTIMIZATION, OU 1
GEORGE AIR FORCE BASE, CALIFORNIA

WELL IDENTIFICATION	COLLECTION		1,1-DCE	CIS-1,2-DCE	TRANS-1,2-DCE	TOTAL 1,2-DCE	TCE	CHLOROFORM	VINYL CHLORIDE
	DATE								
EW-1	10/11/95		ND ^b	NA ^b	NA	ND	33	0.85	ND
EW-1	10/01/98		ND	ND	ND	NA	16	ND	ND
EW-2	10/11/95		ND	NA	NA	ND	16	ND	ND
EW-2	10/01/98		ND	ND	ND	NA	12	ND	ND
EW-3	10/11/95		ND	NA	NA	ND	35	1.3	ND
EW-3	10/01/98		ND	ND	ND	NA	41	1	ND
EW-4	10/11/95		ND	NA	NA	ND	28	1	ND
EW-4	10/01/98		ND	ND	ND	NA	38	0.8	ND
EW-5	10/01/98		ND	ND	ND	NA	14	0.7	ND
EW-6	10/11/95		ND	NA	NA	ND	17	ND	ND
EW-6	10/01/98		ND	ND	ND	NA	4.3	ND	ND
EW-7	10/11/95		ND	NA	NA	ND	32	0.9	ND
EW-7	10/01/98		ND	ND	ND	NA	22	ND	ND
EW-8	10/11/95		ND	NA	NA	ND	12	ND	ND
EW-8	05/01/99		ND	ND	ND	NA	13	ND	ND
EW-9	10/11/95		ND	NA	NA	ND	20	3.6	ND
EW-9	10/01/98		ND	ND	ND	NA	39	1.5	ND
EW-10	10/01/98		ND	ND	ND	NA	2.2	ND	ND
EW-11	10/01/98		ND	ND	ND	NA	33	1.1	ND
EW-12	10/01/98		ND	ND	ND	NA	160	ND	ND
EW-12	11/16/98		ND	3 F	ND	NA	202	ND	ND
EW-12	05/06/99		ND	1.2	ND	NA	193 M ^{c/}	1 B ^{d/}	ND
EW-13	05/01/99		ND	5.6	ND	NA	290	0.07	ND
EW-14	10/01/98		ND	ND	ND	NA	3.1	ND	ND
EW-15	10/01/98		ND	ND	ND	NA	0.9	1.4	ND
EW-16	10/01/98		ND	ND	ND	NA	ND	ND	ND
EW-17	10/01/98		ND	ND	ND	NA	2.4	ND	ND
EW-18	10/01/98		ND	ND	ND	NA	1.8	1.1	ND
FT-01	09/10/95		ND	ND	ND	NA	0.68	ND	ND
FT-01	01/29/96		ND	ND	ND	NA	0.95 J ^{e/}	ND	ND
FT-01	05/21/96		ND	ND	ND	NA	ND	ND	ND
FT-01	10/23/96		ND	ND	ND	NA	ND	ND	ND
FT-01	03/07/97		ND	ND	ND	NA	ND	ND	ND
FT-01	07/13/97		ND	ND	ND	NA	ND	ND	ND
FT-01	11/06/98		ND	ND	ND	NA	3.2	ND	ND
FT-01	05/04/99		ND	ND	ND	NA	3.5 M	0.58 B	ND
FT-02	07/13/97		ND	ND	ND	NA	6.7	ND	ND
FT-02	11/09/98		ND	ND	ND	NA	8.8	ND	ND
FT-02	05/04/99		ND	ND	ND	NA	66.2 M	3.1 B	ND
FT-03	01/29/96		ND	ND	ND	NA	3.1 J	ND	ND
FT-03	05/21/96		ND	ND	ND	NA	8	ND	ND
FT-03	10/24/96		ND	ND	ND	NA	7.2	ND	ND
FT-03	03/07/97		ND	ND	ND	NA	5.7	0.56	ND
FT-03	07/14/97		ND	ND	ND	NA	6.6	ND	ND
FT-03	10/23/97		ND	ND	ND	NA	5.9 J	ND	ND
FT-03	11/09/98		ND	ND	ND	NA	2.9	ND	ND

TABLE 2.1 (Continued)
VOLATILE ORGANIC CHEMICALS IN GROUNDWATER (mg/L)
REMEDIAL PROCESS OPTIMIZATION, OU 1
GEORGE AIR FORCE BASE, CALIFORNIA

WELL IDENTIFICATION	COLLECTION		1,1-DCE	CIS-1,2-DCE	TRANS-1,2-DCE	TOTAL 1,2-DCE	TCE	CHLOROFORM	VINYL CHLORIDE
	DATE								
FT-03	05/04/99		ND	ND	ND	NA	6.2 M	1.3 B	ND
FT-04	09/09/95		ND	ND	ND	NA	7.5	ND	ND
FT-04	05/21/96		ND	ND	ND	NA	ND	ND	ND
FT-04	10/24/96		ND	ND	ND	NA	7.7	ND	ND
FT-04	03/07/97		ND	ND	ND	NA	4.4	ND	ND
FT-04	07/18/97		ND	ND	ND	NA	4.2	ND	ND
FT-04	10/23/97		ND	ND	ND	NA	6.9 J	ND	ND
FT-04	11/06/98		ND	ND	ND	NA	2.9	ND	ND
FT-05	07/22/97		ND	ND	ND	NA	13	ND	ND
FT-05	10/23/97		ND	ND	ND	NA	15 J	ND	ND
FT-05	11/09/98		ND	ND	ND	NA	27	1.2 R** ^U	ND
FT-05	05/04/99		ND	ND	ND	NA	112 M	6.8 B	ND
FT-06	05/04/99		ND	ND	ND	NA	4.7 M	1.1 B	ND
LW-01	07/16/97		ND	ND	ND	NA	3.2	ND	ND
LW-01	10/29/98		ND	ND	ND	NA	2.3	ND	ND
LW-01	04/23/99		ND	ND	ND	NA	1.1	ND	ND
MW-1	09/10/95		ND	ND	ND	NA	ND	ND	ND
MW-1	01/24/96		ND	ND	ND	NA	ND	ND	ND
MW-1	05/31/96		ND	ND	ND	NA	ND	ND	ND
MW-1	10/22/96		ND	ND	ND	NA	ND	ND	ND
MW-1	03/09/97		ND	ND	ND	NA	ND	ND	ND
MW-1	07/11/97		ND	ND	ND	NA	ND	ND	ND
MW-1	10/15/97		ND	ND	ND	NA	ND	ND	ND
MW-1	11/18/98		ND	ND	ND	NA	ND	ND	ND
MW-103	09/08/95		ND	ND	ND	NA	4.1	0.94	ND
MW-103	01/23/96		ND	ND	ND	NA	1.4	ND	ND
MW-103	05/20/96		ND	ND	ND	NA	ND	ND	ND
MW-103	10/26/96		ND	ND	ND	NA	10	0.57	ND
MW-103	02/19/97		ND	ND	ND	NA	11	ND	ND
MW-103	07/21/97		ND	ND	ND	NA	3.4	0.54	ND
MW-103	11/20/98		ND	ND	ND	NA	9	ND	ND
MW-103	04/30/99		ND	ND	ND	NA	4 M	ND	ND
MW-105	09/12/95		ND	ND	ND	NA	ND	ND	ND
MW-105	05/20/96		ND	ND	ND	NA	ND	ND	ND
MW-105	10/23/98		ND	ND	ND	NA	ND	ND	ND
MW-106	05/20/96		ND	ND	ND	NA	ND	ND	ND
MW-106	10/23/98		ND	ND	ND	NA	ND	ND	ND
MW-107	09/12/95		ND	ND	ND	NA	2.3	ND	ND
MW-107	01/26/96		ND	ND	ND	NA	ND	ND	ND
MW-107	06/01/96		ND	ND	ND	NA	ND	ND	ND
MW-107	11/07/96		ND	ND	ND	NA	ND	ND	ND
MW-107	02/24/97		ND	ND	ND	NA	0.81	ND	ND
MW-107	07/14/97		ND	ND	ND	NA	ND	ND	ND
MW-107	10/17/97		ND	ND	ND	NA	1.1 J	ND	ND
MW-107	11/04/98		ND	ND	ND	NA	1	ND	ND
MW-107	04/23/99		ND	ND	ND	NA	ND	ND	ND
MW-108	09/17/94		ND	ND	ND	NA	ND	ND	ND
MW-108	09/12/95		ND	ND	ND	NA	ND	ND	ND
MW-108	01/25/96		ND	ND	ND	NA	ND	ND	ND
MW-108	06/01/96		ND	ND	ND	NA	ND	ND	ND
MW-35	11/10/98		ND	ND	ND	NA	6.2	1 R**	ND
MW-35	05/03/99		ND	ND	ND	NA	5.9 M	2 B	ND
MW-37	05/03/99		ND	ND	ND	NA	ND	ND	ND
NZ-02	09/17/94		ND	ND	ND	NA	ND	ND	ND

TABLE 2.1 (Continued)
VOLATILE ORGANIC CHEMICALS IN GROUNDWATER (mg/L)
REMEDIAL PROCESS OPTIMIZATION, OU 1
GEORGE AIR FORCE BASE, CALIFORNIA

WELL IDENTIFICATION	COLLECTION		1,1-DCE	CIS-1,2-DCE	TRANS-1,2-DCE	TOTAL 1,2-DCE	TCE	CHLOROFORM	VINYL CHLORIDE
	DATE								
NZ-02	06/06/96		ND	ND	ND	NA	ND	ND	ND
NZ-02	10/20/98		ND	ND	ND	NA	ND	ND	ND
NZ-03	07/21/94		ND	ND	ND	NA	ND	ND	ND
NZ-03	04/24/95		ND	ND	ND	NA	ND	ND	ND
NZ-03	11/12/98		ND	ND	ND	NA	0.6 F ^{b/}	ND	ND
NZ-06	10/26/98		ND	ND	ND	NA	4.1	ND	ND
NZ-07	09/11/95		ND	ND	ND	NA	13	3.6	ND
NZ-07	05/21/96		ND	ND	ND	NA	2.8	2.3 U	ND
NZ-07	10/25/96		ND	ND	ND	NA	5.8	2.1	ND
NZ-07	02/18/97		ND	ND	ND	NA	17	1.8	ND
NZ-07	07/21/97		ND	ND	ND	NA	13	1.1	ND
NZ-07	10/23/97		ND	ND	ND	NA	18 J	0.9 U ^{b/}	ND
NZ-07	10/27/98		ND	0.6	ND	NA	42	ND	ND
NZ-07	05/05/99		ND	ND	ND	NA	26.1 M	1.1	ND
NZ-10	11/12/98		ND	ND	ND	NA	2.4	ND	ND
NZ-10	05/05/99		ND	ND	ND	NA	2.9 M	1.3	ND
NZ-11	01/27/96		ND	6.7	ND	NA	250	0.99	ND
NZ-11	05/22/96		ND	7.5	ND	NA	420	0.89 U	ND
NZ-11	10/25/96		ND	7	ND	NA	280	0.78	ND
NZ-11	11/21/98		ND	ND	ND	NA	381	ND	ND
NZ-11	05/07/99		ND	16.5	ND	NA	322 BM	1.5 B	ND
NZ-12	09/11/95		ND	ND	ND	NA	33	ND	ND
NZ-12	05/22/96		ND	ND	ND	NA	28	1.5 U	ND
NZ-12	10/25/96		ND	ND	ND	NA	44	1.9	ND
NZ-12	02/21/97		ND	ND	ND	NA	43	1.7	ND
NZ-12	07/22/97		ND	ND	ND	NA	28	0.77	ND
NZ-12	10/24/97		ND	ND	ND	NA	110 J	ND	ND
NZ-12	11/20/98		ND	ND	ND	NA	187	ND	ND
NZ-12	05/07/99		0.4 F	2	ND	NA	148 BM	1.5 B	ND
NZ-13	07/21/94		ND	ND	ND	NA	ND	ND	ND
NZ-13	04/24/95		ND	ND	ND	NA	ND	ND	ND
NZ-13	09/09/95		ND	ND	ND	NA	1.5	ND	ND
NZ-13	03/05/97		ND	ND	ND	NA	1.3	ND	ND
NZ-13	07/18/97		ND	ND	ND	NA	1.3	ND	ND
NZ-13	10/18/97		ND	ND	ND	NA	1.1 J	ND	ND
NZ-13	11/16/98		ND	ND	ND	NA	2.7	ND	ND
NZ-13	04/28/99		ND	ND	ND	NA	2.1 M	0.74	ND
NZ-14	11/09/98		ND	ND	ND	NA	1	ND	ND
NZ-18	09/17/94		ND	ND	ND	NA	7.8	0.58	ND
NZ-18	02/19/97		ND	ND	ND	NA	6.1	0.55	ND
NZ-18	07/20/97		ND	ND	ND	NA	3.1	ND	ND
NZ-18	10/22/97		ND	ND	ND	NA	3.8 J	ND	ND
NZ-18	11/11/98		ND	ND	ND	NA	6.1	ND	ND
NZ-18	04/30/99		ND	ND	ND	NA	10 M	0.88 B	ND
NZ-20	05/22/96		ND	ND	ND	NA	21	ND	ND
NZ-20	10/25/96		ND	ND	ND	NA	18	ND	ND
NZ-20	02/20/97		ND	ND	ND	NA	ND	ND	ND
NZ-20	10/20/97		ND	ND	ND	NA	13 J	ND	ND
NZ-20	11/17/98		ND	1.6	ND	NA	108	0.93 R**	ND
NZ-20	05/07/99		0.41 F	1.3 J	ND	NA	70.2 BM	1.3	ND
NZ-21	01/26/96		ND	ND	ND	NA	19	1.7	ND
NZ-21	05/22/96		ND	ND	ND	NA	57	ND	ND
NZ-21	10/24/96		ND	ND	ND	NA	86	1.2	ND
NZ-21	02/22/97		ND	ND	ND	NA	89	ND	ND
NZ-21	07/23/97		ND	ND	ND	NA	39	0.77	ND

TABLE 2.1 (Continued)
VOLATILE ORGANIC CHEMICALS IN GROUNDWATER (mg/L)
REMEDIAL PROCESS OPTIMIZATION, OU 1
GEORGE AIR FORCE BASE, CALIFORNIA

WELL IDENTIFICATION	COLLECTION		1,1-DCE	CIS-1,2-DCE	TRANS-1,2-DCE	TOTAL 1,2-DCE	TCE	CHLOROFORM	VINYL CHLORIDE
	DATE								
NZ-21	10/25/97		ND	ND	ND	NA	14 J	ND	ND
NZ-21	11/16/98		ND	ND	ND	NA	33	0.63 R**	ND
NZ-21	05/05/99		ND	ND	ND	NA	29.1 M	1.2	ND
NZ-22	11/16/98		ND	ND	ND	NA	34	ND	ND
NZ-23	09/16/94		ND	ND	ND	NA	8.7 J	ND	ND
NZ-23	05/23/96		ND	ND	ND	NA	25	ND	ND
NZ-23	10/24/96		ND	ND	ND	NA	15	ND	ND
NZ-23	02/19/97		ND	ND	ND	NA	7.6	ND	ND
NZ-23	07/20/97		ND	ND	ND	NA	3.8	ND	ND
NZ-23	10/21/97		ND	ND	ND	NA	3.3 J	ND	ND
NZ-23	10/26/98		ND	ND	ND	NA	11	ND	ND
NZ-24	01/21/96		ND	ND	ND	NA	7.3	ND	ND
NZ-24	11/04/96		ND	ND	ND	NA	4.9	ND	ND
NZ-24	02/18/97		ND	ND	ND	NA	4.8	ND	ND
NZ-24	07/16/97		ND	ND	ND	NA	2.9	ND	ND
NZ-24	10/20/97		ND	ND	ND	NA	4.1 J	ND	ND
NZ-24	10/23/98		ND	ND	ND	NA	11	ND	ND
NZ-24	05/05/99		ND	ND	ND	NA	9.8 M	0.59	ND
NZ-25	05/23/96		ND	ND	ND	NA	49	ND	ND
NZ-25	11/04/96		ND	ND	ND	NA	38	0.77	ND
NZ-25	02/21/97		ND	ND	ND	NA	18	ND	ND
NZ-25	10/24/97		ND	ND	ND	NA	260 J	ND	ND
NZ-25	10/30/98		ND	ND	ND	NA	111	ND	ND
NZ-25	05/06/99		ND	ND	ND	NA	119 M	0.8 B	ND
NZ-27	01/29/96		ND	ND	ND	NA	ND	ND	ND
NZ-27	11/05/96		ND	ND	ND	NA	12	ND	ND
NZ-27	07/21/97		ND	ND	ND	NA	11	ND	ND
NZ-27	10/24/97		ND	ND	ND	NA	44 J	1.4	ND
NZ-27	04/26/99		ND	0.87 F	ND	NA	128 M	ND	ND
NZ-28	09/12/95		ND	ND	ND	NA	26	1.1	ND
NZ-28	01/28/96		ND	ND	ND	NA	11	1.5	ND
NZ-28	11/04/96		ND	ND	ND	NA	9.8	0.62	ND
NZ-28A	05/24/96		ND	ND	ND	NA	13	1.8 U	ND
NZ-28A	02/19/97		ND	ND	ND	NA	4.9	0.66	ND
NZ-28A	10/22/97		ND	ND	ND	NA	5.7 J	0.75	ND
NZ-28A	10/28/98		ND	ND	ND	NA	11	ND	ND
NZ-29	05/31/96		ND	ND	ND	NA	11	ND	ND
NZ-29	11/05/96		ND	ND	ND	NA	12	ND	ND
NZ-29	03/04/97		ND	ND	ND	NA	7.7	ND	ND
NZ-29	07/20/97		ND	ND	ND	NA	5.3	ND	ND
NZ-29	10/22/97		ND	ND	ND	NA	4.2 J	ND	ND
NZ-29	11/05/98		ND	ND	ND	NA	1	ND	ND
NZ-29	04/26/99		ND	ND	ND	NA	ND	ND	ND
NZ-30	05/23/96		ND	7.1	ND	NA	320	0.84 U	ND
NZ-30	02/23/97		ND	ND	ND	NA	330	ND	ND
NZ-30	07/24/97		ND	ND	ND	NA	180	ND	ND
NZ-30	10/25/97		ND	ND	ND	NA	48 J	1.4 U	ND
NZ-30	11/21/98		ND	7 F	ND	NA	350	ND	ND
NZ-31	09/22/94		ND	ND	ND	NA	9.6	ND	ND
NZ-31	07/21/97		ND	ND	ND	NA	21	ND	ND
NZ-31	11/03/98		ND	ND	ND	NA	34	ND	ND
NZ-31	05/07/99		0.42 F	ND	ND	NA	28.7 BM	ND	ND
NZ-32	05/23/96		ND	ND	ND	NA	57	1 U	ND
NZ-32	11/04/96		ND	ND	ND	NA	39	0.65	ND
NZ-32	02/21/97		ND	ND	ND	NA	45	ND	ND

TABLE 2.1 (Continued)
VOLATILE ORGANIC CHEMICALS IN GROUNDWATER (mg/L)
REMEDIAL PROCESS OPTIMIZATION, OU 1
GEORGE AIR FORCE BASE, CALIFORNIA

WELL IDENTIFICATION	COLLECTION		1,1-DCE	CIS-1,2-DCE	TRANS-1,2-DCE	TOTAL 1,2-DCE	TCE	CHLOROFORM	VINYL CHLORIDE
	DATE								
NZ-32	07/23/97		ND	ND	ND	NA	32	ND	ND
NZ-32	10/28/98		ND	ND	ND	NA	57	ND	ND
NZ-32	05/06/99		ND	ND	ND	NA	47.5 M	1.2 B	ND
NZ-33	09/17/94		ND	ND	ND	NA	ND	ND	ND
NZ-34	09/09/95		ND	ND	ND	NA	46	0.86	ND
NZ-34	01/25/96		ND	ND	ND	NA	78 J	ND	ND
NZ-34	05/23/96		ND	2	ND	NA	110 R	0.71 U	ND
NZ-34	10/28/96		ND	2.5	ND	NA	230	0.88	ND
NZ-34	02/23/97		ND	ND	ND	NA	250	ND	ND
NZ-34	07/24/97		ND	ND	ND	NA	62	ND	ND
NZ-34	10/25/97		ND	ND	ND	NA	2.8 J	0.53 U	ND
NZ-34	11/11/98		ND	ND	ND	NA	ND	ND	ND
NZ-34	04/30/99		ND	ND	ND	NA	46 M	1.1 B	ND
NZ-35	01/25/96		ND	ND	ND	NA	11	ND	ND
NZ-35	05/24/96		ND	ND	ND	NA	19	ND	ND
NZ-35	10/28/96		ND	ND	ND	NA	21	ND	ND
NZ-35	02/20/97		ND	ND	ND	NA	59	ND	ND
NZ-35	07/23/97		ND	ND	ND	NA	47	ND	ND
NZ-35	10/25/97		ND	ND	ND	NA	12 J	ND	ND
NZ-35	10/27/98		ND	1.6	ND	NA	37	ND	ND
NZ-35	05/03/99		ND	0.49 F	ND	NA	14.1 M	0.84 B	ND
NZ-36	09/17/94		ND	ND	ND	NA	15	ND	ND
NZ-36	01/21/96		ND	ND	ND	NA	16	ND	ND
NZ-36	05/24/96		ND	ND	ND	NA	25	ND	ND
NZ-36	11/04/96		ND	ND	ND	NA	22	ND	ND
NZ-36	02/21/97		ND	ND	ND	NA	25	ND	ND
NZ-36	07/22/97		ND	ND	ND	NA	11	ND	ND
NZ-36	10/23/97		ND	ND	ND	NA	13 J	ND	ND
NZ-36	10/30/98		ND	ND	ND	NA	24	ND	ND
NZ-36	05/06/99		ND	ND	ND	NA	23.4 M	0.66 B	ND
NZ-37	09/22/94		ND	ND	ND	NA	4.9 N	ND	ND
NZ-37	09/12/95		ND	ND	ND	NA	1.5	ND	ND
NZ-37	06/02/96		ND	ND	ND	NA	2.1	ND	ND
NZ-37	11/06/96		ND	ND	ND	NA	7.2	ND	ND
NZ-37	03/04/97		ND	ND	ND	NA	4.3	ND	ND
NZ-37	07/16/97		ND	ND	ND	NA	3.8	ND	ND
NZ-37	10/22/97		ND	ND	ND	NA	6.2 J	ND	ND
NZ-37	11/04/98		ND	ND	ND	NA	8.9	ND	ND
NZ-37	04/26/99		ND	ND	ND	NA	30.4 M	0.57 B	ND
NZ-39	09/17/94		ND	ND	ND	NA	130	0.54	ND
NZ-39	09/12/95		ND	ND	ND	NA	45	ND	ND
NZ-39	01/21/96		ND	ND	ND	NA	52	ND	ND
NZ-39	05/29/96		ND	ND	ND	NA	110 J	ND	ND
NZ-39	11/05/96		ND	ND	ND	NA	53	ND	ND
NZ-39	02/22/97		ND	ND	ND	NA	55	ND	ND
NZ-39	07/23/97		ND	ND	ND	NA	58	ND	ND
NZ-39	10/25/97		ND	ND	ND	NA	18 J	ND	ND
NZ-39	10/28/98		ND	ND	ND	NA	170	ND	ND
NZ-39	05/07/99		ND	0.6 F	ND	NA	167 M	0.7	ND
NZ-41	09/12/95		ND	ND	ND	NA	ND	ND	ND
NZ-41	06/02/96		ND	ND	ND	NA	ND	ND	ND
NZ-41	11/07/96		ND	ND	ND	NA	ND	ND	ND
NZ-41	02/24/97		ND	ND	ND	NA	0.96	ND	ND
NZ-41	07/14/97		ND	ND	ND	NA	ND	ND	ND
NZ-41	10/17/97		ND	ND	ND	NA	ND	ND	ND
NZ-42	10/26/98		ND	ND	ND	NA	34	0.4 R**	ND
NZ-43	09/11/95		ND	ND	ND	NA	37	ND	ND

TABLE 2.1 (Continued)
VOLATILE ORGANIC CHEMICALS IN GROUNDWATER (mg/L)
REMEDIAL PROCESS OPTIMIZATION, OU 1
GEORGE AIR FORCE BASE, CALIFORNIA

WELL IDENTIFICATION	COLLECTION DATE					TCE	CHLOROFORM	VINYL CHLORIDE
		1,1-DCE	CIS-1,2-DCE	TRANS-1,2-DCE	TOTAL 1,2-DCE			
NZ-44	09/15/94	ND	ND	ND	NA	ND	ND	ND
NZ-44	10/26/98	ND	ND	ND	NA	ND	ND	ND
NZ-46	09/22/94	ND	ND	ND	NA	19	ND	ND
NZ-46	02/20/97	ND	ND	ND	NA	34	ND	ND
NZ-46	07/22/97	ND	ND	ND	NA	16	ND	ND
NZ-46	10/24/97	ND	ND	ND	NA	80 J	ND	ND
NZ-46	11/20/98	ND	ND	ND	NA	27	ND	ND
NZ-46	05/05/99	ND	ND	ND	NA	21.1 M	0.7	ND
NZ-48	01/26/96	ND	ND	ND	NA	17	ND	ND
NZ-48	06/02/96	ND	ND	ND	NA	14	ND	ND
NZ-48	11/06/96	ND	ND	ND	NA	13	0.59	ND
NZ-48	03/05/97	ND	ND	ND	NA	5.7	0.84	ND
NZ-48	07/17/97	ND	ND	ND	NA	3.1	ND	ND
NZ-48	10/21/97	ND	ND	ND	NA	4.5 J	ND	ND
NZ-48	11/04/98	ND	ND	ND	NA	2	ND	ND
NZ-48	04/22/99	ND	ND	ND	NA	2.4 M	ND	ND
NZ-49	09/17/94	ND	ND	ND	NA	0.8	ND	ND
NZ-49	09/12/95	ND	ND	ND	NA	ND	ND	ND
NZ-49	05/29/96	ND	ND	ND	NA	ND	ND	ND
NZ-50	06/01/96	ND	ND	ND	NA	ND	ND	ND
NZ-50	03/10/97	ND	ND	ND	NA	ND	ND	ND
NZ-50	10/28/98	ND	ND	ND	NA	0.7 F	ND	ND
NZ-51	01/24/96	ND	ND	ND	NA	5.1	ND	ND
NZ-51	06/03/96	ND	ND	ND	NA	12	0.69 U	ND
NZ-51	10/30/96	ND	ND	ND	NA	11	0.76	ND
NZ-51	03/06/97	ND	ND	ND	NA	11	0.73	ND
NZ-51	07/21/97	ND	ND	ND	NA	6.1	0.64	ND
NZ-51	10/23/97	ND	ND	ND	NA	4.6 J	ND	ND
NZ-51	11/13/98	ND	ND	ND	NA	5.5	ND	ND
NZ-51	04/29/99	ND	ND	ND	NA	5.2 M	ND	ND
NZ-52	03/19/94	ND	ND	ND	NA	ND	ND	ND
NZ-52	04/18/94	ND	ND	ND	NA	ND	ND	ND
NZ-52	04/22/95	ND	ND	ND	NA	ND	ND	ND
NZ-52	09/14/95	ND	ND	ND	NA	0.55	ND	ND
NZ-52	06/03/96	ND	ND	ND	NA	0.97	ND	ND
NZ-52	10/30/96	ND	ND	ND	NA	1.6	ND	ND
NZ-52	03/06/97	ND	ND	ND	NA	2.5	ND	ND
NZ-52	07/17/97	ND	ND	ND	NA	0.88	ND	ND
NZ-52	11/13/98	ND	ND	ND	NA	ND	ND	ND
NZ-52	04/29/99	ND	ND	ND	NA	ND	ND	ND
NZ-54	03/19/94	ND	ND	ND	NA	ND	ND	ND
NZ-54	04/18/94	ND	ND	ND	NA	ND	ND	ND
NZ-54	07/20/94	ND	ND	ND	NA	ND	ND	ND
NZ-54	04/22/95	ND	ND	ND	NA	ND	ND	ND
NZ-54	01/24/96	ND	ND	ND	NA	0.65	ND	ND
NZ-54	06/03/96	ND	ND	ND	NA	1.8	ND	ND
NZ-54	10/29/96	ND	ND	ND	NA	2.2	ND	ND
NZ-54	03/06/97	ND	ND	ND	NA	2.5	ND	ND
NZ-54	07/17/97	ND	ND	ND	NA	1.1	ND	ND
NZ-54	10/19/97	ND	ND	ND	NA	3.7 J	ND	ND
NZ-54	11/13/98	ND	ND	ND	NA	0.7 F	ND	ND
NZ-54	05/03/99	ND	ND	ND	NA	0.85 FM	0.8 B	ND
NZ-55	03/20/94	ND	ND	ND	NA	5.3	ND	ND
NZ-55	04/18/94	ND	ND	ND	NA	6.6	ND	ND
NZ-55	07/20/94	ND	ND	ND	NA	7.6	ND	ND
NZ-55	04/22/95	ND	ND	ND	NA	12	ND	ND
NZ-55	09/08/95	ND	ND	ND	NA	15	ND	ND

TABLE 2.1 (Continued)
VOLATILE ORGANIC CHEMICALS IN GROUNDWATER (mg/L)
REMEDIAL PROCESS OPTIMIZATION, OU 1
GEORGE AIR FORCE BASE, CALIFORNIA

WELL IDENTIFICATION	COLLECTION		1,1-DCE	CIS-1,2-DCE	TRANS-1,2-DCE	TOTAL 1,2-DCE	TCE	CHLOROFORM	VINYL CHLORIDE
	DATE								
NZ-55	02/20/97		ND	ND	ND	NA	19	ND	ND
NZ-55	07/21/97		ND	ND	ND	NA	4.6	ND	ND
NZ-55	10/22/97		ND	ND	ND	NA	2.2 J	ND	ND
NZ-55	11/11/98		ND	ND	ND	NA	33	ND	ND
NZ-55	04/27/99		ND	5.5	ND	NA	210 M	ND	ND
NZ-56	03/21/94		ND	ND	ND	NA	ND	ND	ND
NZ-56	04/18/94		ND	ND	ND	NA	ND	ND	ND
NZ-56	07/21/94		ND	ND	ND	NA	ND	ND	ND
NZ-56	09/17/94		ND	ND	ND	NA	0.75	ND	ND
NZ-56	04/24/95		ND	ND	ND	NA	ND	ND	ND
NZ-56	01/26/96		ND	ND	ND	NA	ND	ND	ND
NZ-56	05/30/96		ND	ND	ND	NA	ND	ND	ND
NZ-56	02/18/97		ND	ND	ND	NA	ND	ND	ND
NZ-56	07/13/97		ND	ND	ND	NA	ND	ND	ND
NZ-56	10/18/97		ND	ND	ND	NA	ND	ND	ND
NZ-56	11/11/98		ND	ND	ND	NA	ND	ND	ND
NZ-56	04/28/99		ND	ND	ND	NA	0.48 FM	1.2	ND
NZ-57	03/20/94		ND	ND	ND	NA	ND	ND	ND
NZ-57	04/19/94		ND	ND	ND	NA	ND	ND	ND
NZ-57	07/21/94		ND	ND	ND	NA	ND	ND	ND
NZ-57	04/24/95		ND	ND	ND	NA	ND	ND	ND
NZ-57	09/09/95		ND	ND	ND	NA	ND	ND	ND
NZ-57	01/27/96		ND	ND	ND	NA	ND	ND	ND
NZ-57	11/12/98		ND	ND	ND	NA	ND	ND	ND
NZ-58	03/20/94		ND	ND	ND	NA	ND	ND	ND
NZ-58	04/19/94		ND	ND	ND	NA	ND	ND	ND
NZ-58	07/24/94		ND	ND	ND	NA	1.1	ND	ND
NZ-58	04/24/95		ND	ND	ND	NA	ND	ND	ND
NZ-58	01/27/96		ND	ND	ND	NA	1.4	ND	ND
NZ-58	10/20/98		ND	0.4 F	ND	NA	1.4	ND	ND
NZ-58	04/28/99		ND	ND	ND	NA	1 M	0.7	ND
NZ-59	03/19/94		ND	ND	ND	NA	ND	ND	ND
NZ-59	04/18/94		ND	ND	ND	NA	ND	ND	ND
NZ-59	07/20/94		ND	ND	ND	NA	ND	ND	ND
NZ-59	04/23/95		ND	ND	ND	NA	ND	ND	ND
NZ-59	10/21/98		ND	ND	ND	NA	ND	ND	ND
NZ-59B	10/22/98		ND	ND	ND	NA	ND	ND	ND
NZ-59	04/27/99		ND	ND	ND	NA	ND	ND	ND
NZ-63	07/20/94		ND	ND	ND	NA	ND	ND	ND
NZ-63	04/26/95		ND	ND	ND	NA	ND	ND	ND
NZ-67	09/17/94		ND	9	ND	NA	250	1.2	ND
NZ-67	09/13/95		ND	6.8	ND	NA	320	1	ND
NZ-67	01/28/96		ND	7.1	ND	NA	250	1	ND
NZ-67	05/31/96		ND	6.4	ND	NA	360	0.74 U	ND
NZ-67	11/05/96		ND	6.5	ND	NA	290	0.74	ND
NZ-67	02/23/97		ND	ND	ND	NA	320	ND	ND
NZ-67	10/19/97		ND	5.7	ND	NA	120 J	ND	ND
NZ-67	11/20/98		ND	6 F	ND	NA	238	ND	ND
NZ-67	05/07/99		ND	6.3	ND	NA	324 BM	1.2 B	ND
NZ-68	10/07/94		1.1 J	ND	ND	NA	9.8 J	1 J	ND
NZ-68	09/08/95		ND	ND	ND	NA	7.3	1	ND
NZ-68	01/24/96		ND	ND	ND	NA	5.2	0.6	ND
NZ-68	05/30/96		ND	ND	ND	NA	10	0.75 U	ND
NZ-68	10/27/96		1.3	ND	ND	NA	9	0.83	ND
NZ-68	03/06/97		1.2	ND	ND	NA	8.8	0.77	ND
NZ-68	07/20/97		ND	ND	ND	NA	4.5	ND	ND
NZ-68	10/26/97		1	ND	ND	NA	15 J	0.7 U	ND
NZ-68	10/29/98		1.4	ND	ND	NA	7.8	0.71 R**	ND
NZ-68	05/03/99		0.42 F	ND	ND	NA	13.2 M	0.75 B	ND

TABLE 2.1 (Continued)
VOLATILE ORGANIC CHEMICALS IN GROUNDWATER (mg/L)
REMEDIAL PROCESS OPTIMIZATION, OU 1
GEORGE AIR FORCE BASE, CALIFORNIA

WELL IDENTIFICATION	COLLECTION		1,1-DCE	CIS-1,2-DCE	TRANS-1,2-DCE	TOTAL 1,2-DCE	TCE	CHLOROFORM	VINYL CHLORIDE
	DATE								
NZ-70	09/17/94		ND	ND	ND	NA	9.9	ND	ND
NZ-70	09/13/95		ND	ND	ND	NA	7.2	ND	ND
NZ-70	01/28/96		ND	ND	ND	NA	8.5	ND	ND
NZ-70	05/31/96		ND	ND	ND	NA	13 J	ND	ND
NZ-70	11/05/96		ND	ND	ND	NA	13	ND	ND
NZ-70	03/05/97		ND	ND	ND	NA	11	ND	ND
NZ-70	07/21/97		ND	ND	ND	NA	8.2	ND	ND
NZ-70	11/05/98		ND	ND	ND	NA	16	ND	ND
NZ-70	04/27/99		ND	ND	ND	NA	15.2 M	ND	ND
NZ-71	09/17/94		ND	ND	ND	NA	ND	ND	ND
NZ-71	02/24/97		ND	ND	ND	NA	0.57	ND	ND
NZ-71	07/14/97		ND	ND	ND	NA	ND	ND	ND
NZ-71	10/19/97		ND	ND	ND	NA	12 J	ND	ND
NZ-71	11/05/98		ND	ND	ND	NA	ND	ND	ND
NZ-72	09/17/94		ND	ND	ND	NA	ND	ND	ND
NZ-72	09/13/95		ND	ND	ND	NA	ND	ND	ND
NZ-72	01/26/96		ND	ND	ND	NA	ND	ND	ND
NZ-72	06/01/96		ND	ND	ND	NA	ND	ND	ND
NZ-72	10/19/97		ND	ND	ND	NA	5.2 J	ND	ND
NZ-72	01/08/98		ND	ND	ND	NA	0.81	ND	ND
NZ-72	10/21/98		ND	ND	ND	NA	ND	ND	ND
NZ-72	04/22/99		ND	ND	ND	NA	ND	ND	ND
NZ-73	09/17/94		ND	ND	ND	NA	14	ND	ND
NZ-73	01/26/96		ND	ND	ND	NA	14	ND	ND
NZ-73	11/06/96		ND	ND	ND	NA	18	ND	ND
NZ-73	03/05/97		ND	ND	ND	NA	22	ND	ND
NZ-73	07/22/97		ND	ND	ND	NA	15	ND	ND
NZ-73	10/24/97		ND	ND	ND	NA	41 J	1	ND
NZ-73	11/04/98		ND	ND	ND	NA	21	ND	ND
NZ-73	04/23/99		ND	ND	ND	NA	31.4 M	ND	ND
NZ-74	09/17/94		ND	ND	ND	NA	ND	ND	ND
NZ-74	09/11/95		ND	ND	ND	NA	ND	ND	ND
NZ-74	01/27/96		ND	ND	ND	NA	ND	ND	ND
NZ-74	06/06/96		ND	ND	ND	NA	ND	ND	ND
NZ-74	10/29/96		ND	ND	ND	NA	ND	ND	ND
NZ-74	03/11/97		ND	ND	ND	NA	ND	ND	ND
NZ-74	07/13/97		ND	ND	ND	NA	ND	ND	ND
NZ-74	10/20/97		ND	ND	ND	NA	1.6 J	ND	ND
NZ-74	10/21/98		ND	ND	ND	NA	ND	ND	ND
NZ-74	04/27/99		ND	ND	ND	NA	ND	ND	ND
NZ-75	06/02/96		ND	ND	ND	NA	120	ND	ND
NZ-75	11/06/96		ND	ND	ND	NA	110	ND	ND
NZ-75	02/22/97		ND	ND	ND	NA	110	ND	ND
NZ-75	07/24/97		ND	ND	ND	NA	35	ND	ND
NZ-75	10/25/97		ND	ND	ND	NA	ND	ND	ND
NZ-75	11/13/98		ND	ND	ND	NA	62	0.93 R**	ND
NZ-75	05/07/99		ND	ND	ND	NA	41.9 BM	1.8 B	ND
NZ-76	06/01/96		ND	ND	ND	NA	ND	ND	ND
NZ-76	02/24/97		ND	ND	ND	NA	0.5	ND	ND
NZ-76	07/16/97		ND	ND	ND	NA	ND	ND	ND
NZ-76	10/30/98		ND	ND	ND	NA	ND	ND	ND
NZ-76	04/22/99		ND	ND	ND	NA	ND	ND	ND
NZ-77	06/06/96		ND	ND	ND	NA	11	ND	ND
NZ-77	11/07/96		ND	ND	ND	NA	0.63	ND	ND
NZ-77	03/03/97		ND	ND	ND	NA	ND	ND	ND
NZ-77	07/15/97		ND	ND	ND	NA	ND	ND	ND
NZ-77	10/21/97		ND	ND	ND	NA	1.7 J	ND	ND
NZ-77	10/29/98		ND	ND	ND	NA	ND	ND	ND
NZ-77	04/22/99		ND	ND	ND	NA	ND	ND	ND

TABLE 2.1 (Continued)
VOLATILE ORGANIC CHEMICALS IN GROUNDWATER (mg/L)
REMEDIAL PROCESS OPTIMIZATION, OU 1
GEORGE AIR FORCE BASE, CALIFORNIA

WELL IDENTIFICATION	COLLECTION DATE	DCE				TCE	CHLOROFORM	VINYL CHLORIDE
		1,1-DCE	CIS-1,2-DCE	TRANS-1,2-DCE	TOTAL 1,2-DCE			
NZ-78	06/07/96	ND	ND	ND	NA	ND	ND	ND
NZ-78	11/08/96	ND	ND	ND	NA	ND	ND	ND
NZ-78	02/25/97	ND	ND	ND	NA	0.6	ND	ND
NZ-78	07/15/97	ND	ND	ND	NA	ND	ND	ND
NZ-78	10/21/97	ND	ND	ND	NA	1.3 J	ND	ND
NZ-78	11/10/98	ND	ND	ND	NA	ND	ND	ND
NZ-79	05/30/96	ND	ND	ND	NA	ND	ND	ND
NZ-79	11/07/96	ND	ND	ND	NA	ND	ND	ND
NZ-79	03/03/97	ND	ND	ND	NA	1.5	ND	ND
NZ-79	07/16/97	ND	ND	ND	NA	1.8	ND	ND
NZ-79	11/05/98	ND	ND	ND	NA	2	ND	ND
NZ-79	04/28/99	ND	ND	ND	NA	0.95 FM	ND	ND
NZ-80	10/27/96	ND	ND	ND	NA	4.2	ND	ND
NZ-80	03/08/97	ND	ND	ND	NA	4	ND	ND
NZ-80	07/18/97	ND	ND	ND	NA	3.7	ND	ND
NZ-80	10/21/97	ND	ND	ND	NA	2.5 J	ND	ND
NZ-80	11/12/98	ND	ND	ND	NA	3.3	ND	ND
NZ-97	01/08/98	ND	ND	ND	NA	0.81	ND	ND
OW-4	11/10/98	ND	ND	ND	NA	ND	ND	ND
RZ-01	09/08/95	ND	ND	ND	NA	ND	ND	ND
RZ-01	11/17/98	ND	ND	ND	NA	0.5 F	ND	ND
RZ-02	09/13/95	ND	ND	ND	NA	ND	ND	ND
RZ-02	04/20/99	ND	ND	ND	NA	ND	ND	ND

TABLE 2.1 (Continued)
VOLATILE ORGANIC CHEMICALS IN GROUNDWATER (mg/L)
REMEDIAL PROCESS OPTIMIZATION, OU 1
GEORGE AIR FORCE BASE, CALIFORNIA

WELL IDENTIFICATION	COLLECTION		1,1-DCE	CIS-1,2-DCE	TRANS-1,2-DCE	TOTAL 1,2-DCE	TCE	CHLOROFORM	VINYL CHLORIDE
	DATE								
RZ-03	09/14/95		ND	ND	ND	NA	ND	ND	ND
RZ-04	09/14/95		ND	ND	ND	NA	ND	ND	ND

^{a/} ND = Not Detected.

^{b/} NA = Not Analyzed.

^{c/} M = A matrix effect was present.

^{d/} B = The analyte was found in an associated blank, as well as in the sample.

^{e/} J = The analyte was positively identified, the quantitation is an estimation.

^{f/} R = The data are unusable due to deficiencies in the ability to analyze the sample and meet QC requirements.

^{g/} F = The analyte was positively identified but the associated numerical value is below the reporting limit.

^{h/} U = The analyte was analyzed for, but not detected. The associated numerical value is at or below the method detection limit.

Note: Data provided in electronic format by Montgomery Watson, Inc. (August, 1999).

with existing information to refine the conceptual hydrogeologic model of the site, and to assist with interpretation of the physical setting (Section 3) and evaluation of 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, 1999b).

2.2.1 Monitoring Event of April and May 1999

During the period from April 19 through May 8, 1999, 47 wells at GAFB OU1 were sampled by Montgomery Watson (Table 1.1). Field activities associated with collection and analyses of groundwater samples in support of the GAFB OU1 RPO investigation were conducted in accordance with the provisions of the Basewide SAP and Quality Assurance Project Plan (HydroGeoLogic, 1998), as amended by the SAP Addendum of March 1999. As specified in Section 7 of the SAP, fugitive water quality parameters, including electrical conductivity, turbidity, pH, temperature, dissolved oxygen, and oxidation reduction potential (ORP, or Eh) were measured by Montgomery Watson personnel at each sampled well after it had been purged. All groundwater samples collected by Montgomery Watson during the April 1999 monitoring event were analyzed for VOCs using USEPA Method SW8260B (Table 1.1). In conjunction with groundwater sampling activities completed by Montgomery Watson, Parsons ES collected groundwater samples from two other monitoring wells (Upper Aquifer well NZ-59 and Lower Aquifer well MW-107) which had not been included in the monitoring plan. At a limited number of monitoring wells that were sampled for VOCs by Montgomery Watson, Parsons ES also collected groundwater samples for analysis of geochemical parameters, including alkalinity, dissolved total organic carbon, carbon dioxide, methane, ethane, ethene, ferrous iron, manganese, and the common anions nitrate, sulfate, and sulfide (Table 2.2). Methods of sample collection and chemical analyses of water samples are described in detail in the Basewide SAP (HydroGeoLogic, 1998) and the SAP Addendum of March 1999 prepared by Montgomery Watson.

Sampling locations and analytical methods were selected so that duplication of sampling points or chemical analyses by Parsons ES and Montgomery Watson did not occur, thereby avoiding sampling redundancy while providing the additional information necessary for the GAFB OU1 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 GAFB OU1, 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 other remedial alternatives, including MNA.

In addition to collection and analyses of groundwater samples in support of the GAFB OU1 RPO investigation, Parsons ES collected a vapor sample from the influent wet-well of the treatment system, to assess the VOC composition of headspace vapor in the wet-well. The vapor analytical results were used to qualitatively assess the volatilization loss of organic chemicals from extracted groundwater.

TABLE 2.2
SAMPLING LOCATIONS AND ANALYSES
FOR
GROUNDWATER SAMPLES COLLECTED BY PARSONS ES
Monitoring Event of April - May 1999
REMEDIAL PROCESS OPTIMIZATION, OU-1
GEORGE AIR FORCE BASE, CALIFORNIA

Sampling Location	Operable Unit(s)	Site / Area	Aquifer Monitored ^{a/}	Purge Method	Analyses												
					Field						Laboratory						
					Alkalinity (Hach Method 8221)	Carbon Dioxide (Hach Method 1436)	Ferrous Iron (Fe II) (Hach Method 8146)	Manganese (Hach Method 8034)	Sulfate (Hach Method 8051)	Sulfide (Hach Method 8131)	VOCs ^{b/} (Method SW8260B) (by others)	VOCs ^{b/} (Method SW8260B) (by Parsons ES)	Methane, Ethane, Ethene (Method RSK-175)	Chloride (Method E300.0)	Dissolved Organic Carbon (Method 415.1)	Nitrate (Method E300.0)	
MW-107	OU 1	-	L	MSP ^{c/}	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NZ-07	OU 1	-	U	MSP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NZ-10	OU 1	-	U	MSP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NZ-11	OU 1	-	U	MSP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NZ-12	OU 1	-	U	MSP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NZ-18	OU 1	-	U	MSP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NZ-25	OU 1	-	U	MSP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NZ-27**	OU 1	-	U	MSP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NZ-29	OU 1	-	L	MSP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NZ-31	OU 1	-	U	MSP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NZ-34	OU 1	-	U	MSP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NZ-35	OU 1	-	U	MSP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NZ-37	OU 1	-	L	MSP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NZ-39	OU 1	-	U	MSP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NZ-46	OU 1	-	U	MSP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NZ-55	OU 1	-	U	MSP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NZ-59	-	Background	U	MSP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NZ-67	OU 1	-	U	MSP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NZ-70	OU 1	-	L	MSP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
NZ-73	OU 1	-	L	MSP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
RZ-02	-	Background	L	MSP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

^{a/} Aquifer monitored - Upper Aquifer (U); Lower Aquifer (L)

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

^{c/} MSP - Modified Slow Purge

2.2.2 Groundwater Sampling Procedures

Groundwater sampling generally was conducted in accordance with procedures specified in the Basewide SAP (HydroGeoLogic, Inc., 1998). Parsons ES personnel did note a consistent deviation from the SAP, in that the Plan specifies that micropurge techniques would be used to remove groundwater from the wells prior to sampling; but the actual purging technique that was used by Montgomery Watson personnel actually consisted of purging each well, using a submersible pump operated at a relatively elevated rate, for periods of time that often exceeded one hour. The estimated volume of water removed from each well using this technique ranged to over 100 gallons. Subsequent groundwater sampling and field analyses were performed by either Montgomery Watson or Parsons ES personnel, depending on whether the well was included in the schedule monitoring event. Sampling records for wells sampled by Parsons ES are included in Appendix A. Fixed-base analyses for VOCs, nitrate, chloride, and dissolved total organic carbon (TOC) were performed by Applied Physical and Chemical Laboratory, Inc. of Chino, California. Analyses for dissolved methane, ethane, and ethene were performed by Quanterra Environmental Services, Inc., of Austin, Texas. Analyses for VOCs in the influent wet-well vapor sample were performed by Air Toxics, Inc., of Folsom, California.

2.3 OCCURRENCE AND MOVEMENT OF TCE

Montgomery Watson, Inc. forwarded chemical data for samples collected during the groundwater monitoring event of April and May 1999 to Parsons ES after the results of laboratory analyses had been validated by Montgomery Watson. Results of analyses for VOCs are included in Table 2.1.

In general, the concentrations and distribution of TCE in groundwater of the Upper and Lower Aquifers was in accordance with previous results (Figures 1.8 and 1.9). The TCE results obtained from wells FT-05 (in the fire-training area), NZ-27 (near the bluffs north of the NEDA), and NZ-55 (north of the STP percolation ponds) (Figure 1.8) exhibited significant increases over historical results (Table 2.1).

TCE historically has been the contaminant detected at the greatest frequency, highest concentrations, and broadest distribution at GAFB OUI. Low concentrations of chloroform also have been detected relatively frequently, generally at low concentrations, and often in association with TCE (Table 2.1). Other VOCs, including DCE isomers, 1,1,2-TCA and 1,2-DCA, also have been detected occasionally, though at much lower concentrations than TCE. DCE isomers have been detected only in groundwater samples from wells that also contain TCE (e.g., wells NZ-11, NZ-12, NZ-20, NZ-30, NZ-34, NZ-67, and NZ-68).

The concentrations of VOCs generally are greatest near or north of the northern border of the Base (*c.f.*, wells NZ-11, NZ-30, NZ-67, and NZ-39; Figures 1.8 and 1.9; Table 2.1). This distribution of contaminants suggests that TCE may have originated at several widely dispersed locations, rather than at a single discrete source within the NEDA. Advective transport in groundwater has subsequently distributed TCE to downgradient locations at lower concentrations.

A single vapor sample, collected from the headspace of the influent wet-well, was analyzed for VOCs (Table 2.2). TCE was detected, at a concentration of 80 parts per billion by volume

(ppbv) in the wet-well vapor sample (Appendix A). No other VOCs were detected in the vapor sample.

2.4 TRENDS OF TCE CONCENTRATIONS IN GROUNDWATER

If removal of chemical mass is occurring in the subsurface as a consequence of groundwater extraction, natural degradation, or other processes, 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. Therefore, as a first step in evaluating chemical removal from groundwater, it was necessary to identify those sampling locations at which chemical concentrations have decreased through time.

In conjunction with periodic groundwater monitoring, Montgomery Watson (1998d), has completed statistical evaluations of possible trends in TCE concentrations in groundwater at GAFB OU1. These evaluations were conducted using the Mann-Kendall test for trends. The Mann-Kendall nonparametric test (Gilbert, 1987) 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 null hypothesis (i.e., there is no trend in chemical concentrations) was examined for the historical record for each of 44 wells. Rejection of the null hypothesis indicates that an increasing or decreasing trend is present.

The historical concentration records of eight wells in the Upper Aquifer and three wells in the Lower Aquifer display trends of decreasing TCE concentrations through time (Figures 2.6 and 2.7). The concentrations of TCE in groundwater at five Upper Aquifer wells and one Lower Aquifer well were determined to be statistically increasing. No temporal trend in TCE concentrations was apparent in the historical concentrations from the other 27 wells.

No apparent pattern can be discerned in the spatial distribution of wells displaying increasing or decreasing trends in TCE concentrations (Figures 2.6 and 2.7). Several of the wells displaying trends of decreasing concentrations are located near the large arroyo north of the Base boundary (Figure 2.6). However, nearby (occasionally adjacent) wells may display trends of increasing concentrations. For example, the historical record for well FT-05 in the Fire Training Area displays a trend of decreasing concentrations, while TCE concentrations at adjacent well FT-02 are increasing. Of particular interest are the trends in TCE concentrations in the Lower Aquifer, west of the VVWRA treatment facility (Figure 2.7). The concentrations of TCE in groundwater samples from well NZ-48, in the upgradient part of the Lower Aquifer plume, are decreasing, as are the concentrations in samples from well LW-1, near the downgradient edge of the plume. By contrast, the concentrations of TCE in samples from well NZ-73, between well NZ-48 and LW-1, have been increasing through time.

The lack of apparent trends in TCE concentrations – in particular, the absence of decreasing concentration trends near potential source areas and increasing concentration trends in downgradient locations, suggests that the TCE plumes at GAFB OU1 are generally stable (USEPA, 1998). This may be a result of TCE removal and plume control occurring due to groundwater extraction, or may be a consequence of other TCE attenuation mechanisms.

2.5 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 GAFB OU1. 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 in the total mass of contamination in the subsurface without the addition of nutrients. The major bioremediation processes that act upon CAHs are reviewed in detail in Appendix B.

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

2.5.1 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 only infrequently at OU1, and at much lower concentrations than TCE. VC has not been detected in any groundwater sample collected since 1994 (Table 2.1). DCE isomers have been detected in groundwater samples from a relatively limited number of wells (EW-12, NZ-07, NZ-11, NZ-12, NZ-20, NZ-27, NZ-30, NZ-31, NZ-34, NZ-35, NZ-39, NZ-55, NZ-58, NZ-67, and NZ-68). Without exception, TCE also has been detected in all samples in which DCE was detected. The co-occurrence of TCE and DCE isomers in the same samples indicates that some degradation of TCE is occurring. However, the low concentrations of DCE relative to TCE in these samples, and the lack of detectable concentrations of VC, suggest that if dehalogenation is occurring, those processes are proceeding relatively slowly.

Ethane and ethene are the final products in the series of reductive dehalogenation reactions involving chlorinated ethanes and ethenes (Appendix B). Therefore, if TCE were completely

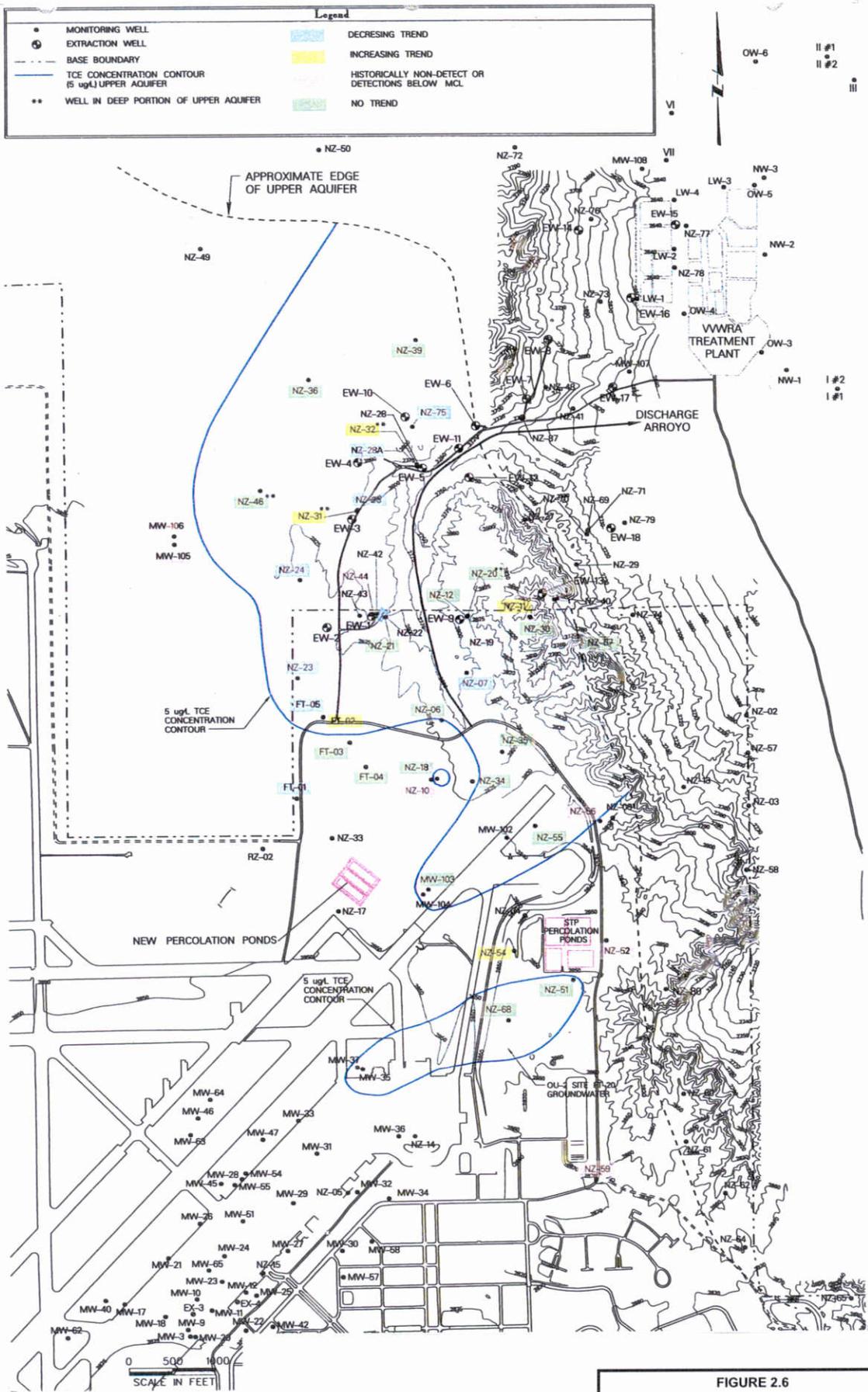


FIGURE 2.6

TCE TREND ANALYSIS OF THE UPPER AQUIFER AT OU1 (OCTOBER 1998)

Remedial Process Optimization
George AFB, California

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Denver, Colorado

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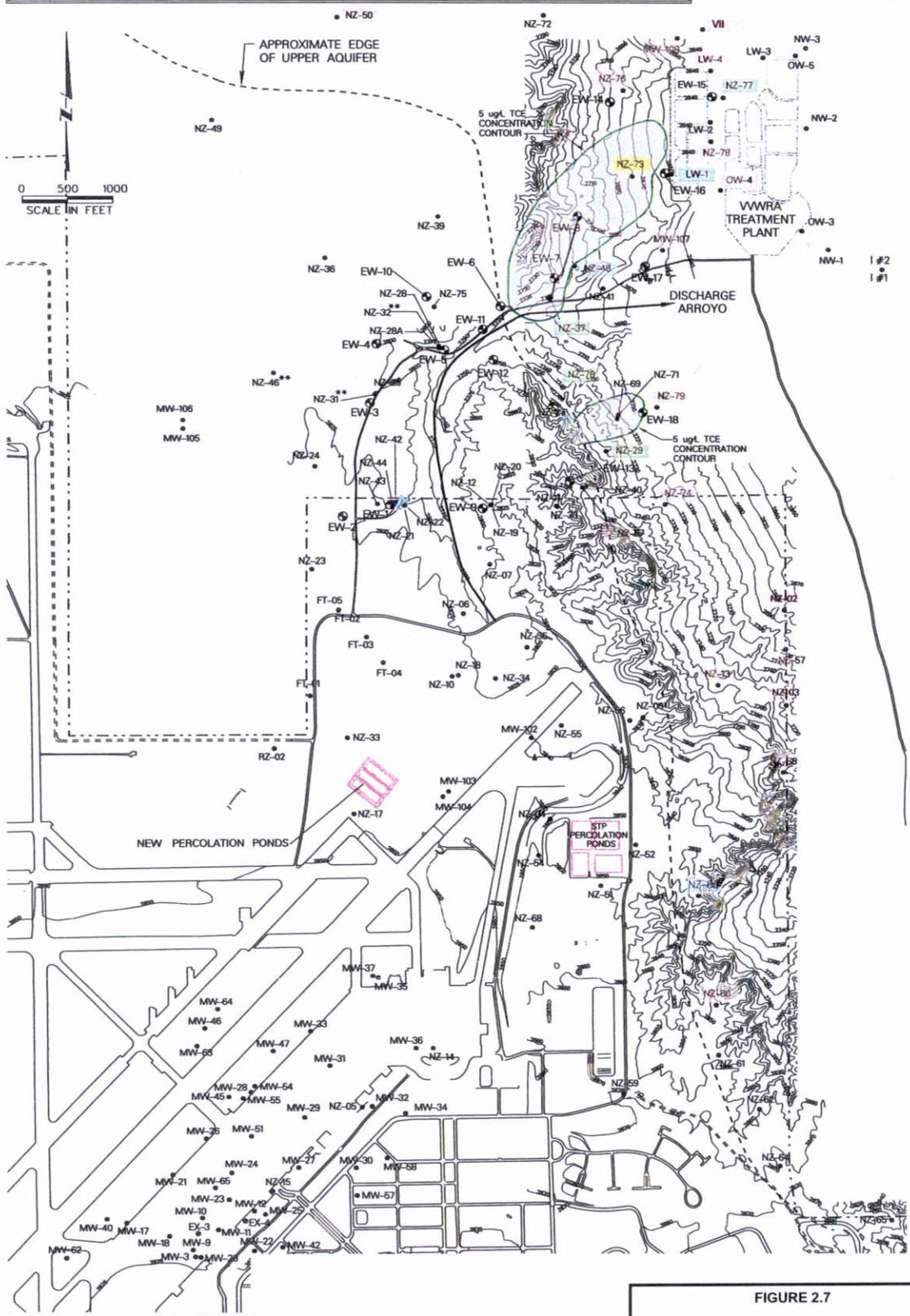
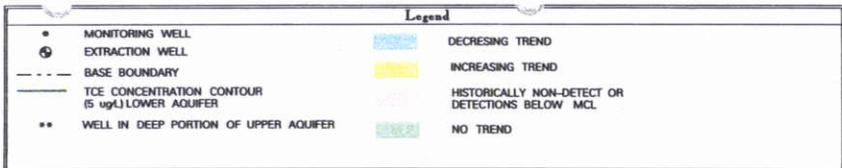


FIGURE 2.7
TCE TREND ANALYSIS
OF THE LOWER AQUIFER
AT OU1 (OCTOBER 1998)
 Remedial Process Optimization
 George AFB, California
PARSONS
PARSONS ENGINEERING SCIENCE, INC.
 Denver, Colorado

Source: Montgomery Watson 1999d.

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degraded through its chain of daughter products, these compounds should appear. Groundwater samples collected during April-May 1999 were analyzed for dissolved gases (Table 2.2). Neither ethane nor ethene was detected in any groundwater sample (Table 2.3), confirming that if TCE is degrading, the reactions are occurring at relatively slow rates.

TCE can also be degraded co-metabolically under aerobic conditions (Appendix B). Chloroform is a possible daughter product of aerobic degradation of TCE. Chloroform has frequently been detected in groundwater samples that also contained TCE (Table 2.1); however, the co-occurrence of chloroform and TCE is not strongly correlated statistically. Therefore, while aerobic degradation of TCE appears to be possible at GAFB OU1, this cannot be confirmed with the available information.

2.5.2 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 2.8, 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 2.8 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 April and May 1999 ranged from 0.23 millivolts (mV) to 144.5 mV (Table 2.3). The lowest ORP value was measured at well NZ-35, completed in the Upper Aquifer near suspected TCE source areas in the NEDA (Figure 1.8). The ORP value measured at “background” well RZ-02 also was low (6 mV; Table 2.3). However, this probably is not an indication of natural conditions in the Upper Aquifer. Rather, well RZ-02 may be downgradient from an area in which petroleum fuels are present in groundwater (IT Corporation, 1992). Degradation of petroleum fuels also would lower the ORP values in downgradient wells.

The highest value of ORP (144.5 mV) was measured at well NZ-59, near the eastern Base boundary, and south of all known areas of chemical disposal or fuel releases (Figure 1.8). Well NZ-59 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 40 to 100 mV (Table 2.3), possibly indicating that the progressive use of electron acceptors in the order shown on Figure 2.8 has caused groundwater in contaminated areas to become more reducing. However, groundwater beneath GAFB OU1 is probably not sufficiently reducing to support significant iron- or sulfate reduction and methanogenesis (Figure 2.8).

2.5.3 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., dissolved oxygen [DO], nitrate, and sulfate) are depleted, and byproducts of electron acceptor reduction (e.g., ferrous iron, methane, and sulfide) are increased (Appendix B). By measuring these changes, it is possible to evaluate the relative importance of natural attenuation mechanisms occurring at a site.

DO values measured in site groundwater ranged from 1.21 to 8.84 milligrams per liter (mg/L), with the lowest DO concentration detected at well RZ-02 (Table 2.3). Again, this probably is not an indication of naturally occurring conditions in the Upper Aquifer, but occurs because well RZ-02 is downgradient from an area in which petroleum fuels are present in groundwater (IT Corporation, 1992). The concentrations of DO at three wells (wells NZ-18, NZ-34, and NZ-59) were each approximately 8 mg/L (Table 2.3). These wells are approximately upgradient or distal from potential source areas in the NEDA. It therefore seems likely that a DO concentration of about 8 mg/L may be representative of “background” DO concentrations.

The concentrations of DO in downgradient areas generally range from about 3 mg/L to 5 mg/L (Table 2.3). This disparity between plume and background DO concentrations suggests that oxygen is being utilized in aerobic degradation processes. However, dehalogenation reactions generally do not proceed, or proceed at very slow rates, if the concentrations of DO are greater than about 1 mg/L (USEPA, 1998). It is therefore unlikely that the DO is being consumed in dehalogenation reactions; rather, the microbial population may be using DO in reactions involving native organic carbon substrate, or other sources of anthropogenic carbon (e.g., petroleum fuels). It is also possible that operation of the groundwater extraction wells at the site draws oxygenated groundwater into the plume area, and that degradation reactions do not proceed rapidly enough to quickly deplete the DO.

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 was detected in all samples that were analyzed for nitrate in April and May, 1999 (Table 2.3). The lowest concentration of nitrate (1 mg/L) was detected at well NZ-59, which may be representative of “background” conditions. Groundwater samples from wells in most other locations contained nitrate at relatively elevated concentrations (up to 33.5 mg/L). The cause of elevated nitrate concentrations is not known, but may be a consequence of past sewage disposal or fertilizing practices. With the exception of the disparity in concentrations between “background” levels and levels in the northern part of OU1, no spatial trends in the distribution of nitrate are apparent.

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 April-May 1999 monitoring event were analyzed for sulfate and sulfide (Table 2.2). Sulfate was detected in all groundwater samples, at concentrations ranging from 75.78 mg/L (in the sample from well NZ-39), to 254.2 mg/L in the sample from well NZ-59 (the “background” well). The concentrations of sulfate in groundwater within and downgradient from the NEDA generally ranged from about 80 to 120 mg/L (Table 2.3). The differences between possible background sulfate concentrations and concentrations within the CAH plume suggests that sulfate reduction may be occurring at least locally in site groundwater.

TABLE 2.3
GROUNDWATER GEOCHEMICAL DATA
REMEDIAL PROCESS OPTIMIZATION, OU-1
GEORGE AIR FORCE BASE, CALIFORNIA

Sample Location	Sample Date	Temp (°C) ^{a/}	pH	Conductivity (mS/cm) ^{b/}	Dissolved Oxygen (mg/L) ^{c/}	Redox Potential (mV) ^{d/}	Field Total Alkalinity (mg/L)	Chloride (mg/L)	Nitrate (mg/L)	Field Sulfate (mg/L)	Field Sulfide (mg/L)	Field Manganese (mg/L)	Ferrous Iron (mg/L)	Carbon Dioxide (mg/L)	DOC (mg/L)	(CH4) Methane (ug/L) ^{e/}	(C2H6) Ethane (ug/L)	(C2H5) Ethene (ug/L)
NZ-07	05/05/99	23.5	7.81	0.716	3.11	67	260	73.8	23.7 J	78.54	0.016	0.1	ND	11	ND	ND	ND	ND
NZ-10	05/05/99	20.9	7.52	0.622	3.83	66	220	58.6	21.3 J	76.8	0.01	0.1	ND	ND	1.3	ND	ND	ND
NZ-11	05/07/99	26.5	7.23	0.667	3.36	NA	260	63.1	31.2	86.4	0.024	ND	0.11	11	ND	ND	ND	ND
NZ-12	05/07/99	27.1	7.22	0.662	4.18	NA	260	65.1	30.1	96	0.022	0.1	0.02	10	1.1	ND	ND	ND
NZ-12 ^{j/}		NA	NA	NA	NA	NA	260	NA	NA	94.16	0.027	ND	0.03	10	NA	NA	NA	NA
NZ-18	04/30/99	21.9	7.66	0.649	8.84	46	140	73.1	21.9	153.96	0.011	ND	ND	ND	2.5	ND	ND	ND
NZ-25	05/06/99	NA	NA	NA	NA	NA	200	59.7	23.4 J	77.82	0.025	0.2	ND	ND	1.3	ND	ND	ND
NZ-27	04/26/99	28.4	7.41	0.628	4.04	NA	240	61	5.8	114	0.079	0.1	0.15	ND	2.1	ND	ND	ND
NZ-29	04/26/99	26.4	8.32	0.376	3.22	NA	140	15	1	114	0.019	ND	ND	ND	1	ND	ND	ND
NZ-31	05/07/99	24.6	8.02	0.375	6.54	99	80	36.2	16.2	100.8	0.012	0.4	ND	ND	1.7	ND	ND	ND
NZ-34	04/30/99	21.2	7.55	0.654	7.88	38	160	80.2	26.7	116.58	0.014	ND	ND	ND	3.3	ND	ND	ND
NZ-35	05/03/99	20.8	7.38	0.706	3.89	0.23	240	65	31.9	87.78	ND	0.1	ND	ND	8.4	ND	ND	ND
NZ-37	04/26/99	27	7.21	0.601	7.25	NA	240	50	3.1	122.4	0.008	0.3	ND	ND	ND	ND	ND	ND
NZ-39	05/07/99	27.3	7.60	0.567	3.90	NA	180	57.8	23.6	75.78	0.008	0.3	ND	ND	ND	ND	ND	ND
NZ-46	05/05/99	26.3	7.35	0.602	4.91	55	220	53.6	23.6 J	77.16	0.008	0.2	0.02	ND	2.2	ND	ND	ND
NZ-55	04/27/99	24.6	7.29	0.788	2.41	NA	260	71	15	128.04	0.011	ND	ND	13	9.3	ND	ND	ND
NZ-59	04/27/99	26.42	7.82	948	7.81	144.5	220	86	1	254.22	0.009	0.2	ND	ND	8.1	ND	ND	ND
NZ-59 ^{j/}		NA	NA	NA	NA	NA	200	NA	NA	251.4	0.009	0.1	0.01	ND	NA	NA	NA	NA
NZ-67	05/07/99	27.3	7.42	0.673	5.87	NA	280	62.4	33.5	91.88	0.024	0.1	0.08	12	ND	ND	ND	ND
NZ-70	04/27/99	25.9	8.68	0.477	5.18	NA	120	56	5.5	93.24	0.064	ND	ND	ND	4	ND	ND	ND
NZ-73	04/23/99	25	7.74	0.582	5.88	60	220	42	3.76	137.05	0.012	ND	ND	ND	ND	ND	ND	ND
NZ-73 ^{j/}		NA	NA	NA	NA	NA	200	NA	NA	140.95	0.01	ND	ND	ND	NA	NA	NA	NA
MW-107	04/23/99	22.91	8.47	449	5.18	138.7	160	14	1.29	98.4	ND	ND	ND	ND	1	ND	ND	ND
RZ-02	04/19/99	27.5	8.90	0.346	1.21	6	160	6.3	0.4	89.28	0.033	ND	ND	ND	ND	ND	ND	ND

^{a/} C = degrees Centigrade.

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

^{c/} mg/L = milligrams per liter.

^{d/} mV = millivolts.

^{e/} ug/L = micrograms per liter.

^{f/} ND = not detected.

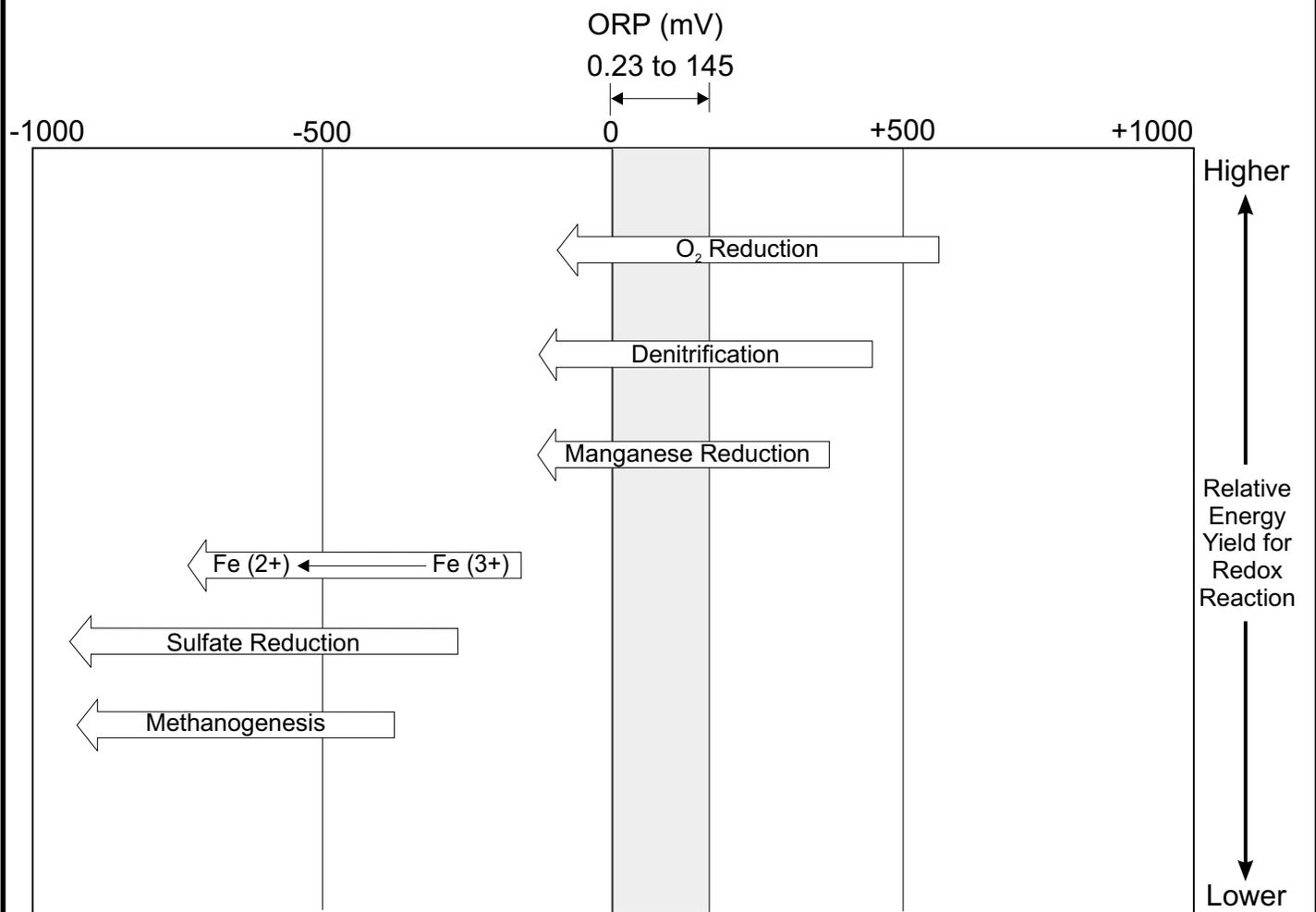
^{g/} NA = not analyzed.

^{h/} U = The analyte was analyzed for and is not present above the reported sample quantitation limit.

^{i/} J1 = The analyte is qualified as an estimated value solely because it is greater than the method detection limit and less than the practical quantitation limit indicating no laboratory quality issues.

^{j/} Duplicate of preceding sample.

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Notes

ORP = Oxidation Reduction Potential

Range of ORP measured at Operable Unit 1

1. These reactions would be expected to occur in sequence if the system is moving toward equilibrium.
2. These redox processes occur in order of their energy-yielding potential (provided microorganisms are available to mediate a specific reaction). Reduction of a highly oxidized species decreases the ORP of the system.
3. The ORP of the system determines which electron acceptors are available for organic carbon oxidation.
4. Redox sequence is paralleled by an ecological succession of biological mediators.

FIGURE 2.8

SEQUENCE OF MICROBIALLY MEDIATED REDOX PROCESSES

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Denver, Colorado

Adapted from Stumm and Morgan, 1981 and Norris *et al.*, 1994.

The occurrence of sulfate reduction was confirmed by the appearance of sulfide at detectable concentrations in most groundwater samples from the Upper and Lower Aquifers (Table 2.3). As a general rule, sulfide is an unstable sulfur species under oxidizing conditions, and can persist only under reducing conditions. Detectable concentrations of sulfide in groundwater is regarded as an indication of strongly reducing conditions (Hounslow, 1995), suggesting that at least locally, conditions in groundwater may be sufficiently reducing to promote reductive dehalogenation.

2.5.4 Metabolic Byproducts

The geochemical data indicate that low concentrations of ferrous iron and (locally) soluble manganese are being produced in some parts of the plume as a result of ferric iron and manganese reduction, respectively (Table 2.3). However, the concentrations of dissolved iron and manganese were all extremely low; and no spatial trend is apparent in the distribution of these constituents.

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 and carbon dioxide were analyzed in 1999 groundwater samples (Table 2.2) to evaluate the potential for methanogenesis.

Methane was not detected in any groundwater sample analyzed for this parameter, indicating that methanogenesis is not a significant process at GAFB OU1. Carbon dioxide was detected in 6 of the 21 samples (Table 2.3). Four of the 6 wells in which carbon dioxide was detected (wells NZ-07, NZ-11, NZ-12, and NZ-67) are in the same general area, near the northern boundary of the Base (Figure 1.8). The TCE daughter product *cis*-1,2-DCE has also been detected in groundwater samples collected from each of these wells on one or more occasions (Table 2.1). The presence of significantly elevated carbon dioxide concentrations in groundwater in areas where CAH compounds are also present is an indication of biologic activity. The co-occurrence of DCE isomers and carbon dioxide provides confirmation that, at least locally, TCE is degrading.

2.5.5 Alkalinity

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)] in an area with CAH concentrations elevated above background conditions can be used to infer that hydrocarbon compounds (or native organic carbon) have been destroyed through aerobic and/or anaerobic microbial respiration.

Total alkalinity (as calcium carbonate [CaCO_3]) 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 GAFB OU1 ranged from 80 mg/L to 260 mg/L (Table 2.3). 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.

2.5.6 Summary of CAH Biodegradation at GAFB OU1

The prevalence of TCE throughout the CAH plume, combined with the relative absence of reductive dehalogenation daughter products (i.e., *cis*-1,2-DCE, VC, and ethene), is a direct indication that significant biotransformation of TCE via reductive dehalogenation is not occurring, despite the localized presence of anaerobic, reducing conditions in site groundwater. This conclusion is supported by the following observations:

- Conditions in groundwater throughout the Upper and Lower Aquifers are generally aerobic; oxygen concentrations are generally > 3 mg/L; and ORP values indicate that oxidizing conditions prevail. Dehalogenation reactions preferentially proceed under anaerobic, reducing conditions, and are hindered by DO concentrations greater than about 1 mg/L (USEPA, 1998, and Appendix B). Although anaerobic conditions may occur in restricted areas, groundwater is not sufficiently reducing in most areas of GAFB OU1 to promote significant reductive dehalogenation. This is demonstrated by the relatively elevated DO concentrations, the low concentrations of ferrous iron and dissolved manganese (all less than 1 mg/L), the absence of methane at detectable concentrations, and the generally low concentrations of dissolved organic carbon. According to guidance documents (USEPA, 1998), dissolved organic carbon concentrations less than 20 mg/L may not constitute a sufficient carbon and energy source to promote reductive dehalogenation.
- According to USEPA (1998) guidance, sulfate may compete with CAHs as an electron acceptor (i.e., sulfate may be preferentially used by microorganisms instead of CAHs) if sulfate concentrations exceed 20 mg/L. As described in Section 2.5.3, sulfate concentrations in groundwater samples ranged from 75.78 to 254 mg/L (Table 2.3). Therefore, although available data indicate that reductive dehalogenation may be occurring at slow rates, on a localized basis, sulfate may be used preferentially as an electron acceptor in site groundwater, limiting the biotransformation of TCE.

Highly chlorinated CAHs such as TCE generally are not degraded directly under aerobic conditions (Appendix B). Therefore, biodegradation of significant mass of TCE is probably not occurring across most of the site. Less-chlorinated CAHs such as *cis*-1,2-DCE and VC are typically more easily biodegraded in aerobic environments. However, production of these compounds appears to be extremely limited at GAFB OU1 (Table 2.1). Cometabolic or abiotic transformation of TCE may be occurring in site groundwater, producing chloroform as a degradation daughter product. However, occurrence of these processes is difficult to document. Because the cometabolism rate decreases with increasing degree of chlorination, it is likely that cometabolism of TCE, if it is occurring in site groundwater, is occurring at a slow rate. The relative scarcity of evidence supporting biodegradation of TCE indicates that other attenuation processes (e.g. sorption and dispersion) may be relatively more important in attenuating the concentrations of TCE in groundwater at GAFB OU1.

2.6 RISK EXPOSURE PATHWAYS AND POTENTIAL RECEPTORS

Hypothetical receptors that could potentially be exposed to TCE in groundwater at GAFB OU1 include industrial workers and future residents on-Base or at downgradient locations. The depth to groundwater in most areas of GAFB OU1 is generally greater than 100 feet bgs. This depth to groundwater precludes the possibility of exposure for workers engaged in excavation activities. Groundwater beneath and downgradient from the Base is not currently utilized as a drinking-water source (Section 1); however, under future land-use conditions, groundwater potentially could be used as a drinking water source. There currently are no active production wells within the limits of the TCE plumes; and the nearest production wells, located at the VVWRA facility north of the Base, are not currently used for drinking water. Institutional controls limiting access to and uses of groundwater beneath GAFB OU1 are currently in place, and will so remain for the duration of remediation activities. In light of current institutional and physical constraints, no receptors are likely to be exposed to CAH in groundwater within the Upper or Lower Aquifers.

2.7 REFINEMENT OF CONCEPTUAL HYDROGEOLOGIC MODEL

Examination of the available historical information and the results of groundwater sampling completed in April and May 1999, can be used to refine the conceptual hydrogeologic model of GAFB OU1, originally presented in the ROD, to address the apparent discrepancies noted in Section 2.1. The primary discrepancies were associated with the nature of hydraulic communication between the Upper and Lower Aquifer, and the occurrence and movement of TCE in groundwater from potential source areas into the Upper Aquifer, and ultimately from the Upper Aquifer into the Lower Aquifer. These apparent discrepancies, and their potential resolution in a refined conceptual model, are explored in subsequent discussion.

2.7.1 Hydraulic Communication and Migration Pathways

Groundwater within the Upper Aquifer moves generally from south to north and northeast beneath GAFB OU1. However, the hydraulics of perched groundwater systems make it unlikely that groundwater “cascades” over the “edge” of the aquitard, eventually moving into the Lower Aquifer (Section 2.1). The low (or nonexistent) rates of recharge to the Upper Aquifer indicate that relatively low rates of groundwater discharge from the Upper Aquifer could maintain the observed hydraulic gradient in the groundwater system west of the bluffs. Evaporative or evapotranspiration discharge along the bluffs is one possible discharge mechanism. During field activities in April and May 1999, cottonwood trees (*Populus deltoides*) were observed at several locations along the base of the bluffs and within arroyos incised in the bluffs. Cottonwoods are phreatophytes, and consume considerable quantities of water. The existence of cottonwood trees at a particular location is generally regarded as an indication that the water table is relatively shallow (Meinzer, 1927).

Examination of the relative configuration of the potentiometric surface in the Upper Aquifer and the topography of the land surface north of the Base boundary provides another possible explanation of groundwater discharge. Groundwater elevations measured near the bluffs (in the vicinity of well EW-11) have historically been at about 2,700 feet amsl (Figure 1.4). Near this location, the large north/northeast-trending arroyo has incised a channel into the bluffs; the base of the channel, just south of well EW-11, is at an elevation of 2,710 feet amsl (Figures 1.8, 2.1, and 2.4). At this point, groundwater may be present beneath the base of the ephemeral channel at a depth of about 10 feet bgs. During stream incision into the bluffs, the arroyo probably also eroded some depth into the aquitard (Figure 2.4). Stream incision into the silt/clay aquitard,

followed by periodic deposition of material derived from the overlying alluvial units, would produce an ephemeral stream channel composed of relatively coarse-grained, clastic material overlying the silt and clay of the aquitard. The coarse-grained deposits filling the ephemeral channel would be juxtaposed with the water-bearing interval of the Upper Aquifer, and would thus be in hydraulic communication with the Upper Aquifer (Figure 2.9). In this situation, groundwater is free to move out of the Upper Aquifer into the deposits of beneath the channel of the ephemeral stream in the arroyo, and thence down the arroyo channel to its point of discharge onto the alluvial fan at the base of the bluffs. Groundwater discharging into the fan could continue to percolate to greater depths as unsaturated (vadose zone) flow, eventually moving into the Lower Aquifer north and east of the bluffs. Arroyo channels may thus function as pathways for preferential movement of groundwater, and of groundwater containing dissolved TCE, from the Upper Aquifer into the Lower Aquifer.

2.7.2 Solvent Disposal and Migration

The historical pattern of solvent disposal at most Air Force bases (small batches of solvents, including TCE, disposed of in sanitary sewers or discharged directly onto the ground) suggests that CAHs likely entered the subsurface from multiple surface or near-surface sources as pure-phase TCE, TCE dissolved in water, or a multiphase liquid consisting of water with an undissolved component of pure-phase TCE. The multiphase liquid could have originated from several sources, including leaking sanitary sewer lines, stormwater outfalls, equipment or aircraft wash water, or limited surface discharges. This scenario may explain the occurrence of TCE in groundwater at relatively elevated concentrations, at locations some distance from the NEDA (e.g., wells NZ-11, NZ-30, NZ-67, and NZ-39). Therefore, TCE in groundwater of the Upper Aquifer may be a consequence of spills or discharges at multiple small sites in the northern part of GAFB, rather than originating at one or more discrete source areas exclusively within the NEDA.

If groundwater moves preferentially from the Upper Aquifer into the Lower Aquifer through alluvium lining the arroyos, then the occurrence and distribution of TCE in groundwater within the Lower Aquifer should provide some indication of this migration pathway. In fact, TCE has been detected in the Lower Aquifer at concentrations greater than the MCL for TCE (5 µg/L) in two general areas: near the base of the bluffs west of the VVWRA facility, and in a restricted area near the base of the bluffs north of the GAFB boundary (Figure 1.9). The larger TCE plume occurs in the Lower Aquifer, immediately beneath and downgradient from the point at which the large, northeast-trending arroyo debouches onto the bajada at the base of the bluffs bordering the Mojave River. The smaller plume is beneath a second, though smaller arroyo. The locations and distributions of TCE in groundwater within the Lower Aquifer therefore generally support the concept of preferential groundwater movement, and associated chemical migration, from the Upper to the Lower Aquifers in saturated alluvium beneath the arroyo channels.

2.7.3 Refined Conceptual Hydrogeologic Model

The revised conceptual model is based on the original conceptual hydrogeologic model developed for GAFB OU1 and presented in the ROD (Figure 1.3 and Section 2.1), and, based on the preceding discussions, incorporates the following refinements:

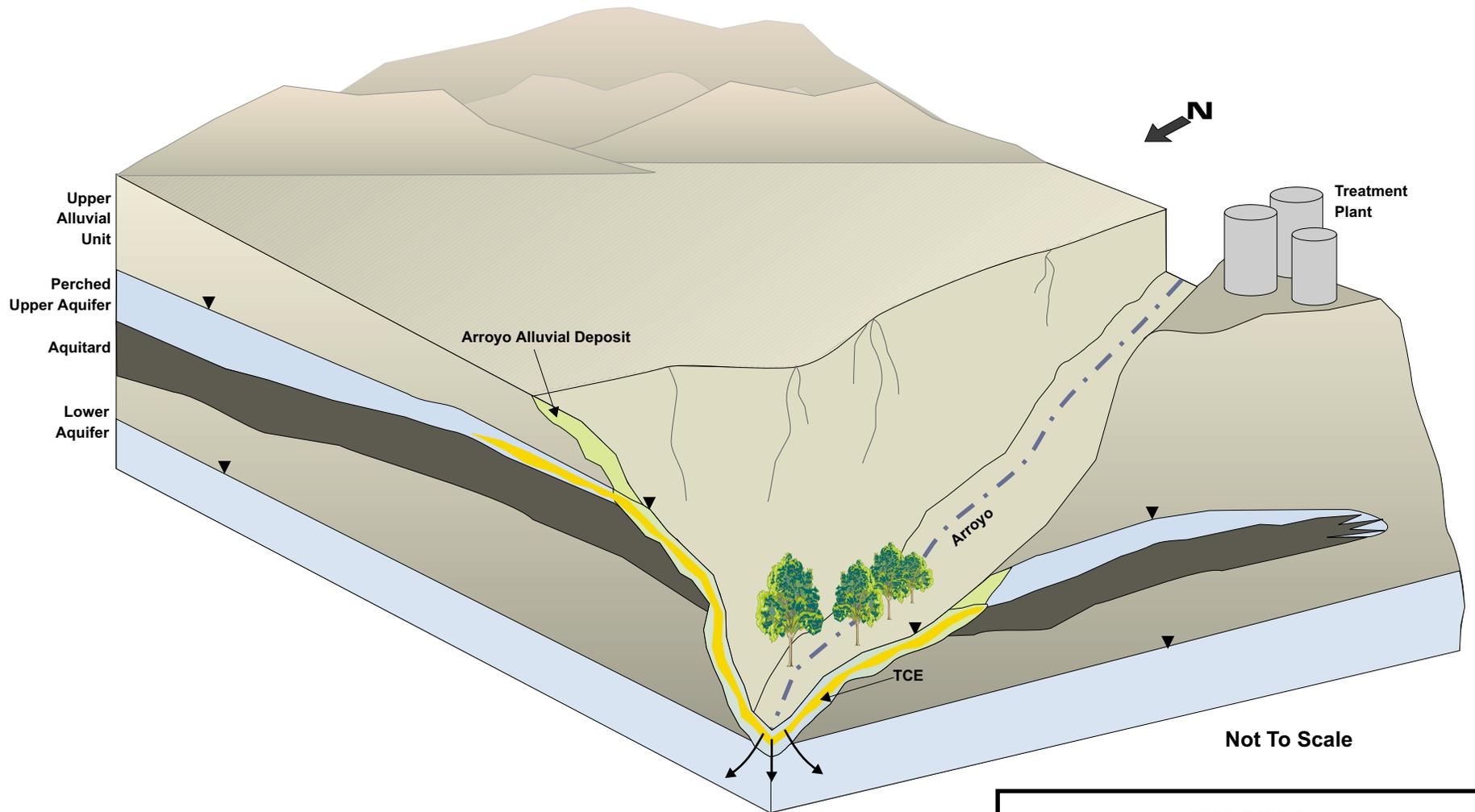


FIGURE 2.9
CONCEPTUAL MODEL OF TCE MIGRATION FROM UPPER TO LOWER AQUIFER
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Denver, Colorado

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- Recharge to the Upper Aquifer is probably limited. Some recharge to the Upper Aquifer may occur from precipitation falling in the San Bernardino Mountains south of GAFB and percolating into alluvial fans along the mountain front (Martin, 1994). However, as a consequence of the relatively great distances from the mountains to GAFB, groundwater travel times are quite long.
- Most groundwater recharging the Lower Aquifer originates in the Mojave River (Izbicki *et al.*, 1995; Lines, 1996). During river flood stages, groundwater moves from the stream channel into the adjacent saturated alluvium, and thence into the Lower Aquifer. During lower stages, groundwater moving parallel to the river as underflow in the saturated alluvium also can move into the Lower Aquifer. Downstream from (north of) GAFB, groundwater from the Lower Aquifer discharges along gaining reaches of the Mojave River.
- The Upper and Lower Aquifers are in hydraulic communication only at relatively discrete points along the base of the bluffs that border the Mojave River floodplain. Points of groundwater movement out of the Upper Aquifer occur where surface drainage (arroyo) erosion has breached the aquitard, enabling groundwater to move out of the Upper Aquifer into unconsolidated alluvium along the ephemeral channels. Groundwater then moves through the alluvium to the base of the bluffs, and percolates into the Lower Aquifer via unsaturated-flow mechanisms. It is likely that some groundwater is discharged from the Upper Aquifer as evapotranspiration and/or seepage along the bluffs.
- The sources of TCE in groundwater of the Upper Aquifer are not currently known, but probably consist of several relatively small, distinct discharge points, spread across a wide area.
- TCE in groundwater of the Lower Aquifer has probably migrated from the Upper Aquifer along the channels of arroyos that function as pathways for preferential movement of groundwater (Figure 2.9). Therefore, the locations at which TCE migrates from the Upper Aquifer into the Lower Aquifer are probably areally restricted and limited in number.
- Significant biotransformation of TCE via reductive dehalogenation mechanisms is probably not occurring at GAFB OU1, despite the localized presence of anaerobic, reducing conditions in site groundwater. Other natural attenuation processes, including sorption and dispersion, are probably more important in reducing the concentrations of TCE in groundwater at GAFB OU1.

Some uncertainty is associated with particular aspects of the refined conceptual hydrogeologic model. In particular, the nature of the hydraulic connection between the Upper and Lower Aquifers is not completely understood, and hydraulic conditions within the alluvium beneath the arroyos has not previously been evaluated. Completion of additional characterization activities in selected locations (e.g., along the arroyos) will probably be necessary to resolve the remaining uncertainties (Section 5).

SECTION 3

EVALUATION OF CLEANUP GOALS

As discussed in Section 1, the RPO evaluation provides an opportunity to review the RAOs and cleanup goals for GAFB OU1, and to increase the degree of interaction and communication with regulatory officials responsible for oversight of remediation activities. This enables site information to be updated, and can potentially lead to revision of cleanup goals.

Enforcement actions at GAFB began in 1986, with adoption of a Cleanup and Abatement Order by Lahontan RWQCB (Montgomery Watson, 1994). This resulted in the initiation of site investigation activities under the IRP. In 1990, GAFB was placed on the National Priorities List (NPL) by USEPA, and in October 1990, the Air Force entered into a Federal Facilities Agreement (FFA) with USEPA Region 9, the California Department of Health Services (DHS; now the California Environmental Protection Agency [CalEPA] Department of Toxic Substances Control [DTSC]), and the Lahontan RWQCB. These regulatory agencies continue to oversee investigation and remediation activities at GAFB. In 1994, the Secretary of CalEPA designated DTSC as the lead agency for remediation activities at all military installations in California. DTSC is responsible for coordinating cleanup activities, and for ensuring that the RWQCB's concerns regarding water quality issues are addressed.

Provisional cleanup goals typically are established during the CERCLA RI process by considering potentially applicable or relevant and appropriate requirements (ARARs). The RI/FS for OU1 at GAFB was completed under the jurisdiction of USEPA Region 9 and CalEPA (JMM, 1992 and 1993). Section 121(d) of CERCLA requires that remedial actions attain all promulgated "applicable or relevant and appropriate standard(s), requirement(s), criteria, or limitations(s)" (i.e., ARARs), unless specific requirements for not doing so are satisfied (42 United States Code [USC] §9621(d); Title 40 Code of Federal Regulations [CFR] Part 300.5).

There are three kinds of ARARs – chemical-specific, location-specific, and action-specific. The identification of ARARs applied to GAFB OU1 is discussed below.

3.1 CHEMICAL-SPECIFIC ARARS

The chemical-specific ARARs for groundwater in OU1 are federal drinking water standards and those standards promulgated by the State of California that are more stringent than the federal standards. Cleanup levels are set at health-based levels reflecting current and potential groundwater use, and receptor exposure (Montgomery Watson, 1994). For systemic (noncarcinogenic) contaminants, cleanup levels represent the concentration to which humans could be exposed on a daily basis without appreciable adverse effects occurring during their lifetime. For carcinogens, cleanup levels must fall within a range that will produce no more than 10^{-4} (one in 10,000) to 10^{-6} (one in 1,000,000) excess carcinogenic risk (40 CFR 300.430[e][2][i][A][2]). According to California Proposition 65, an excess carcinogenic risk of

10⁻⁵ represents a level of “no significant risk”. Soil ARARs are not available, and other potential cleanup goals for soil were not specified in the ROD because no source area for TCE has been identified for OU1.

Currently established drinking water regulations include MCLs for specific contaminants (Section 1412 of the Safe Drinking Water Act, 42 USC 300(g)(1), National Primary Drinking Water Regulations, 40 CFR Part 141). The federal MCL of 5 µg/L for TCE was selected by CalEPA as the groundwater cleanup standard for OU1, and this standard is applied to all groundwater beneath and downgradient from the NEDA at GAFB OU1 (Montgomery Watson, 1994).

3.2 LOCATION-SPECIFIC ARARS

Location-specific ARARs are restrictions placed on the concentrations of hazardous substances or the conduct of activities solely because they occur in specific locations. Some examples of specific locations to which ARARs could be applied include floodplains, wetlands, historic places, and sensitive ecosystems or habitats (USEPA, 1988). Endangered species and their habitats are protected under the Endangered Species Act (ESA) (16 USC §1531-1543). The desert tortoise and the Mohave ground squirrel are potentially sensitive, rare, or threatened species in the vicinity of GAFB OU1 that are protected under the ESA. Therefore, the ESA was identified in the ROD as an ARAR for on-site actions (Montgomery Watson, 1994).

3.3 ACTION-SPECIFIC ARARS

Action-specific ARARs are restrictions that define acceptable treatment and disposal procedures for hazardous substances. These ARARs generally establish performance, design, or other similar action-specific controls or restrictions on particular kinds of activities related to management of hazardous substances or pollutants, such as Resource Conservation and Recovery Act of 1976 (RCRA) regulations for waste treatment, storage, and disposal. These requirements are invoked for particular activities that are selected to accomplish a remedy; therefore, the type and nature of these requirements is dependent upon the particular remedial or removal action undertaken at a site, and different actions or technologies often are subject to different action-specific ARARs.

Domestic use of water ("drinking water") is considered to be the highest beneficial use, and remediation to drinking-water standards affords the greatest level of protection and cleanup. Most environmental regulations dealing with groundwater in California, including the Porter-Cologne Water Quality Control Act, are intended to protect groundwater as a drinking-water resource. In the “*Findings and Declarations*” for the Act (§174 *et seq.*),

“The Legislature hereby finds and declares that in order to provide for the orderly and efficient administration of the water resources of the state it is necessary to establish a control board which shall exercise the adjudicatory and regulatory functions of the state in the field of water resources.”

“It is also the intention of the Legislature to combine the water rights and the water pollution and water quality functions of state government to provide for consideration of water pollution and water quality, and availability of unappropriated water whenever applications for appropriation of water are granted or waste discharge requirements or water quality objectives are established.”

As required by the California Porter-Cologne Water Quality Control Act, the Lahonton RWQCB defines the beneficial uses of various water bodies for the Mojave River Basin.

The Lahonton Basin Plan, which designates water bodies within the basin, and their beneficial uses, classifies aquifers within the OU1 area as having "*existing or potential beneficial uses as sources of drinking water*" (Lahontan RWQCB, 1998). This regional plan has been promulgated by the state, and portions thereof currently are considered ARARs with respect to OU1. The identification of the beneficial uses of the groundwater at OU1 serves as the basis for selection of the federal MCL of 5 µg/L for TCE as the standard for groundwater cleanup, and the identification of maximum TCE concentrations of 5 µg/L and median TCE concentrations of 2.5 µg/L, as measured at the effluent sampling port of the treatment system, and of 0.5 µg/L, as measured at the percolation ponds, as the standards for discharge of treated air-stripper effluent (Montgomery Watson, 1994). Because of the generally low influent TCE concentrations, cleanup standards for air-stripper off-gas air emissions were not specified in the ROD (Montgomery Watson, 1994).

3.4 RPO EVALUATION AND THE REGULATORY FRAMEWORK

Groundwater beneath GAFB OU1 is designated as a municipal-use resource ("MUN") in the Lahontan Basin Plan (Lahontan RWQCB, 1998); therefore, RAOs and cleanup goals at GAFB OU1 were established based on the assumption that all groundwater beneath and downgradient from the NEDA represents a potential source of drinking water. However, a water body is a source (or potential source) of drinking water only if it is in current domestic use, or will be available for use at some point in the future. In certain circumstances, institutional controls (e.g., restrictions on the use of groundwater) may effectively preclude particular uses of water. Furthermore, although the Water Resource Board of the State of California has adopted a non-degradation policy for groundwater, adverse impacts on a body of water that may affect its potential uses do not occur at the point of introduction of contaminants, but rather occur at points of exposure of potential receptors, which is the point at which MCLs and other drinking-water standards are measured (40 CFR §141.2). In recognition of these facts, the framework of environmental regulation in recent years has evolved from strict application of numerical standards to the application of risk-based standards at individual sites, while incorporating careful consideration of site-specific factors and potential use of resources, including land and water (American Society for Testing and Materials [ASTM], 1999).

Chemical release sites vary considerably in terms of complexity, physical and chemical characteristics, and in the potential risks that they may pose to human health and the environment. The risk-based corrective action (RBCA) process addresses this diversity by using a tiered approach that 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. Current conditions at GAFB OU1 suggest that re-evaluation of the RAOs and cleanup goals specified in the ROD for the site (Montgomery Watson, 1994) may be appropriate for the following reasons:

- The maximum concentrations of TCE in much of the groundwater system downgradient from the NEDA are below detection limits or MCLs, and TCE concentrations in some areas are declining (Figures 2.6 and 2.7).
- Groundwater directly beneath the NEDA is not currently used as a source of drinking water; and no completed pathway currently exists for exposure of potential receptors to

groundwater downgradient from OU1. Imposition of institutional controls could effectively prevent such use/exposure in the future, while attenuation mechanisms continue to reduce the mobility, toxicity, or mass of contaminants in groundwater.

- Dissolved TCE originating at the NEDA has migrated in groundwater a distance of perhaps several thousand feet past the northern boundary of GAFB (Figures 1.8 and 1.9). However, the potential for further migration of TCE at concentrations of potential human-health concern to the nearest identified potential exposure point, the VVWRA wells 3,500 feet north of GAFB, in the absence of active groundwater extraction, is not certain.

These observations suggest that an RPO evaluation of the regulatory framework under which the RAOs and cleanup goals for GAFB OU1 were established may be appropriate (Figure 3.1).

3.5 APPLICABILITY OF ARARS AND ALTERNATE STANDARDS

As discussed above, examination of the regulatory framework under which the RAOs and cleanup goals were established for a given site is part of the RPO evaluation (Parsons ES, 1999a). Therefore, the RAOs for GAFB OU1, and the ARARs under which the RAOs were developed and the remedial alternatives were screened, were evaluated to determine if they remain applicable, relevant, and appropriate in light of current site conditions and the evolution of environmental regulations. Alternate cleanup goals also were evaluated.

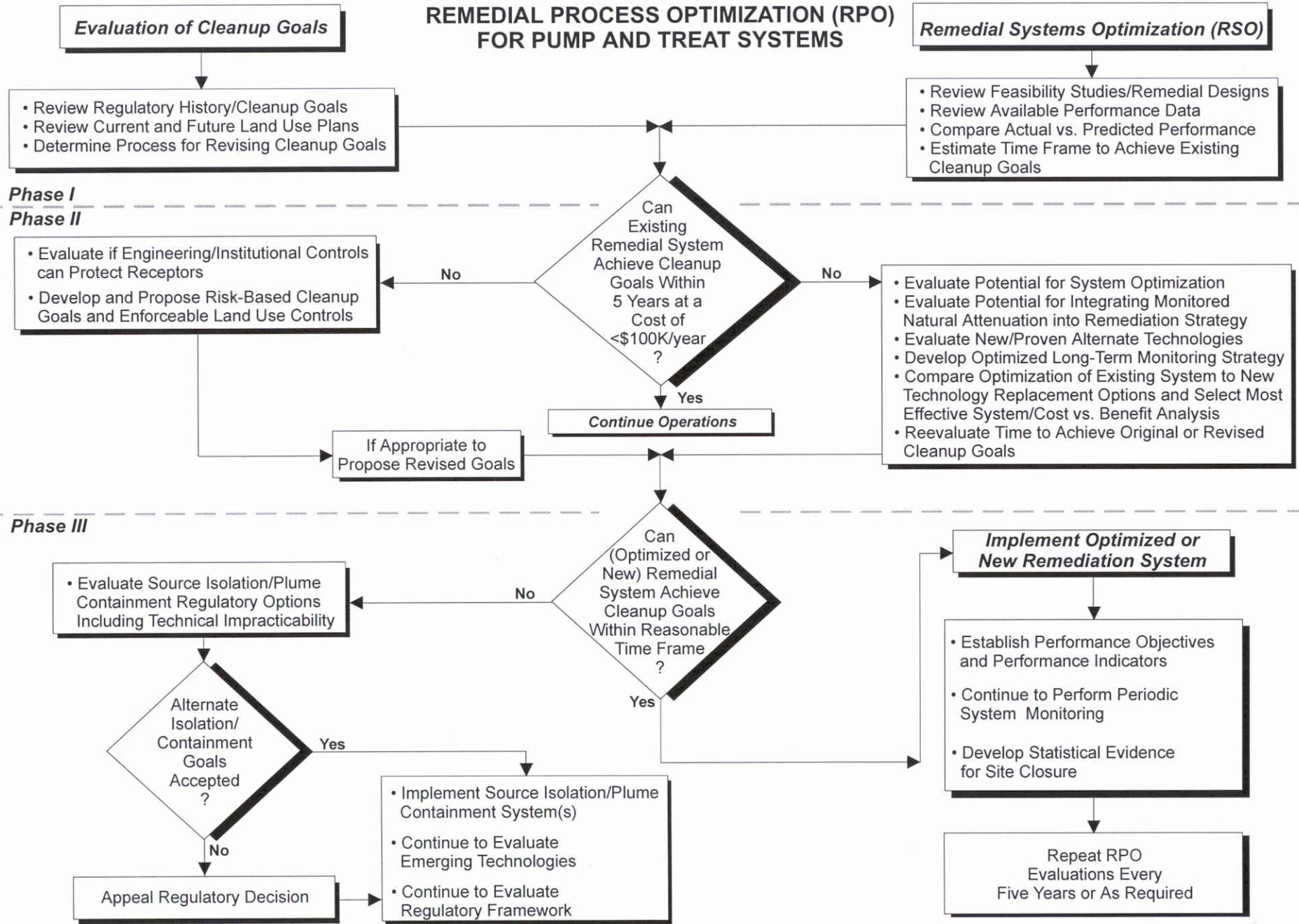
3.5.1 ARAR-Based Cleanup Goals

A 1992 human-health endangerment assessment completed as part of the RI (JMM, 1992) indicated that other remedial measures, in addition to the nine-well groundwater extraction system then in operation, should be implemented for affected groundwater beneath and downgradient from the NEDA. Accordingly, a second FS was completed to summarize and reassess the results of the earlier FS, and to revise the results to bring them into compliance with then-current standards (JMM, 1993). As part of the second FS, RAOs were identified based on the results of the risk assessment, ARARs, and standards to be considered (TBCs).

As stated in the 1994 ROD for GAFB OU1, the primary RAO for groundwater associated with OU1 was identified as "*protection of human health and the environment*" (Montgomery Watson, 1994). After a series of negotiations among the Air Force, the Lahontan RWQCB, and USEPA Region 9, the federal MCL for TCE in drinking water (5 µg/L) was identified as the chemical-specific ARAR establishing the final cleanup level for TCE in groundwater beneath the NEDA, although groundwater beneath the NEDA was not then in use as a drinking-water supply. The State of California's Water Resources Control Board Resolution 68-16 (the "non-degradation" policy) was identified as the action-specific ARAR for discharge of treated water into the percolation ponds at OU1 (JMM, 1993; Montgomery Watson, 1994). The RAOs identified in the ROD for GAFB OU1 were as follow:

- Prevent receptor exposure to contaminated water that poses a risk of greater than 1×10^{-6} (*Risk Objective*);
- Reduce the TCE contamination in OU1 groundwater to concentrations below the federal MCL of 5 µg/L (*Cleanup Objective*);

**FIGURE 3.1
REMEDIAL PROCESS OPTIMIZATION (RPO)
FOR PUMP AND TREAT SYSTEMS**



3-5

- Reduce the TCE concentrations in treated groundwater effluent to meet the enforceable level of 2.5 µg/L on a median basis with a maximum discharge level of 5 µg/L. The concentrations of TCE in the percolation ponds were not to exceed 0.5 µg/L (*Discharge Objective*);
- Eliminate or reduce the potential for further migration of the existing TCE plume in groundwater (*Containment Objective*); and
- Specify a treatment system that can be expanded to address a larger area/volume of groundwater, if needed (*Design Objective*).

3.5.2 Exposure Pathway Analysis

An exposure pathway analysis identifies the human and ecological receptors that could potentially come into contact with site-related chemicals and the contaminant migration pathways through which these receptors might be exposed (Appendix B). To have a completed exposure pathway, there must be a source of contamination, a mechanism(s) of release, a pathway of transport to an exposure point, an exposure route, and a receptor. If any of these elements does not exist, the exposure pathway is considered incomplete, and receptors will not come into contact with site-related chemicals. Assumptions about current and future land uses at a site form the basis for identifying potential receptors, potential exposure routes, reasonable exposure scenarios, and appropriate remediation goals. USEPA (1991) advises that the land use associated with the highest (most conservative) potential level of exposure and risk that can reasonably be expected to occur should be used to guide the identification of potential exposure pathways and to determine the level to which the site must be remediated.

The human-health endangerment assessment used to establish the risk and cleanup objectives for groundwater at GAFB OU1 assumed that groundwater from the Upper Aquifer was not currently used as a water supply. Therefore, no current residential groundwater exposure pathway was regarded as complete, and risks were not calculated. The future, potentially-exposed population included on- and off-site residents (children and adults), who were assumed to use groundwater from the Upper Aquifer as a source of potable water (JMM, 1992). Even though this exposure scenario is unrealistically conservative, the highest excess carcinogenic risk to a future resident, using groundwater beneath the NEDA, was estimated to be 9×10^{-5} , for the 95-percent upper-bound confidence limit for the combined ingestion, dermal, and inhalation routes. Most exposure routes generated estimates of excess carcinogenic risk in the range of 1×10^{-5} to 1×10^{-6} (JMM, 1992). These risk levels are within the acceptable range established in the National Hazardous Substances Pollution Contingency Plan (NCP) (1×10^{-4} to 1×10^{-6}). With the exception of the values for the inhalation exposure route (which assumes that a hypothetical future resident would be exposed to TCE volatilized from groundwater while showering), the risk levels were also within the range established by Proposition 65 of the State of California as representing “no significant risk” ($\leq 1 \times 10^{-5}$). This suggests that an updated risk evaluation, completed using more realistic assumptions, could result in the adoption of alternative RAOs and cleanup goals.

3.5.3 Risk-Based Cleanup Goals

To evaluate alternative cleanup goals for groundwater at OU1, an example risk-based screening level (RBSL) was developed for TCE in groundwater using a generic industrial

exposure scenario. The RBSL illustrates how the RBCA process can be used to develop cleanup goals based on more realistic land use and exposure assumptions for comparison to the cleanup goals established in the ROD.

The RBSL developed for TCE (Appendix C) and the cleanup goal presented in the ROD (Montgomery Watson, 1994) are compared in Table 3.1. The RBSL was developed for a generic, industrial land-use scenario, which is consistent with the expected land-use for GAFB OU1. The example RBSL was developed based on the following exposure assumptions:

- Groundwater at GAFB OU1 is not a source of drinking water; and institutional controls will be sufficient to prevent such use for the foreseeable future;
- An on-site well will be used to supply water for on-site irrigation purposes only (no consumption);
- Groundskeepers may be exposed through dermal contact to contaminants in extracted groundwater used for landscape irrigation;

TABLE 3.1
EXAMPLE RISK-BASED CLEANUP GOAL
OU1 TCE PLUME
REMEDIAL PROCESS OPTIMIZATION
GEORGE AFB, CALIFORNIA

Contaminant	Example Risk-Based Cleanup Goal for OU1 Groundwater (µg/L) ^{a/}	Current OU1 Groundwater Cleanup Goal (µg/L) ^{b/}
TCE	1,130	5

^{a/} Generic industrial risk-based screening level for groundwater, see Appendix C.

^{b/} From the record of decision for OU1 (Montgomery Watson, 1994).

- The dermal contact exposure route is the only potentially significant completed exposure route for the groundskeeper;
- Based on assumed attire, the hands, forearms, and lower legs would be the body parts dermally exposed;
- The groundskeeper will irrigate up to once per week for 50 weeks per year. The irrigation frequency in the warmer months may be 2 times per week, but in the winter this would occur less frequently, thereby averaging approximately once per week for a given year; and
- The risk-based cleanup goals are based on 1×10^{-6} excess carcinogenic risk, as required by the Lahonton RWQCB (1998) Basin Plan.

Because TCE in groundwater occurs at depths generally greater than 40 feet bgs at GAFB OU1, other direct exposure routes (such as incidental ingestion of or dermal contact with groundwater by an intrusive construction worker) are considered incomplete, and were not

included in this evaluation. Details of the assumptions, exposure models, and input parameters used to develop the RBSL for TCE are presented in Appendix C.

The RBSL for TCE, established using a generic, non-ingestion industrial exposure scenario, is nearly three times the highest concentrations of TCE historically detected in groundwater at GAFB OU1 (Section 1.3.4). RBSLs for TCE assuming that groundwater consumption occurs under generic industrial land-use scenarios also are presented in Appendix C. These cleanup goals are one to two orders of magnitude greater than the MCL for TCE listed in Table 3.1, but lower than the maximum detected TCE concentration of 420 µg/L in the Upper Aquifer. Therefore, any alternative remedial strategies for GAFB OU1 should also include land-use restrictions to prevent groundwater consumption.

It should be noted that the risk-based cleanup goal presented in Table 3.1 was developed using generic exposure assumptions for industrial settings, and does not represent actual site conditions at OU1. Site-specific risk-based cleanup goals could be developed for GAFB OU1 as a part of the 5-year ROD review process, if regulatory approval can be obtained for such development. The TCE cleanup goal presented in Table 3.1 is based on USEPA's (1996) conservative default parameters and assumptions for the industrial scenario. Therefore, if the exposure assumptions used to develop site-specific risk-based goals are similar to those presented above, the site-specific goal for TCE likely would be less conservative than the one presented in Table 3.1.

3.5.4 Alternate Cleanup Goals

Under current Lahontan RWQCB regulations, the Air Force may apply for an alternate cleanup goal for TCE in groundwater at GAFB OU1. The Lahontan RWQCB Basin Plan (1998) and Title 27 of the California Code of Regulations (CCR) include guidelines to be followed in applying for concentration limits greater than background (CLGB). The guidelines state that a RWQCB can establish a CLGB only if the Board finds that it is technologically or economically infeasible to achieve the background value for that constituent, and that the constituent will not pose a substantial current or potential hazard to human health or the environment as long as the CLGB is not exceeded. To establish a CLGB for a chemical of concern, Title 27 states that the RWQCB should consider the following factors that could lead to potential adverse effects on groundwater quality and beneficial uses:

- The physical and chemical characteristics of the waste at the site;
- The hydrogeological characteristics of the facility and surrounding land;
- The quantity of groundwater and the direction of groundwater flow;
- The proximity and withdrawal rates of groundwater users;
- The current and potential future uses of groundwater in the area;
- The existing quality of groundwater, including other sources of contamination or pollution and their cumulative impact on groundwater quality;
- The potential for health risks caused by human exposure to waste constituents;
- The potential damage to wildlife, crops, vegetation, and physical structures caused by exposure to waste constituents; and
- The persistence and permanence of the potential adverse effects.

As required by the Porter-Cologne Water Quality Control Act and the Lahontan Basin Plan, if changes in RAOs and cleanup levels for groundwater at GAFB OU1 are proposed in accordance with Title 27 guidelines, these must be approved by the full Regional Board.

3.5.5 Technical Impracticability Waiver

There are provisions in federal and state regulations for exceptions to the application of MCLs as ARARs. In making exceptions for water use designation, the Lahontan Basin Plan considers the criteria in the Regional Board Resolution No. 6-89-94, including conditions at a site where “there is contamination that cannot reasonably be treated for domestic use either by Best Management Practices or best economically achievable practices”. Under the current regulatory framework, groundwater at GAFB OU1 may meet such criteria. Non-attainability of MCLs in groundwater would also need to be demonstrated under USEPA’s (1993) technical impracticability (TI) waiver protocol. ARARs may be waived by USEPA for any six of the reasons specified in the NCP (CERCLA 121[d][4]), including technical impracticability from an engineering perspective. The TI evaluation generally must include the following components based on site-specific information and analyses (USEPA, 1993):

- Specific ARARs or media cleanup standards for which TI determinations are sought;
- Spatial area over which the TI waiver will apply;
- Conceptual model that describes site geology, hydrology, groundwater contamination sources, chemical migration, and fate;
- An evaluation of the restoration potential of the site, including data and analyses that support assertions that attainment of ARARs or media cleanup standards is technically impractical from an engineering perspective. At a minimum, this generally should include:
 - A demonstration that containment sources have been identified and have been or will be removed and contained to the greatest extent possible;
 - An analysis of performance of any ongoing or completed remedial action;
 - Predictive analysis of the time frames to attain required cleanup levels using available technologies; and
 - 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 time frame.
- Estimate of cost of the existing or proposed remedy options, including construction and OM&M costs; and
- Any additional information or analyses that USEPA deems necessary for the TI evaluation.

The process of applying for a TI waiver, and providing the necessary documentation, is typically arduous, and may require a period longer than 1 year. Nevertheless, under certain

circumstances, the relative costs and benefits involved in seeking a TI waiver can compare favorably with the relative costs and benefits associated with maintaining an existing remediation system.

3.6 INSTITUTIONAL CONTROLS

Adoption of risk-based or alternate cleanup goals, or pursuit of a TI waiver will require cooperation of federal, state, and local government agencies, and implementation of land-use controls. Effective, long-term land-use planning and zoning may be desirable to ensure that future remedial actions are compatible with future uses of the land. Institutional controls are considered to be an important complement to other treatment technologies, and in most cases are critical to the successful implementation of a remedial action.

The primary RAO for groundwater at GAFB OU1 is to reduce the concentrations of TCE in groundwater to levels below potentially applicable regulatory standards or guidelines, or to levels that will not pose substantial risk to potential human or ecological receptors. Because TCE is already present in groundwater within the Upper Aquifer at the NEDA, and within a restricted part of the Lower Aquifer north of the GAFB boundary, short-term compliance with promulgated drinking water standards is not possible. However, groundwater in these areas is not currently used as a potable water supply; and effective institutional controls could be imposed to ensure that groundwater is not used as a potable water supply through the duration of a particular remedial action. Thus, the magnitude of remediation required in areas that could be placed under institutional control is different than remediation that might be required in areas that may be available for unrestricted groundwater use. Institutional controls therefore are likely to be a necessary and key component of any groundwater remediation strategy for this site.

Institutional controls restricting the uses of groundwater at GAFB OU1 were imposed as a condition of the ROD (Montgomery Watson, 1994), and could be extended or broadened in scope, as necessary, to accommodate the requirements of risk-based, or other alternate cleanup goals.

SUMMARY

Examination of the structure and results of the human-health endangerment assessment, used as a basis for the cleanup goals specified in the ROD, suggest that the assumptions used to develop the exposure scenarios were unnecessarily conservative, and produced unrealistically elevated estimates of human-health risk. Even so, the highest excess carcinogenic risk to a future resident using groundwater beneath the NEDA for domestic purposes, for the 95-percent upper-bound confidence limit for the combined ingestion, dermal, and inhalation pathways, was estimated to be 9×10^{-5} . This is within the acceptable range established in the NCP (1×10^{-4} to 1×10^{-6}). Alternate risk-based cleanup goals for TCE in groundwater generated using a more realistic, non-consumption industrial exposure scenario, are nearly three times the highest concentrations of TCE historically detected in groundwater at GAFB OU1, suggesting that the current cleanup goal established in the ROD may be lower than necessary. Furthermore, the level of risk estimated to occur under this exposure scenario is well within the levels considered by the State of California (Proposition 65) to represent “no significant risk”.

Several mechanisms are available for negotiating alternate or risk-based cleanup goals, including guidance established in the Lahontan RQCB Basin Plan (1998), 27 CCR, and USEPA's (1993) TI waiver process. Adoption of alternate or risk-based goals will require the

cooperation of local, state, and federal agencies, and should be a matter for discussion during planned reviews of the ROD for GAFB OU1.

Institutional controls restricting the uses of groundwater at GAFB OU1 are currently required by the ROD (Montgomery Watson, 1994), and could be extended or broadened in scope, as necessary, to accommodate the requirements of risk-based or other alternative cleanup goals. Such controls would be used to restrict the locations and types of groundwater wells that could be installed in the plume vicinity.

SECTION 4

EVALUATION OF REMEDIAL SYSTEM

In Section 3, the rationale for installation of the current remediation system for OU1 was discussed in the context of remediation goals established for the site. Possible procedures for evaluating and establishing alternative cleanup objectives were also examined.

The overall objectives of the groundwater pump-and-treat system at GAFB OU1 were established in the ROD (Montgomery Watson, 1994). Because the effectiveness and efficiency of a remediation system are directly related to its ability to achieve its objectives (e.g., RAOs), attainment of RAOs can be used as a measure of system performance. Evaluation of a system during the RPO process occurs in two phases:

Phase I – Annual performance evaluations to examine system performance to date, to recommend minor modifications to the system, and to assess whether a more involved evaluation is necessary (i.e., Phase II).

Phase II – A more rigorous review of the entire remedial decision and implementation process.

This section focuses on a Phase II review of the existing pump-and-treat system (remedial decisions are evaluated in Section 3) leading to short-term recommendations, and identification of longer-term opportunities for improvement (Section 5).

4.1 FEASIBILITY STUDIES, RECORD OF DECISION, REMEDIAL ACTION OBJECTIVES, AND PERFORMANCE CRITERIA

A two-phase FS was completed for GAFB OU1 in 1988 (JMM, 1988b) using 1985 guidance under CERCLA (USEPA, 1985). The preferred remedial alternative identified during the initial FS consisted of groundwater extraction, removal of VOCs from extracted groundwater using air stripping, and recharge of treated groundwater to the Upper Aquifer by infiltration from the former STP percolation ponds. The first phase of the groundwater extraction and treatment system, consisting of nine pumping wells, an influent wet-well, an air stripping tower, an effluent wet-well, and associated piping, electrical power, and ancillary equipment, was installed and operational by late 1991 (Montgomery Watson, 1998c).

As stated in the ROD for OU1, the primary RAO for groundwater associated with OU1 was identified as "protection of human health and the environment" (Montgomery Watson, 1994). This broad objective was framed in terms of a series of specific RAOs, identified in the ROD as addressing ARARs (Section 3). These specific objectives, introduced in Section 3.5.1 and listed in Table 4.1, represent potential evaluation criteria for system performance. The Risk, Cleanup, and Containment Objectives generally apply to groundwater remaining in the subsurface; the Discharge Objective applies to the above-ground treatment system; and the Design Objective applies to expansion of the existing system, if necessary (Table 4.1).

TABLE 4.1
MEASURABLE PERFORMANCE CRITERIA
REMEDIAL PROCESS OPTIMIZATION, OU1
GEORGE AIR FORCE BASE, CALIFORNIA

Remedial Action Objective	Corresponding Performance Criterion	Rationale
1. Prevent exposure to contaminated water that poses a risk of greater than 1×10^{-6} (<i>Risk Objective</i>).	None.	Groundwater pump-and-treat alone cannot prevent exposure to TCE already in groundwater. Institutional controls, currently in place, prevent exposure to contaminated groundwater.
2. Reduce the TCE contamination in groundwater beneath the NEDA to below the federal MCL of 5 µg/L (<i>Cleanup Objective</i>).	Remove sufficient TCE mass from the subsurface so that the maximum TCE concentration in groundwater at any point beneath OU1 does not exceed 5 µg/L.	OU1 groundwater is assumed to be a current source of drinking water. In the absence of adoption of site-specific risk-based cleanup goals, the federal MCL for TCE is presumed to be protective of human health.
3. Reduce the TCE in treated groundwater effluent to meet the enforceable level of 2.5 µg/L TCE on a median basis with a maximum discharge level of 5 µg/L. The concentrations of TCE in the percolation ponds are not to exceed 0.5 µg/L (<i>Discharge Objective</i>).	None.	Applicable only to effluent from the treatment system. Current discharge limitations were established on the basis of California's "non-degradation" policy for groundwater. The limitations presume that all water discharged to infiltration ponds will migrate to groundwater, and that all dissolved TCE in effluent will also migrate to groundwater. In reality, most TCE likely will volatilize, and the remainder is unlikely to migrate to groundwater.
4. Eliminate or reduce the potential for further migration of the existing TCE plume in groundwater (<i>Containment Objective</i>).	Remove all TCE from groundwater beneath OU1; or, failing that, continue pumping to control plume migration	If TCE remains in groundwater, in the absence of pumping, it will migrate with the natural hydraulic gradient toward the Mohave River.
5. Specify a treatment system that can be expanded to address a larger area/volume, if needed (<i>Design Objective</i>).	None.	This RAO not applicable to evaluation of effectiveness/efficiency of current system.

Performance criteria for any system should be viewed as measurable milestones on the road to achieving site cleanup objectives and site 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 at least annually to assess system effectiveness/efficiency.

Several of the RAOs, as stated in the ROD (Montgomery Watson, 1994), are not directly applicable as criteria of system performance (e.g., the Risk Objective listed in Table 4.1). Therefore, as part of this RPO evaluation, measurable performance criteria for the OU1 groundwater pump-and-treat system were developed based on the RAOs. The performance criteria, and the rationale for their selection, are provided in Table 4.1 for each of the RAOs.

In some circumstances, cleanup to a concentration-based standard (e.g., the federal MCL) can mean reducing the average concentration of contaminants within a plume to a level below the concentration-based standard. However, taken in conjunction with the State of California's non-degradation policy, RAO 2 appears to require that remediation will continue until the concentration of TCE at every point in the groundwater system beneath, or down-gradient of the NEDA is below the federal MCL of 5 µg/L. In the absence of detailed knowledge of the distribution of TCE mass and concentrations at every point in groundwater beneath GAFB OU1, it is not possible to predict the TCE mass that must be removed in order to reduce the concentrations of TCE at every point in the groundwater system to levels below 5 µg/L. Therefore, Performance Criterion 2, associated with the Cleanup Objective, cannot be applied, in its current form. Rather, the estimated rates of mass removal will be used as a surrogate for the rate of concentration reduction in Performance Criterion 2.

Performance Criteria 2 and 4, associated with the Cleanup and Containment Objectives, are the standards that will be examined in the evaluation of system effectiveness.

4.2 EFFECTIVENESS/EFFICIENCY EVALUATION OF CURRENT PUMP-AND-TREAT SYSTEM

4.2.1 Effectiveness of Current Extraction System

The current groundwater extraction system includes 18 wells – 10 wells completed in the Upper Aquifer, and intended to remove TCE mass, and 8 wells completed in the Lower Aquifer, and intended to contain plume migration (Montgomery Watson, 1999c). The design production rates for the individual wells in the current extraction system range from 2 gpm to 160 gpm (Table 4.2); the actual production rates of wells completed in the Upper Aquifer (2 to about 50 gpm) are generally much lower than the production rates of wells completed in the Lower Aquifer (20 to 200 gpm).

Ultimately, the effectiveness of a remediation system is judged by evaluating how well it achieves its objectives; and it is optimized if it is effectively achieving its objectives at the lowest total cost, in the shortest period of time, or both. The effectiveness of the complete system, and of the individual wells in the system, were evaluated in terms of the two complementary objectives of Performance Criterion 4 – mass removal and plume containment (Tables 4.1 and 4.3). Although incremental improvements in the effectiveness and efficiency of a groundwater extraction system may be achieved through changes in well placement or depth intervals of

TABLE 4.2
RECENT PRODUCTION HISTORY OF GROUNDWATER EXTRACTION WELLS
REMEDIAL PROCESS OPTIMIZATION, OU-1
GEORGE AIR FORCE BASE, CALIFORNIA

Extraction Well	Producing Unit ^a	Screened Interval (feet bgs ^b)	Approximate Saturated Thickness (feet)	Design Production Rate (gpm ^c)	Actual Production Discharge Rate (Date)							Approximate TCE Concentration in Well Discharge		Current TCE Removal Rate	
					6/29/1998	9/21/1998	12/28/1998	3/29/1999	5/4/1999	6/1/1999	6/28/1999	(µg/L ^d)	(Date)	(lbs/year ^e)	
					(gpm)	(gpm)	(gpm)	(gpm)	(gpm)	(gpm)	(gpm)				
EW-1	Upper	108 -- 148	39	20	24	20	20	20	20	22	21	21	16	10/15/1998	1.5
EW-2	Upper	96 -- 136	25	12	8	10	10	14	14	13	17	12	10/15/1998	0.9	
EW-3	Upper	86 -- 126	31	20	24	17	12	12	3	17	18	41	10/15/1998	3.2	
EW-4	Upper	90 -- 130	40	6	12	12	12	9	8	9	9	38	10/15/1998	1.5	
EW-5	Upper	50 -- 80	26	2	9	NA	0	0	2	2	2	14	10/15/1998	0.1	
EW-6	Lower	160 -- 230	78	35	52	38	8	8	43	41	43	4.3	10/15/1998	0.8	
EW-7	Lower	133 -- 173	35	50	52	40	52	52	24	23	24	22	10/15/1998	2.3	
EW-8	Lower	105 -- 185	59	90	150	NA	NA	100	92	87	92	13	5/11/1999	5.2	
EW-9	Upper	92 -- 132	58	36	52	40	40	40	13	6	2	39	10/15/1998	0.3	
EW-10	Upper	115 -- 145	33	3	NA	NA	0	0	1.23	1.65	1.76	2.2	10/15/1998	0.0	
EW-11	Upper	34 -- 54	19	7	52	NA	NA	30	0.63	0.17	2.15	33	10/15/1998	0.3	
EW-12	Upper	37 -- 57	16	3	0	0	0	NA	0.6	0.22	0	193	5/6/1999	0.0	
EW-13	Upper	75 -- 95	21	3	0	0	0	NA	0.11	0.07	0.04	290	5/11/1999	0.05	
EW-14	Lower	114 -- 164	63	115	120	120	58	112	62	56	108	3.1	10/15/1998	1.5	
EW-15	Lower	72 -- 122	62	160	85	NA	NA	160	NA	NA	NA	0.9	10/15/1998	0.0	
EW-16	Lower	83 -- 133	60	110	75	0	105	105	NA	NA	NA	ND	10/15/1998	0.0	
EW-17	Lower	90 -- 140	60	110	90	90	110	120	23	203	96	2.4	10/15/1998	1.0	
EW-18	Lower	125 -- 175	55	120	150	NA	NA	120	93	76	78	1.8	10/15/1998	0.6	

^a Producing Units: Upper = Upper Aquifer; Lower = Lower Aquifer.

^b bgs= below ground surface.

^c gallons per minute.

^d micrograms per liter.

^e pounds per year.

TABLE 4.3
CURRENT CONDITIONS COMPARED WITH PERFORMANCE CRITERIA
REMEDIAL PROCESS OPTIMIZATION, OU-1
GEORGE AIR FORCE BASE, CALIFORNIA

Extraction System Component Performance Criteria

A: Effectively remove TCE mass from groundwater beneath GAFB OU1				B: Effectively contain TCE plume															
Measurable Quantities	Current Conditions	Percent Complete	Relative Effectiveness	Measurable Quantities			Current Conditions			Relative Effectiveness									
Complete Groundwater Extraction System	880 lbs of TCE initially present in subsurface at GAFB OU1	About 113 lbs of TCE removed (January 1992 through October 1998)	13 percent	Ineffective	Areal extent of plumes (increasing vs decreasing)			Extent of plumes not well defined			Effective								
					Trends in chemical concentrations (increasing vs decreasing)			Concentration trends generally decreasing (or no trend apparent)			Effective								
				Relative Effectiveness			Well Location ^{d/}			Capture Radius ^{e/}			Downgradient Concentration Trends ^{f/}			Relative Effectiveness			
				Effective ^{a/}	Marginal ^{b/}	Ineffective ^{c/}	Good	Poor	Uncertain	Idealized Capture Radius (feet)	Adequate	Inadequate	Uncertain	Increasing	Decreasing	No Trend	Effective	Marginal	Ineffective
Individual Extraction Wells:																			
	EW-1	1.5		0				0		200		0			0		0		
	EW-2	0.9			0			0		450		0			0				0
	EW-3	3.2		0			0		730	0			0	0		0			
	EW-4	1.5		0			0		1,200	0			0	0		0			
	EW-5	0.1				0	0		260		0				0		0		
	EW-6	0.8			0			0	8,980	0					0		0		
	EW-7	2.3		0				0	2,870	0				0			0		
	EW-8	5.2		0			0		6,300	0			0				0		
	EW-9	0.3			0		0		1,570		0				0		0		
	EW-10	0.0				0		0	1,200			0		0					0
	EW-11	0.3			0		0		210			0			0		0		
	EW-12	0.0				0		0	150		0				0				0
	EW-13	0.05				0	0		520		0				0		0		
	EW-14	1.5		0				0	3,410			0			0				0
	EW-15	0.0				0		0	500			0			0				0
	EW-16	0.0				0		0	250		0			0			0		
	EW-17	1.0		0				0	500		0				0				0
	EW-18	0.6			0			0	700	0					0		0		

^{a/} Individual well that removes TCE at a rate of 1 lb/yr or greater

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

^{c/} Individual well that removes TCE at a rate of 0.1 lb/yr or less

^{d/} Well is situated on groundwater flowpath downgradient of areas containing relatively higher concentrations

^{e/} Radius of capture is adequate to intercept migrating TCE

^{f/} TCE concentrations at down-gradient locations display trend of decreasing or unchanging concentrations

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extraction, the opportunities to optimize the currently operating groundwater extraction and treatment system are restricted by the physics of the system and the nature and distribution of TCE in groundwater.

4.2.1.1 Mass Removal

Evaluation of Complete System

The ROD estimated that a period of 30 years would be required to achieve the groundwater RAOs for GAFB OU1 (Montgomery Watson, 1994). Using the results of October 1998 groundwater monitoring, Montgomery Watson (1998d) estimated that approximately 745 pounds (lbs.) of TCE remained in groundwater in the Upper Aquifer, and about 22 lbs. of TCE remained in groundwater of the Lower Aquifer. By October 1998, the groundwater pump-and-treat system had removed about 113 lbs. of TCE (Montgomery Watson, 1999a; Figure 4.1), indicating that at the beginning of system operation, a total mass of perhaps 880 lbs. of TCE had been present dissolved in groundwater and sorbed to soil at GAFB OU1. Therefore, an estimated 10 to 15 percent of the TCE mass originally present in groundwater has been removed in the 9 years since initial system installation. Note that Montgomery Watson (1998d) actually estimated that in 1994, about 1,029 lbs. of TCE was present in the subsurface. However, in order for the mass of TCE to decrease from 1,029 lbs. to 767 lbs., about 262 lbs. of TCE would have to have been removed, rather than the estimated actual removal of 113 lbs. Parsons ES cannot explain the discrepancy.

Presumably, any TCE remaining in groundwater would be free to migrate if the groundwater extraction/containment system were shut down; therefore, Performance Criterion 4 states in essence that the groundwater pump-and-treat system will remove all TCE from groundwater at GAFB OU1, or the system will remain in operation in perpetuity. Using the current rate of TCE removal (about 5.5 pounds per quarter, or 22 pounds per year), and the estimated amount of TCE remaining in the groundwater system, it is possible to estimate the total length of time required to remove all TCE currently in groundwater at OU1. The estimate suggests that if current TCE removal rates are sustained, all TCE mass would be removed from OU1 groundwater by mid-2033 (Figure 4.2). Given the amount of TCE mass removed from groundwater during the first 9 years of system operation (about 10 to 15 percent of the estimated TCE mass), and the estimated time to achieve complete TCE removal at current removal rates (33 years), the groundwater pump-and-treat system will not achieve Performance Criterion 4 in the projected 30-year schedule established in the ROD. If current removal rates can be sustained, approximately 280 pounds of TCE (about 30 percent) of the estimated initial mass of TCE would remain in groundwater at OU1 after 30 years of system operation (Table 4.3).

In reality, the rate of TCE removal probably will decline through time, as concentrations in extracted groundwater decrease. This phenomenon will result in much longer times than projected to remove all the TCE from GAFB OU1 groundwater. In fact, because diffusion may have allowed TCE to enter what are generally considered to be “impermeable” strata, it is possible that TCE could remain in the subsurface indefinitely, and no extraction system would be successful in removing the remaining TCE mass. The likelihood of such an occurrence at most sites was officially recognized in May 1992, when the USEPA Office of Solid Waste and Emergency Response (OSWER) issued Directive No. 9283.1-06, which acknowledges the ineffectiveness of pump-and-treat for aquifer remediation. This situation is depicted schematically for GAFB OU1 in Figure 4.3; because of declining mass-removal rates,

groundwater pump-and-treat remediation could continue for a period longer than 100 years, and nearly one-half the original mass of TCE would still remain in groundwater.

Evaluation of Individual Wells

It may be possible to improve the effectiveness of the complete extraction system by evaluating the effectiveness of individual wells. The recent production history of all operating extraction wells is presented in Table 4.2, together with the concentrations of TCE detected in the discharge effluent of individual wells. Effluent TCE concentrations were most recently measured in May 1999 (wells EW-8 and EW-13) and October 1998 (all other wells). Examination of annual rates of TCE removal for individual wells indicates that more than 80 percent of TCE mass removed from groundwater on an annual basis is being extracted by just seven wells (wells EW-1, EW-3, EW-4, EW-7, EW-8, EW-14, and EW-17; Figure 4.4). Mass removal at wells EW-1, EW-3, EW-4, and EW-7 is accomplished because these wells collect groundwater at moderate rates (20 to 40 gpm) and extract TCE at moderate concentrations (16 $\mu\text{g/L}$ to about 40 $\mu\text{g/L}$).

By contrast, wells EW-8, EW-14, and EW-16 accomplish mass removal by extracting TCE at relatively low concentrations (2 to about 16 $\mu\text{g/L}$), while extracting groundwater at relatively high rates (about 100 gpm). Virtually no mass removal is occurring at wells EW-5, EW-10, EW-12, EW-13, EW-15, or EW-16 (Figure 4.4) due to low rates of groundwater withdrawal, low TCE concentrations in extracted groundwater, or both. Wells EW-5, EW-10, EW-12, EW-13, EW-15, and EW-16 are therefore regarded as ineffective at achieving removal of TCE mass from groundwater; and five other wells (wells EW-2, EW-6, EW-9, EW-11, and EW-18) are only marginally effective in removing TCE mass (Tables 4.2 and 4.3).

4.2.1.2 Plume Containment

Evaluation of Complete System

The characteristics of plume migration may be evaluated by examining changes in the areal distribution of TCE through time, or by examining changes in TCE concentrations through time at individual well locations within, or downgradient from a plume. In some locations, in particular near the bluffs along the Mojave River, TCE concentrations in groundwater have not been well defined. Consequently, possible changes in areal extent of the plume through time cannot be reliably evaluated (Table 4.3).

Effectiveness of the system in containing the plume can be evaluated by looking for evidence of increases in TCE concentrations through time in down-gradient monitoring wells. In general, either no trends or decreasing trends in chemical concentrations have been identified through evaluation of the monitoring histories of individual wells (Section 2.4; Montgomery Watson, 1998d). Therefore, the current groundwater extraction system is regarded as effective in containing the plume and limiting the migration of TCE in the Upper and Lower aquifers (Table 4.3), although the effectiveness of the system in removing TCE mass is limited.

Evaluation of Individual Wells

An individual extraction well is regarded as effective in limiting TCE migration if all of the following conditions are fulfilled at the well (Table 4.3):

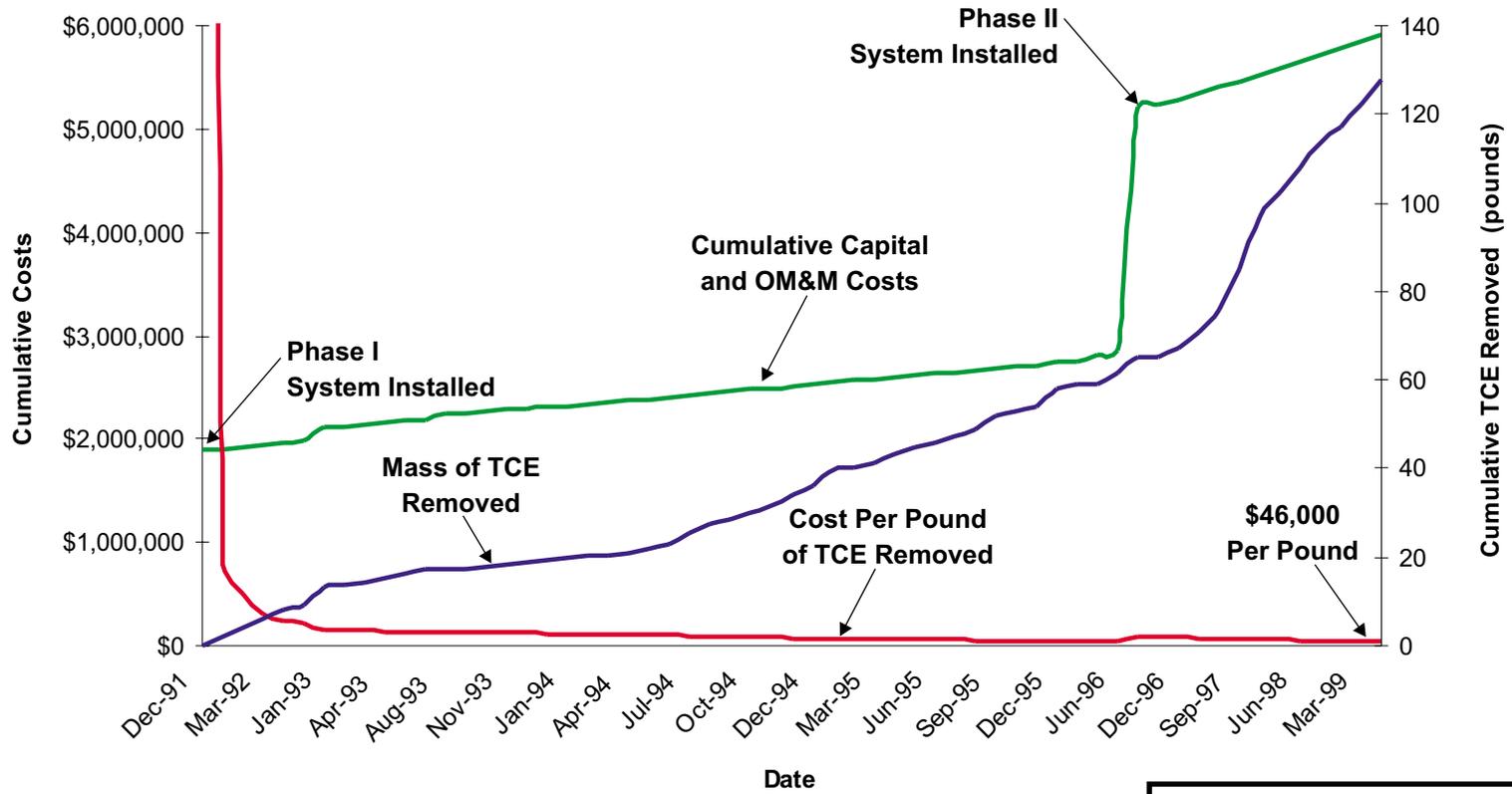


FIGURE 4.1
CUMULATIVE TCE MASS REMOVAL AND COSTS THROUGH TIME

Remedial Process Optimization
George AFB, California

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Denver, Colorado

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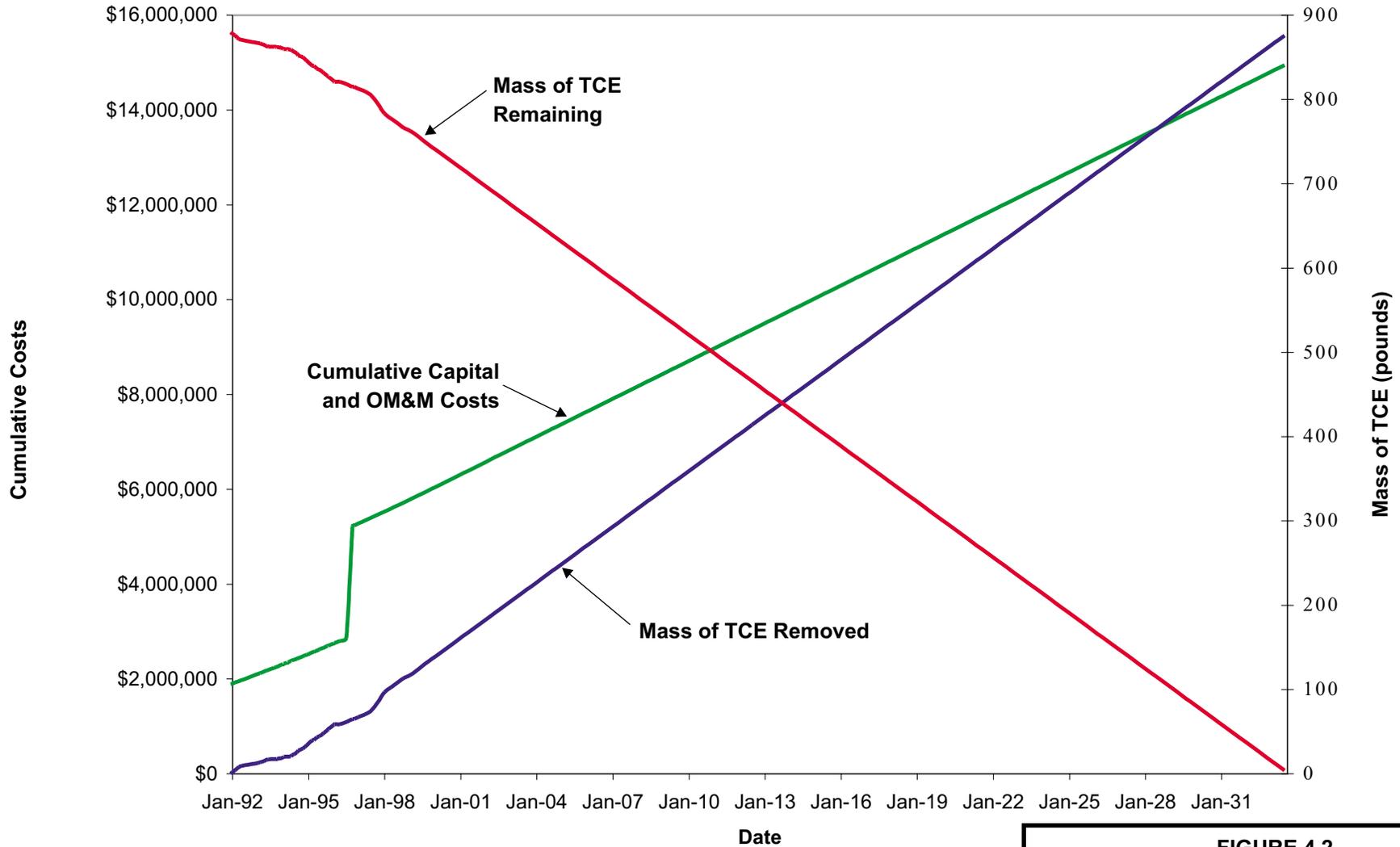


FIGURE 4.2
PROJECTED TCE MASS REMOVAL AND COSTS THROUGH TIME (REMOVAL RATE REMAINS CONSTANT)

Remedial Process Optimization
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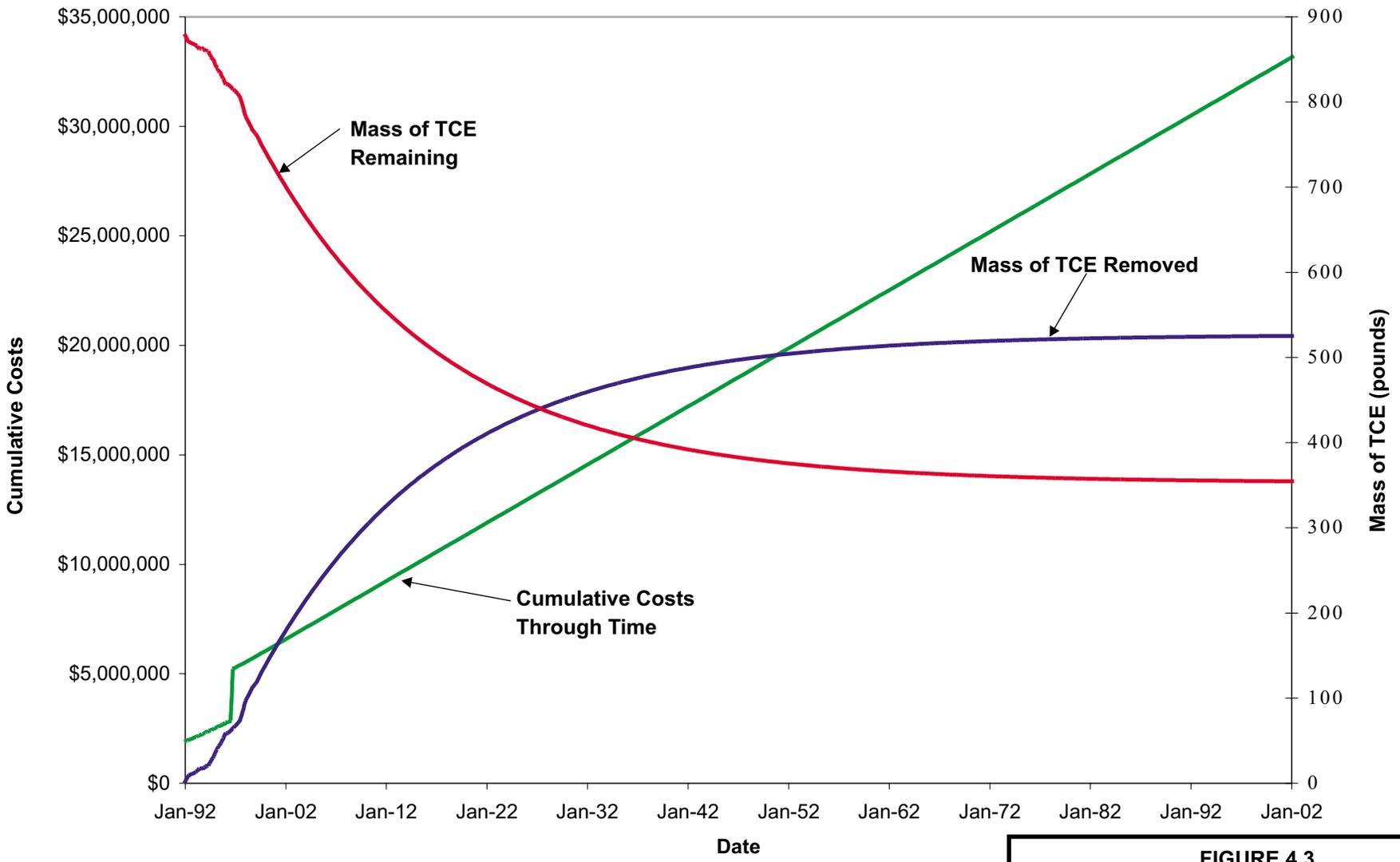


FIGURE 4.3
PROJECTED TCE MASS REMOVAL AND COSTS THROUGH TIME (REMOVAL RATE DECLINES)
Remedial Process Optimization
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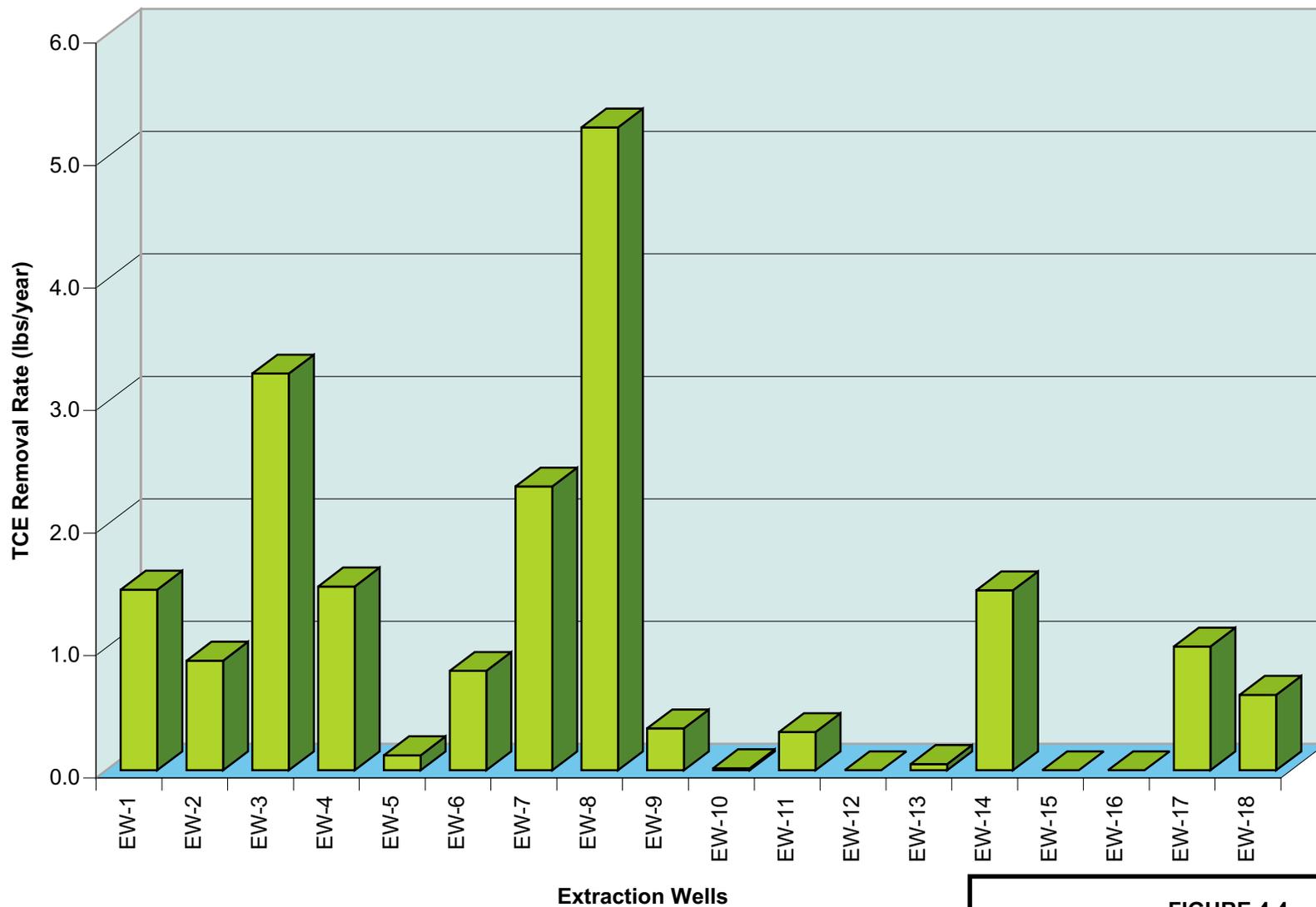


FIGURE 4.4
ANNUAL MASS REMOVAL RATES OF TCE BY WELL
Remedial Process Optimization
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- The well is located on a groundwater flowpath downgradient from areas within which TCE is present in groundwater at concentrations that are higher than in areas downgradient from the well;
- The “capture zone” of the well (the area within which TCE will move toward the well, rather than past the well with groundwater movement) is adequate to intercept migrating TCE; and
- TCE concentrations in groundwater downgradient from the well decrease or do not change through time.

The location, radius of capture, and trends in downgradient concentrations were qualitatively evaluated for the 18 extraction wells at GAFB OU1 (Table 4.4). The location of an extraction well was judged to be “good” if the well was immediately downgradient from a zone of relatively elevated TCE concentrations, or was on a flowpath originating at such a zone. TCE concentration trends were evaluated using information provided by Montgomery Watson (1998d).

The radius of capture of each extraction well was estimated using screening-level capture-zone analyses (Keely and Tsang, 1983). Analytical techniques for estimating extraction-well capture zones are relatively simplistic, and do not account for aquifer heterogeneities; nevertheless, a screening-level assessment provides a qualitative means of evaluating the relative effectiveness of a particular well in limiting chemical migration. The radius of capture for a particular well depends on the well pumping rate, the aquifer transmissivity, and the natural groundwater hydraulic gradient in the vicinity of the well. The design extraction rate of each well was used to estimate the radius of capture, even though most extraction wells are routinely pumped at rates lower than the design rate (Table 4.4). Use of the higher pumping rate in calculations will generate a larger (“more effective”) capture-zone estimate. Transmissivity of the aquifer near each well was estimated using the results of aquifer tests, where available (wells EW-1, EW-14, EW-15, EW-16, EW-17, and EW-18), or using the estimated specific capacity of the well (Table 4.4) and an approximate relationship between well specific capacity and aquifer transmissivity (Driscoll, 1986). Groundwater hydraulic gradients (Table 4.4) were estimated from potentiometric-surface maps generated by Montgomery Watson (1998d). The radius of capture for each well was then qualitatively evaluated. The capture zone for a particular well was judged to be “adequate” if it transected all, or most groundwater flowpaths originating at higher-concentration areas upgradient from the well, or if it overlapped one or more capture zones associated with adjacent wells.

The results of the qualitative assessment of the effectiveness of individual groundwater extraction wells, based on the capacity of each well to limit the migration of TCE, indicate that two wells (wells EW-3 and EW-4) are relatively effective in limiting TCE migration; six wells (wells EW-2, EW-10, EW-12, EW-14, EW-15, and EW-17) are relatively ineffective in limiting TCE migration; and the performance of the remaining ten wells is marginal (Table 4.2).

4.2.2 Effectiveness of Treatment System

Extracted groundwater is treated by passing it through an air-stripping tower to remove TCE prior to discharge to the infiltration ponds south of the treatment plant (Figures 1.10 and 1.11). The results of analyses of water samples collected from the influent and effluent lines of the treatment plant (Montgomery Watson, 1999c) indicate that the concentrations of TCE in influent

TABLE 4.4
APPROXIMATE RADII OF CAPTURE ESTIMATED
FOR
GROUNDWATER EXTRACTION WELLS
REMEDIAL PROCESS OPTIMIZATION, OU-1
GEORGE AIR FORCE BASE, CALIFORNIA

Extraction Well	Producing Unit ^a	Screened Interval (feet bgs ^b)	Approximate Saturated Thickness (feet)	Design Production Rate (gpm ^c)	Approximate Specific Capacity (gpm/ft ^d)	Approximate Transmissivity (ft ² /day ^e)	Local Hydraulic Gradient (ft/ft ^f)	Approximate Radius of Capture (feet)
EW-1	Upper	108 -- 148	39	20	0.8	1,200	0.008	200
EW-2	Upper	96 -- 136	25	12	1.2	320	0.008	450
EW-3	Upper	86 -- 126	31	20	1.3	330	0.008	730
EW-4	Upper	90 -- 130	40	6	0.24	60	0.008	1,200
EW-5	Upper	50 -- 80	26	2	0.18	50	0.015	260
EW-6	Lower	160 -- 230	78	35	0.6	150	0.0025	8,980
EW-7	Lower	133 -- 173	35	50	2.5	670	0.0025	2,870
EW-8	Lower	105 -- 185	59	90	2.0	550	0.0025	6,300
EW-9	Upper	92 -- 132	58	36	0.84	220	0.01	1,570
EW-10	Upper	115 -- 145	33	3	0.17	40	0.006	1,200
EW-11	Upper	34 -- 54	19	7	0.8	210	0.015	210
EW-12	Upper	37 -- 57	16	3	0.50	130	0.015	150
EW-13	Upper	75 -- 95	21	3	0.27	70	0.008	520
EW-14	Lower	114 -- 164	63	115	2.4	1,300	0.0025	3,410
EW-15	Lower	72 -- 122	62	160	3.4	12,400	0.0025	500
EW-16	Lower	83 -- 133	60	110	2.4	16,800	0.0025	250
EW-17	Lower	90 -- 140	60	110	2.4	8,400	0.0025	500
EW-18	Lower	125 -- 175	55	120	3.0	6,600	0.0025	700

^a Producing Units: Upper = Upper Aquifer; Lower = Lower Aquifer.

^b bgs = below ground surface.

^c gpm = gallons per minute.

^d gpm/ft = gallons per minute per foot of drawdown; estimated using design production rate.

^e ft²/day = feet squared per day; estimated using results of aquifer tests (where available) or specify capacity.

^f ft/ft = feet per foot.

water, collected from a sampling port upstream of the influent wet-well, are less than 10 µg/L (in April 1999, the influent concentration of TCE was 6 µg/L), and the concentrations of TCE in treated effluent are below the detection limit (0.5 µg/L). This indicates that the treatment plant is effective in meeting the effluent treatment performance requirement (Performance Requirement 3 and associated RAO 3; Table 4.1).

However, the low influent concentrations of TCE suggest that treatment of extracted groundwater may not be necessary. During April 1999, Parsons ES personnel collected a vapor sample from the headspace of the influent wet-well of the treatment system (Figure 1.11 and Section 2.3.2). The vapor headspace sample was collected in a SUMMA[®] canister, and submitted to Air Toxics, Inc., of Folsom, California for analysis of VOCs. TCE was detected in the vapor sample, at a concentration of 80 parts per billion by volume (ppbv), indicating that at least some dissolved TCE is volatilizing from influent water in the wet-well prior to treatment.

The Henry's Law constant for a chemical is a measure of the relative tendency of a chemical to volatilize from the dissolved phase (in water) to the vapor phase (in air). Henry's Law can be applied for TCE as follows:

$$\frac{C_{vapor}}{C_{dissolved}} = H_{mol}$$

where

C_{vapor} = concentration of TCE in vapor phase [mol/L],

$C_{dissolved}$ = concentration of TCE dissolved in water, at equilibrium with vapor-phase concentration [mol/L], and

H_{mol} = mole-fraction based Henry's Law constant for TCE [642.5 atm-mol fraction]

This application allows the concentration of TCE dissolved in water in the influent wet-well, in equilibrium with a vapor-phase concentration of 80 ppbv, to be estimated. The results of the calculation indicate that the concentration of TCE in water in the influent wet-well is probably less than the detection limit for TCE (0.5 µg/L). It therefore seems possible that most TCE in the influent stream is volatilized in the influent wet-well prior to air-stripping treatment.

Because TCE is a volatile chemical, discharge of extracted groundwater to the infiltration ponds, or other surface feature, would also result in rapid volatilization of TCE, even without air stripping. A discharge system that maximizes air/water contact (e.g., a spray system for discharge to the infiltration ponds) could replace the existing air stripper and provide equivalent treatment.

It therefore seems likely that air-stripping treatment of extracted groundwater prior to discharge is not necessary. Adoption of other disposal options could result in significant cost savings, because long-term OM&M costs associated with pumping water to the treatment plant, operation of the treatment plant, and pumping treated water to the infiltration ponds may be reduced or eliminated. Potential disposal options are discussed briefly in Section 4.5.

4.3 EVALUATION OF MONITORING PROGRAM

Designing an effective monitoring program involves locating groundwater monitoring wells and developing a site-specific groundwater sampling and analysis strategy so as to maximize the amount of information that can be obtained while minimizing incremental costs. An effective monitoring program will provide information regarding plume migration and changes in chemical concentrations through time, enabling decision-makers to verify that remediation is occurring at rates sufficient to achieve RAOs. The design of the monitoring program should 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 the 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 containment system and to trigger a contingency remedy if contaminants are detected. Primary factors to consider are (at a minimum) distance to potential receptors, groundwater seepage velocity, types of contaminants, aquifer heterogeneity, potential surface water impacts, and the effects of the remediation system. These factors will influence well spacing and sampling frequency. Typically, the faster the seepage velocity and the shorter the distance to receptor exposure points, the greater the sampling frequency. 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 remediation system is effective, then over the long term, historical groundwater monitoring data should demonstrate a clear and meaningful decreasing trend in concentrations at appropriate monitoring points.

Monitoring of the TCE plume is conducted periodically at OU1 to provide information regarding chemical and hydraulic (gradient) conditions within, and downgradient from the plume (Section 1.3.6). The groundwater monitoring program is intended to provide water-level and analytical data for use in ensuring compliance with requirements of the ROD, and for evaluating the overall effectiveness of the extraction system. Key components of the groundwater extraction and treatment system are also monitored, enabling periodic evaluation of overall system performance.

In conjunction with the cessation of pumping from Lower Aquifer extraction wells EW-6, EW-14, EW-15, EW-16, and EW-17 in June 1999, the Remedial Project Management Group for GAFB instituted a revised monitoring program to evaluate trends in plume migration and containment in the Lower Aquifer in detail (Montgomery Watson, 1999b). Groundwater samples are to be collected quarterly from a limited subset of monitoring wells completed in the Lower Aquifer. Wells LW-1, NZ-41, NZ-72, and NZ-73 have been designated as “internal” (i.e., performance) monitoring wells, and wells LW-4, MW-107, MW-108, NZ-76, NZ-77, and NZ-78 have been designated as “perimeter” (i.e., contingency) monitoring wells.

Montgomery Watson (1999b) calculated groundwater flow velocities in the Lower Aquifer northeast of the Mojave River bluffs as part of the rationale for identifying wells to be included in the monitoring program. Travel times from the distal edge of the TCE plume in the Lower Aquifer to the contingency monitoring wells were then estimated using the calculated groundwater flow velocities. The estimated travel times ranged from 277 days to 462 days, and did not account for the effects of sorption and retardation; TCE was assumed to be act as a

“conservative” chemical that would migrate advectively in the subsurface at the velocity of groundwater flow. The length of time required for a constituent to migrate in groundwater from the edge of the TCE plume to the vicinity of the contingency wells – approximately 1 year – suggests that annual groundwater monitoring, rather than semiannual monitoring, may be adequate to evaluate possible temporal changes in the extent of TCE in groundwater.

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 wells NZ-10 and NZ-18, located less than 100 feet apart in the central part of the NEDA. Other groundwater samples are collected from wells in areas in which TCE has been detected, but at concentrations below the MCL. For example, TCE has been detected in samples from wells NZ-03, NZ-13, and NZ-58, at concentrations that consistently have been below 3 µg/L since 1994 (Figure 1.9 and Table 2.1). These wells are at the base of the bluffs, northeast of the STP percolation ponds, and are not downgradient from any area within which groundwater contains TCE at elevated concentrations. Interpretation of the refined conceptual hydrogeologic model for GAFB OU1 (Section 2.7) suggests that the opportunities for migration of additional TCE into groundwater in this area are extremely limited; and the low concentrations of TCE (currently ranging from 0.6 µg/L to 2.1 µg/L) in groundwater at this location indicate that continued migration of TCE at concentrations greater than the detection limit will not occur. Therefore, the rationale for continued collection and analysis of samples from these wells is not clear.

Statistical techniques can be applied to the design and evaluation of monitoring programs to assess the quality of information generated during monitoring, and to optimize monitoring networks. Parsons ES examined data generated during April 1999 using geostatistical techniques in a screening-level evaluation of the monitoring network currently utilized at GAFB OU1. Geostatistics, or the Theory of Regionalized Variables (Clark, 1987; Rock 1988; American Society of Civil Engineers [ASCE], 1990a and 1990b), is concerned with variables that have values dependent on location, and are continuous in space, but which vary in a manner too complex for simple mathematical description. The theory of regionalized variables begins from the premise that the differences in values of a spatial variable depends only on the distances between sample locations, and the relative orientations of sample locations -- that is, the values of a variable (e.g., concentrations of TCE) measured at two locations that are spatially "close together" will be more similar than values of that variable measured at two locations that are "far apart". If the known sample values are used, the value of the variable (e.g., chemical concentrations) at any point within the sampled region can be estimated, in the process known as “kriging” (Clark, 1987; ASCE, 1990a and 1990b). An additional advantage of kriging as an estimation technique is that the standard deviations (“errors”) associated with the values estimated at each point in the spatial domain also are calculated during the kriging process. Areas containing estimated concentration values having elevated standard deviations associated with them represent locations where additional information could be collected to reduce uncertainties regarding the extent of chemicals in the subsurface. This observation implies that the monitoring program could be “optimized” by using available information to identify those areas having the greatest associated uncertainty. Conversely, sampling points can be successively eliminated from simulations, and the standard deviations examined, to evaluate if significant loss of information (represented by elevated standard deviations) occurs as the number of sampling points is reduced. Repeated application of geostatistical estimating techniques, using tentatively identified sampling locations, can then be used to generate a sampling program that would provide an acceptable level of uncertainty regarding chemical distribution, with the minimum possible number of samples collected.

The public-domain geostatistical software package GEO-EAS (Englund and Sparks, 1992), developed by USEPA, was used to evaluate sampling uncertainty in TCE concentrations detected in groundwater samples collected at GAFB OU1 in April 1999, using kriging techniques. The sample mean and standard deviation, and median kriging standard deviation were first calculated using the results obtained from all groundwater monitoring wells sampled in April 1999 (Table 4.5). Note that the analytical results for samples collected from groundwater extraction wells were not used in the analysis, because chemical concentrations in samples from extraction wells are representative of average conditions within a relatively large volume of the groundwater system (within the radius of capture of the well), and are not regarded as representative of conditions at a point in space. The kriging results were then cross-validated, and the median and maximum deviations between the kriged results and actual sample results were obtained. This provides a measure of the amount of uncertainty associated with a particular kriging realization.

A screening-level series of kriging calculations was then completed, with the results of analyses from several groundwater monitoring wells successively removed from the data set (Table 4.5). These results were compared with the initial calculations, completed using the results from 44 of the 47 OU1 wells sampled in April 1999, to evaluate the amount of information loss (increases in kriging error) resulting from use of fewer monitoring points. (The results for wells MW-35, NZ-51, and NZ-68 were excluded from the evaluation, because it was felt that the low concentrations of TCE in groundwater at these locations are not related to TCE in groundwater beneath, and down-gradient of the NEDA.) In the first series of calculations, four wells (wells NZ-13, NZ-20, NZ-29, and NZ-58) were removed from the data set; and a kriging realization was completed using the concentrations of TCE detected in 40 wells in April 1999. The sample mean concentration and standard deviation were similar to the base-case (44 wells) mean and standard deviation, while the median kriging standard deviation increased slightly. More importantly, in the results of cross-validation the median and maximum concentration deviations were reduced, indicating that no important information had been lost by eliminating these four wells from the network. Similar realizations were completed using TCE concentrations from 36 wells and from 34 wells. The cross-validation for the 34-well realization produced median and maximum concentration deviations that were appreciably lower than the cross-validation deviations produced using the 44-well base-case realization. This suggests that the number of groundwater monitoring wells included in the existing groundwater monitoring network could be reduced by as much as one-fourth to one-third with no appreciable loss of information.

The procedure that was followed in constructing kriging realizations was not rigorous, but rather was conducted as a series of screening-level simulations, to evaluate whether the technique could be successfully applied to optimize the groundwater monitoring network. The results of the screening simulations suggest that a more detailed application of geostatistical techniques could be useful in refining the existing monitoring program. Furthermore, development of semivariograms of chemical concentrations enables the underlying statistical structure of the chemical data to be evaluated. Subsequent kriging realizations can provide unbiased representations of the distribution of chemicals at different locations in the subsurface, enabling the extent of chemicals to be evaluated more accurately and effectively.

4.4 COST EVALUATION

The system expansion in 1996 is reported to have cost \$2.3 million (in 1996 dollars; Table 4.6) (Courington, 1998), and annual 1998 OM&M costs were reported to be about \$250,000 (in 1998 dollars). Assuming an equivalent installation cost for the initial phase of the system in

TABLE 4.5
SUMMARY OF SCREENING-LEVEL EVALUATION
OF GROUNDWATER MONITORING PLAN
REMEDIAL PROCESS OPTIMIZATION, OU-1
GEORGE AIR FORCE BASE, CALIFORNIA

Monitoring Well Results Used in Calculations	Monitoring Wells Removed from Plan	Number of Monitoring Wells Included	Mean Sample TCE Concentration (µg/L)	Sample Standard Deviation	Median Kriging Standard Deviation	Cross-Validation Results	
						Median TCE Concentration Deviation (µg/L)	Maximum TCE Concentration Deviation (µg/L)
All wells north of STP percolation ponds sampled during April 1999 event	None (44 wells total)	44	7.3	71.1	64.8	24.7	126.3
Wells sampled during April 1999 event; 4 wells removed	NZ-13 NZ-29 NZ-20 NZ-58	40	6.4	67.7	67.4	23.8	124.8
Wells sampled during April 1999 event; 8 wells removed	NZ-10 NZ-48 NZ-13 NZ-58 NZ-20 FT-03 NZ-29 LW-01	36	8.4	73.3	69.2	32.4	117.2
Wells Sampled during April 1999 event; 10 wells removed	NZ-10 NZ-32 NZ-13 NZ-58 NZ-20 FT-02 NZ-29 FT-03 NZ-31 LW-01	34	5.8	67.4	74.4	17.9	121.3

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TABLE 4.6
SUMMARY OF CAPITAL, OPERATION, MAINTENANCE,
AND MONITORING COSTS
REMEDIAL PROCESS OPTIMIZATION, OU1
GEORGE AIR FORCE BASE, CALIFORNIA

Item	Cost
Capital Costs	
Phase I System Installation ^{a/}	\$1,890,000 ^{b/}
Phase II System Installation ^{a/}	\$2,300,000 ^{c/}
Total Capital Costs	\$4,190,000
Operation, Maintenance, and Monitoring Costs	
Estimated Annual OM&M ^{d/}	\$250,000
Projected Total (total after additional 33 years) ^{e/}	\$14,230,000
Projected Total (total after additional 100 years) ^{f/}	\$30,980,000
Cost Per Mass of TCE Removed	
Cost per pound of TCE removed (to date)	\$46,200
Cost per pound of TCE removed (43-year period)	\$16,170
Cost per pound of TCE removed (100-year period)	\$35,200

^{a/} Courington, 1998

^{b/} 1991 dollars.

^{c/} 1996 dollars.

^{d/} 1998 dollars.

^{e/} Total projected OM&M costs if 43-year total period is required for cleanup; constant 1999 dollars.

^{f/} Total projected OM&M costs if additional 100-year period is required for cleanup; constant 1999 dollars.

1991, and assuming an annual discount rate of 4 percent, the installation cost of the initial nine-well system was about \$1.9 million (in inflation-adjusted dollars). Parsons ES estimates that the annual cost of the current monitoring program is about \$150,000 per year (in 1999 dollars) (Table 4.7). Therefore, power, inspections, and other long-term O&M costs total about \$100,000 per year. System OM&M costs since 1991 can also be projected to inflation-adjusted dollars (Figure 4.1). The cumulative system cost to date, calculated by accruing capital expenditures (two phases of system installation) and annual OM&M costs from 1991 to the present, is estimated to be about \$6 million (in constant dollars, adjusted for inflation to 1999 dollars). As of July 1999, a total mass of about 128 pounds of TCE is estimated to have been removed from the subsurface by the groundwater extraction and treatment system at GAFB OU1 (Montgomery Watson, 1999c), resulting in a cost per pound of TCE removed to date of about \$46,000 (Figure 4.1 and Table 4.6).

As described in the ROD (Montgomery Watson, 1994), the time required to achieve the RAOs, and the design life of the remedial system, for groundwater at OU1 was originally

TABLE 4.7
COST ESTIMATE FOR CURRENT GROUNDWATER MONITORING PROGRAM^{a/}
REMEDIAL PROCESS OPTIMIZATION, OU-1
GEORGE AIR FORCE BASE
CALIFORNIA

Cost type	Quantity	Units	Unit Cost	Cost
COSTS FOR EACH SEMI-ANNUAL EVENT				
Labor for sample collection				
3 people for 18 days at \$60/hr	432	hours	\$ 60.00	\$ 25,920.00
Labor for data validation and data management				
2 people for 6 days at \$60/hr	96	hours	\$ 60.00	\$ 5,760.00
Laboratory Analyses				
Primary samples; VOCs by method SW8260 (50 groundwater monitoring wells; 18 extraction wells)	68	samples	\$ 150.00	\$ 10,200.00
QA/QC samples; VOCs by method SW8260	37	samples	\$ 150.00	\$ 5,550.00
Other Direct Costs				
Equipment rental (PID, pH/Eh, O ₂ /CO ₂ , etc.)	18	days	\$ 400.00	\$ 7,200.00
Vehicle rental (2 vehicles for 18 days)	36	days	\$ 45.00	\$ 1,620.00
Per Diem (3 people for 18 days at \$110 ea/day)	54	days	\$ 110.00	\$ 5,940.00
Miscellaneous field supplies				\$ 1,500.00
Reporting				
Labor (at representative labor rate)	160	hours	\$ 65.00	\$ 10,400.00
Miscellaneous and other direct costs				\$ 2,500.00
SUBTOTAL SEMI-ANNUAL COST (1999 dollars)				\$ 76,590.00
ANNUAL COSTS (2 SEMI-ANNUAL EVENTS PER YEAR)			semi-annual costs x 2	\$ 153,180.00
TOTAL COSTS FOR 33 YEARS			annual costs x 33	
TOTAL COST (constant 1999 dollars)				\$ 5,054,940.00

^{a/} Estimate by Parsons ES.

estimated to be 30 years. The present worth of capital and OM&M costs through the 30-year design life was projected to be about \$7.8 million (Montgomery Watson, 1994). If TCE removal proceeds at the current rate (about 22 pounds per year; see Section 4.2), all TCE mass would be removed from OU1 groundwater by mid-2033 (a 43-year total period of operation), at a total cost (in inflation-adjusted dollars) of about \$25 million, or about \$14 million (in constant 1999 dollars) (Figure 4.2 and Table 4.6). However, if the rate of TCE removal declines through time, as is likely, groundwater pump-and-treat remediation could continue for a period longer than 100 years, at a cost of about \$400 million in inflation-adjusted dollars, or about \$31 million in constant 1999 dollars (Figure 4.3 and Table 4.6). Note that these long-term cost estimates neglect additional capital expenditures that would be necessary for such items as well rehabilitation or replacement of pumps and treatment-system equipment.

4.5 ALTERNATIVE TECHNOLOGY EVALUATION

Groundwater contamination at GAFB OU1 is apparently a consequence of the migration of solvent constituents to the water table of the Upper Aquifer from several geographically dispersed source areas, with subsequent dispersion throughout portions of the Upper Aquifer and eventual migration to the Lower Aquifer in isolated areas (Section 2). Several factors must be considered during the identification of alternative remedial technologies for addressing groundwater contamination at GAFB OU1. These factors fall into two general categories. The first category includes physical site characteristics such as groundwater depth, gradient, flow direction, and soil type, which influence the types of remedial technologies most appropriate for the site. The second category involves assumptions about future land uses and potential receptor exposure pathways.

The physicochemical characteristics of the CAH compounds greatly influence the effectiveness and selection of remedial technologies. CAHs are highly volatile, moderately soluble in water, and adsorb to soil to a moderate degree. These characteristics allow CAH compounds to leach from contaminated soil and dissolve in and migrate with groundwater (Appendix B). All of the CAH compounds are susceptible to *in situ* degradation through biotic and abiotic mechanisms; in fact, *in situ* biological degradation is in many instances the most important fate process acting to remove dissolved CAH compounds from the subsurface environment. The degradation of CAH compounds is reviewed in Section 2.5, and is described in detail in Appendix B.

Site geology and hydrogeology have profound effects on the movement and fate of contaminants, and the effectiveness and scope of the required remedial technologies. For example, the effectiveness of pump-and-treat and air sparging technologies is greatly restricted in hydrogeologic units that contain significant fractions of silt and clay material. In fact, the fine-grained strata within the Upper Alluvial unit are a principal reason for the limited effectiveness of groundwater extraction in the Upper Aquifer (see Section 4.2). The depth to groundwater and saturated thickness of the affected hydrogeologic unit also can influence the selection of appropriate technologies. In most areas of GAFB OU1, the depth to the potentiometric surface of the Upper Aquifer is on the order of 100 feet, restricting consideration of technologies to those that are unaffected, or are minimally affected, by the depth to water.

An exposure pathway analysis identifies the human and ecological receptors that could potentially come into contact with site-related chemicals and the contaminant migration pathways through which these receptors might be exposed. To have a completed exposure

pathway, there must be a source of contamination, a mechanism(s) of release, a pathway of transport to an exposure point, an exposure point, and a receptor. If any of these elements does not exist, the pathway is considered incomplete, and receptors will not be exposed to site-related chemicals (Appendix B).

Evaluation of the potential long-term effectiveness of remedial approaches or technologies for groundwater at GAFB OU1 must determine whether the approach will be sufficient to reduce chemical toxicity and minimize plume expansion so that potential receptor exposure pathways involving contaminants in groundwater remain incomplete. Assumptions about current and future land uses at a site form the basis for identifying potential receptors, potential exposure pathways, reasonable exposure scenarios, and appropriate remediation goals. USEPA (1991) advises that the land use associated with the highest (most conservative) potential level of exposure and risk that can reasonably be expected to occur should be used to guide the identification of potential exposure pathways and to determine the level to which the site must be remediated.

George AFB is currently in the process of conversion and redevelopment as an industrial park and general aviation facility. The Base is under the jurisdiction of the Air Force Base Conversion Agency (AFBCA), and institutional controls limiting access to and uses of groundwater beneath GAFB OU1 are currently in place. The depth to groundwater in most areas of GAFB OU1 is generally greater than 100 feet bgs, and groundwater beneath the Base is not utilized as a drinking-water source (Sections 1 and 3). The depth to groundwater precludes receptor exposures, even for workers engaged in excavation activities. In light of current institutional and physical constraints, no receptors are likely to be exposed to CAHs in groundwater within the Upper or Lower Aquifers.

Assumptions about hypothetical future land uses must also be made to ensure that the remedial technologies or alternatives considered for groundwater at GAFB OU1 are adequate and sufficient to provide long-term protection. The future use of the Base is projected to be similar to current uses (industrial park/general aviation). Therefore, no potential future receptor exposure pathways are likely to be completed, provided groundwater originating in the Upper or Lower Aquifers in GAFB OU1 is not used to meet potable water demands. Therefore, any technology considered will continue to require some level of institutional control during remediation.

In addition, alternate technologies considered for application at GAFB OU1 must address the RAOs established in the ROD (Table 4.1). In particular, technologies considered for groundwater in the subsurface must meet the requirements of RAOs 2 and 4 (reduce the concentrations of TCE in groundwater below the MCL of 5 µg/L, and reduce or eliminate TCE migration); and technologies considered for *ex situ* groundwater treatment must meet the requirements of RAO 3 (median concentrations of TCE in air-stripper effluent no greater than 2.5 µg/L, with maximum concentrations not to exceed 5 µg/L). Because extractive technologies in operation at GAFB OU1 have been demonstrated to be relatively inefficient and ineffective in achieving RAOs 2 and 3, Parsons ES recommends that two alternative *in situ* technologies, MNA and phytoremediation, be examined in detail for potential applicability.

Monitored Natural Attenuation

As discussed in Section 2, “natural attenuation” of contaminants refers to the occurrence of natural processes in soil and groundwater environments that act without human intervention to reduce the mass, toxicity, mobility, volume, and/or concentration of contaminants in these media.

Mechanisms for natural attenuation of CAHs include nondestructive mechanisms (advection, dispersion, dilution from recharge, sorption, and volatilization) that act to reduce contaminant concentrations via dilution or transfer to another medium, and destructive mechanisms (abiotic chemical transformation and biodegradation) that actually remove contaminant mass.

The results of assessment of the potential for RNA (Section 2.5) suggest that biodegradation of TCE in groundwater at GAFB OU1 may be occurring, but only in limited areas or at slow rates. Consequently, natural attenuation of TCE in groundwater at GAFB OU1 is probably occurring primarily as a consequence of non-destructive mechanisms (sorption, dispersion during migration). Because TCE is sorbed to organic carbon and clay minerals in the aquifer matrix, the rate of migration of TCE is typically slower than the rate of groundwater movement (TCE is “retarded” during migration; Appendix B). In the absence of continuing contributions of TCE mass to groundwater, as TCE moves in groundwater away from its point of introduction to groundwater, it becomes distributed through an ever-increasing volume of the aquifer by advective and dispersive mechanisms. This produces decreasing concentrations of TCE with increasing down-gradient distance, as is reflected by the areal distribution and concentrations of TCE in groundwater at GAFB OU1.

In the presence of induced hydraulic gradients due to pumping, it is difficult to distinguish the effects of nondestructive attenuation mechanisms from the effects of groundwater extraction, in limiting migration of detectable TCE concentrations downgradient from GAFB. Therefore, although biodegradation does not appear to be an effective attenuation mechanism for promoting TCE removal from groundwater, it is not possible to completely eliminate natural attenuation from consideration as a potential remediation alternative. Ideally, in order to fully evaluate the natural attenuation alternative, the groundwater extraction system would be completely shut down for some extended period of time, and periodic groundwater monitoring would continue so that temporal changes in chemical concentrations and plume configuration could be evaluated. After temporal changes and concentration trends had been monitored through that period, it should be possible to assess the degree to which natural attenuation processes can limit the migration of TCE, and to predict a range of maximum TCE migration distances.

Effective in June 1999, five extraction wells in the Lower Aquifer (wells EW-6, EW-14, EW-15, EW-16, and EW-17) were temporarily shut down (Section 1.3.5). This provides an opportunity to assess in greater detail the potential effectiveness of natural attenuation in the Lower Aquifer north of GAFB. The results of LTM conducted in this area subsequent to shut-down of the wells should be used in the evaluation. Other opportunities for further evaluating natural attenuation resulting from nondestructive mechanisms will arise if other extraction wells are removed from operation (Section 5).

4.5.2 Phytoremediation

Phytoremediation Processes

Phytoremediation is defined as the use of plants to remove, degrade, or sequester pollutants in contaminated soil or groundwater. Under this definition, phytoremediation can be regarded as the use of plants to hydraulically control the migration of a contaminant plume via uptake and transpiration mechanisms, and to aid in the remediation of dissolved contaminants through rhizosphere degradation or gradual volatilization. Plants have profound effects on physical, chemical, and biological processes in soils, and can significantly affect the environmental fate of organic chemicals in soil systems. Plants increase microbial and chemical activity on and around

their root surfaces, thereby potentially accelerating the microbial degradation of organic contaminants. Root exudates may act as electron donors for organic contaminants that are biodegraded through reductive dechlorination. Uptake, transpiration, and/or metabolism of organic chemicals may be important in some cases. These processes are accelerated by the mass flow of solution to the root surface induced by the transpiration of water from plant leaves.

If the water being used by the vegetation for transpiration is being supplied by the groundwater, plants may assist in controlling the migration of contaminant plumes and possibly enhance transfer of contaminated groundwater into the microbially rich rhizosphere (Davis *et al.*, 1996). The relative impact of vegetation on groundwater is dependent on many factors including depth to groundwater and soil conditions. In low- permeability areas where recharge is low, groundwater use by plants may depress the groundwater table significantly. Where the recharge rate is high, such as in sandy soils near a surface water, the impact may not be as great. An annotated bibliography for watersheds in the western US indicates that annual water use by cattails, cottonwoods, rushes, reeds, sedges, and tamarisk can exceed 60 inches of water. A 10-foot by 50-foot strip planted in such vegetation could remove more than 18,700 gallons of water per year from the subsurface.

In certain cases, plant uptake and associated metabolism of CAHs also may be important. Plant membranes are composed of a lipid bi-layer that prevents the uptake of almost all highly water-soluble compounds except plant nutrients, which are actively absorbed via specific ion pumps. The plant uptake of organic compounds tends to increase with the lipid solubility of the compounds up to a log of their octanol-water partition coefficient ($\log K_{ow}$) of about 2 (Briggs *et al.*, 1982). Highly lipophilic compounds ($\log K_{ow} > 3$) are thought to cross plant membranes more slowly than compounds of intermediate lipophilicity ($\log K_{ow}$ 1 to 3) because highly lipophilic compounds are tightly bound to the lipid membranes and are insoluble in the aqueous cytoplasm inside the cell. Translocation from roots to shoots also is optimal for chemicals with intermediate lipophilicity, and translocation appears to increase with transpiration (Ryan *et al.*, 1988). TCE is considered to be a compound of intermediate lipophilicity, having a $\log K_{ow}$ of 2.5. However, while TCE uptake into plants has been observed, the quantitative relationship between groundwater concentration and the overall plant removal rate has not been established (Anderson *et al.*, 1992; Newman *et al.*, 1997; Schnable *et al.*, 1996). Metabolism of TCE in plant tissue also has been described, with chlorinated alcohols and aliphatic acids being reported as byproducts (Newman *et al.*, 1997; Edwards *et al.*, 1997).

Microbial degradation of CAHs such as TCE occurs under both anaerobic and aerobic environmental conditions. Anaerobic micro-sites are commonly found throughout aerobic rhizosphere (root-zone) regions. Saturated soil conditions can increase the likelihood of anaerobic sites because oxygen diffusion is reduced when soil pores are filled with water. The plant rhizosphere contains an abundance of organic compounds, originating from both plant deposition and microbial metabolism. Anaerobic conditions in the rhizosphere may therefore favor reductive dechlorination of CAHs.

Under aerobic conditions, a variety of bacteria, including methane and propane oxidizers, ammonia oxidizers, and toluene (aromatic) oxidizers, have been shown to oxidize CAHs cometabolically. Although optimal conditions are uncommon, comparisons of TCE mineralization in planted versus unplanted soil suggest that vegetation may accelerate TCE degradation (Walton and Anderson, 1990).

There are cost advantages to using phytostabilization compared to using conventional technologies (e.g., pump and treat). Capital and long-term OM&M costs are much lower. Depending on the size of tree and the need for supplemental irrigation, costs per tree could range from \$35 to \$280 for installation and \$10 to \$30 per year for maintenance.

Potential for Application of Phytoremediation

Successful implementation of phytoremediation in the saturated zone requires that the depth to groundwater be relatively shallow so that the roots of the phreatophytic plants can readily reach the water table. The effectiveness of phytoremediation systems is enhanced with increasing density of plantings: greater density of phreatophytes produces a larger uptake of water and chemicals. Such systems are thus most efficient and effective when plantings can be restricted to relatively small areas.

Interpretation of the refined conceptual hydrogeologic model of GAFB OU1 (Section 2) suggests that the primary route of hydraulic communication between groundwater within the Upper and Lower Aquifers is through the saturated alluvium beneath the channels of arroyos incised through the aquitard near the bluffs overlooking the Mojave River (Section 2.7 and Figure 2.9). The relatively restricted extent of TCE in the Lower Aquifer, and its presence in groundwater of the Lower Aquifer beneath points at which the arroyos debouch into the bajada bordering the Mojave River floodplain, suggest that the arroyos apparently also function as pathways for preferential migration of TCE in groundwater from the Upper Aquifer to the Lower Aquifer.

Phreatophytic vegetation (cottonwood trees) was observed to be thriving at some locations within arroyos that trend to the north and northeast on the bluff paralleling the Mojave River. The occurrence of immature cottonwood trees indicates that the depth to groundwater at these locations is probably no greater than about 10 to 20 feet (Meinzer, 1927; Chappell, 1998). This is corroborated by the general configuration of the potentiometric surface in the Upper Aquifer (Section 2.7 and Figure 1.4), which indicates that the depth to water in the Upper Aquifer is relatively shallow beneath the arroyos.

The saturated thickness and saturated cross-section of alluvial materials within the arroyos most likely is limited; however, because past investigations apparently have not specifically addressed the arroyo channels, the actual depth to water and the saturated thickness of the Upper Aquifer beneath the arroyos are unknown. Furthermore, the subsurface relationships among the Upper and Lower Aquifers, the aquitard, and the potentiometric surfaces in the two units near the edge of the bluffs are not clear (Section 2). Available information indicates that a phytoremediation system, targeted at reducing the movement of TCE-contaminated groundwater down the arroyos to the Lower Aquifer, could be successfully implemented. However, additional information regarding the depth to water, presence/depth to the aquitard beneath arroyos, and identification of appropriate locations for plantings should be obtained prior to implementation of a phytoremediation treatability test.

Potential Treatment and Disposal Options

It is possible that the concentrations of TCE in extracted groundwater could be reduced to acceptable levels using treatment mechanisms or disposal options other than the existing air-stripping system. If subsequent evaluation demonstrates that the concentrations of TCE in water within the influent wet-well are acceptable, water could be pumped from the wet-well to the

infiltration ponds without further treatment. If elevated concentrations of TCE remain in water within the wet-well, other alternatives could be implemented. For example, water in the wet-well could be agitated, to increase turbulence; or discharge of water to the infiltration ponds could be accomplished by spraying, thereby promoting TCE volatilization.

In the longer term, other candidate disposal areas at lower elevations north of the treatment plant should be identified. Disposal at lower elevations will enable the costs of pumping water up-hill to be reduced or eliminated.

Should none of these alternative treatment/disposal options be acceptable, the Air Force should consider discharge at the nearest publicly-owned treatment works (POTW) (the VVWRA facility north of GAFB). This would require obtaining a POTW discharge permit, and would entail treatment and discharge fees. However, as a consequence of much lower hydraulic potential and resulting reductions in associated pumping costs (water would be moving down-hill rather than up-hill), such an option ultimately could be less costly than pumping treated effluent to the current infiltration ponds.

SECTION 5

RECOMMENDATIONS

Section 3 and 4 provided an overview and evaluation of the remedial decision process that resulted in installation of the current groundwater pump-and-treat system at GAFB OU1, 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.

5.1 SHORT-TERM RECOMMENDATIONS

System Improvements

Based on the current performance and the historical results of the groundwater pump-and-treat system at OU1, the existing system is neither effective nor efficient at removing dissolved TCE mass. More than 80 percent of TCE mass removal is accomplished by seven wells in the 18-well network; and a number of the extraction wells are not ideally located, or have a radius of capture inadequate to accomplish the plume-containment objective. As discussed in Section 4, the technical capability of the pump-and-treat system to achieve the clean-up criteria outlined in Section 3.2 or the performance criteria outlined in Section 4.1 within a reasonable timeframe is doubtful. As acknowledged by the USEPA per their request to temporarily discontinue pumping at five Lower Aquifer extraction wells, there is no benefit to continued operation of some components of the existing system. Therefore, the following recommendations are made to improve system performance.

Recommendation 1: Discontinue pumping at extraction wells EW-5, EW-6, EW-10, EW-11, EW-12, EW-13, EW-14, EW-15, EW-16, EW-17, and EW-18.

Rationale: As discussed in Section 4, virtually no mass removal is occurring at wells EW-5, EW-10, EW-12, EW-13, EW-15, or EW-16; and the concentrations of TCE in the extracted groundwater from wells EW-6, EW-10, and EW-14 through EW-18 have been below the cleanup objectives specified in the ROD (Montgomery Watson, 1994). Furthermore, wells EW-5, EW-6, EW-10, EW-12, and EW-14 through EW-18 are poorly located, or have inadequate capture radii to accomplish the objective of controlling plume migration. Cessation of pumping at the 11 wells would allow the following to occur:

- Observe if there are temporal increases in TCE concentrations in groundwater near the shut-down extraction wells. Such increases (known as a “rebound effect”) commonly occur after pumping ceases.

- Reduce the volume of water requiring treatment or disposal by more than 50 percent (based on the rated capacity of the shut-down wells).
- Reduce service time required for extraction wells.
- Reduce the overall system OM&M cost by lowering labor, utility, and analytical expenses (see Section 5.1.1).

Recommendation 2: Conduct a pilot-scale treatability study to evaluate the concentrations of TCE in groundwater extracted from the remaining on-line wells, prior to treatment. If TCE concentrations are sufficiently low, consider discharge of extracted groundwater directly to the infiltration ponds or another surface location. A collection and discharge system that maximizes air/water contact (e.g., induced turbulence in the influent wet-well, or a spray system for discharge to the infiltration ponds) could replace the existing air stripper and provide equivalent treatment. If regulatory agency approval cannot be obtained for this disposal option, consider disposal and treatment at the VVWRA facility north of GAFB.

Rationale: Sampling results for the influent wet-well (Section 4) suggest that TCE concentrations in untreated groundwater upstream from the air stripper may be at or below detection limits. Average influent concentrations are expected to rise as ineffective extraction wells are taken off-line. However, average TCE concentrations in extracted groundwater will probably remain below about 20 µg/L. In light of the relative volatility of TCE, it is likely that any TCE in extracted water will be lost during handling and discharge, obviating the need for further treatment.

If direct discharge of extracted groundwater is deemed unacceptable, consider discharge at the nearest publicly-owned treatment works (POTW) (the VVWRA facility). This would require obtaining a POTW discharge permit, and would entail treatment and discharge fees. However, as a consequence of much lower hydraulic potential and resulting reductions in associated pumping costs (water would be moving down-hill rather than up-hill), such an option ultimately could be less costly than pumping treated effluent to the current infiltration ponds.

As a result of eliminating the current air-stripping treatment system, the following benefits would accrue:

- Increase efficiency of system by eliminating the pumping head from wells through the air-stripping system.
- Reduce service time required for treatment system.
- Reduce the overall system OM&M cost by lowering labor and utility expenses.

Many of the same efficiencies and cost savings are expected to result for either direct discharge to the ponds or discharge to a POTW.

Monitoring Program Improvements

It was estimated that the current groundwater LTM program would cost approximately \$5 million (in constant 1999 dollars; Table 4.7) over the remaining 33-year period of system operation that may be required for attainment of the ROD cleanup goals (under optimal conditions). 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 are defined. Sampling procedures and protocols were also reviewed. Current sampling procedures generate considerable quantities of groundwater, produced during well purging; however, the incremental cost of handling and treating produced water is probably small, because groundwater produced during purging and sampling is transported to the existing treatment plant, discharged to the influent wet-well, and treated. However, low-cost alternatives to conventional sampling techniques have recently been developed and evaluated (Parsons ES, 1999c), and could be applied to the groundwater monitoring program at GAFB OU1. A short-term opportunity exists to revise the groundwater monitoring program while providing sufficient data to monitor changes in plume extent.

Recommendation 3: Reduce the frequency of sampling from semi-annual to annual, reduce the number of wells sampled during long-term groundwater monitoring, and evaluate whether monitoring using recently-developed diffusion samplers is appropriate.

Rationale: Because there are no current or potential receptors imminently at risk through identified exposure pathways, and because TCE concentrations in OU1 groundwater are generally stable or decreasing (Section 4), semi-annual monitoring is deemed to be excessive. The available historical data provide a sufficient baseline for understanding plume trends. The times estimated for groundwater in the Lower Aquifer to migrate from the current leading edge of the plume to downgradient compliance wells range from 277 to 462 days (Montgomery Watson, 1999b). These travel times were calculated using the pore velocity of groundwater, and do not account for chemical sorption or retardation (Appendix B), and are thus strictly applicable only to a conservative tracer. The calculated travel times are sufficiently long that no significant changes are anticipated to occur in plume extent that would cause concern to potential receptors over a one-year period.

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 installed during site characterization. Using a screening-level geostatistical evaluation, it was determined that sampling fewer wells would provide sufficient data to monitor plume migration, configuration, and concentration trends. At a minimum, the number of groundwater monitoring wells could be reduced from 47 to 34, while still providing the same level of information necessary to achieve monitoring objectives. Table 5.1 lists the wells recommended for sampling in a possible 34-well program.

TABLE 5.1
POSSIBLE LONG-TERM MONITORING PROGRAM (34 WELLS)
REMEDIAL PROCESS OPTIMIZATION, OU-1
GEORGE AIR FORCE BASE, CALIFORNIA

Sampling Location	Operable Unit(s)	Site / Area	Aquifer Monitored	Purge Method	Chemical Analyses	
					VOCs	Natural Attenuation Parameters
FT-01	OU 1	-	U	MSP	✓	
FT-05	OU 1	-	U	MSP	✓	
MW-103	OU 1	-	U	MSP	✓	✓
MW-107	OU 1	-	L	MSP		✓
MW-35	OU 1	-	U	MSP	✓	✓
MW-37b	OU 2	Background	L	MSP	✓	
NZ-07	OU 1	-	U	MSP	✓	✓
NZ-11	OU 1	-	U	MSP	✓	
NZ-12	OU 1	-	U	MSP	✓	✓
NZ-18	OU 1	-	U	MSP	✓	
NZ-21	OU 1	-	U	MSP	✓	✓
NZ-24	OU 1	-	U	MSP	✓	
NZ-25	OU 1	-	U	MSP	✓	✓
NZ-27**	OU 1	-	U	MSP	✓	
NZ-34	OU 1	-	U	MSP	✓	
NZ-35	OU 1	-	U	MSP	✓	
NZ-36	OU 1	-	U	MSP	✓	
NZ-37	OU 1	-	L	MSP	✓	✓
NZ-39	OU 1	-	U	MSP	✓	
NZ-46	OU 1	-	U	MSP	✓	
NZ-48	OU 1	-	L	MSP	✓	✓
NZ-52	OU 1	-	U	MSP	✓	
NZ-54	OU 1	-	U	MSP	✓	
NZ-55	OU 1	-	U	MSP	✓	
NZ-56	OU 1	-	U	MSP	✓	
NZ-67	OU 1	-	U	MSP	✓	
NZ-70	OU 1	-	L	MSP	✓	
NZ-72	OU 1	-	L	MSP	✓	
NZ-73	OU 1	-	L	MSP	✓	✓
NZ-75	OU 1	-	U	MSP	✓	✓
NZ-76	OU 1	-	L	MSP	✓	
NZ-77	OU 1	-	L	MSP	✓	
NZ-79	OU 1	-	L	MSP	✓	✓
RZ-02	-	Background	L	MSP	✓	✓

** NZ-27 will be sampled if water level is sufficient

MSP - Modified Slow Purge

VOCs - Volatile Organic Compounds analyzed by SW8260B

Natural Attenuation Parameters include sulfate and dissolved iron

Sulfate analyzed by Hach Method 8051

Dissolved Iron analyzed by Hach Method 8146

Parsons ES also recommends that a rigorous statistical evaluation be completed to identify the subset of wells in the monitoring network that can provide the appropriate level of information necessary to achieve monitoring objectives at the lowest cost.

An innovative sampling apparatus (“diffusion sampler,” has recently been developed by the USGS, and is being evaluated by Parsons ES, on behalf of AFCEE/ERC (Parsons ES, 1999c). Preliminary results of the evaluation indicate that the analytical results obtained using diffusion samplers are comparable to the results obtained using conventional or micropurging techniques. Furthermore, monitoring programs conducted using diffusion sampling equipment are much less labor intensive than conventional techniques, and are projected to cost far less than other sampling methods (conventional or micropurging).

5.1.1 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 long-term remediation projects such as the cleanup of groundwater at GAFB OU1. 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 1999 dollars, through the remaining project life cycle (a “constant-dollar” analysis). Assuming that the current TCE removal rate remains constant, the remaining project life cycle was estimated to be 33 years (Section 4).

System

The cost impacts associated with modifying system operations in accordance with Recommendations 1 and 2 were projected for the 33 years possibly remaining in the project life cycle. As shown on Figure 4.2, if none of the RPO recommendations are implemented, the total projected costs in constant 1999 dollars at the end of the 43-year total project life would be approximately \$15 million, of which about \$10.7 million is for OM&M costs. If Recommendations 1 and 2 are implemented, total project costs in constant 1999 dollars at the end of the remaining 33-year period would be approximately \$12.7 million, or a 15-percent decrease in anticipated total costs and a decrease of over 50 percent in annual operating expenses (Table 5.2). Based on the available data, implementation of these operational changes will most likely have no significant impact on achieving the cleanup objectives.

TABLE 5.2
RPO SUMMARY: SHORT-TERM RECOMMENDATIONS AND POTENTIAL COST SAVINGS
REMEDIAL PROCESS OPTIMIZATION, OU1
GEORGE AIR FORCE BASE, CALIFORNIA

Current System				Short-Term Optimization Recommendations	Optimized System				Difficulty of Implementation
System Component	Estimated Annual Cost ^{a/}	Estimated Total Remaining Cost ^{a/}			Estimated Annual Cost Savings	Cost Savings Over Remaining 33-Year Project Life Cycle ^{b/}	Cost Savings Over Remaining 100-Year Project Life Cycle ^{c/}	Reduction in Time to Meet Cleanup Goals	
		33-Year Period of Operation Remaining ^{b/}	100-Year Period of Operation Remaining ^{c/}						
18 groundwater extraction wells	\$60,000	\$2.0 million	\$6.0 million	Remove 11 of 18 existing extraction wells from service.	\$30,000	\$990,000	\$3.0 million	None	Moderate - Requires regulatory approval.
Air-stripping treatment system	\$40,000	\$1.3 million	\$4.0 million	Terminate air-stripping treatment of extracted groundwater.	\$40,000	\$1.3 million	\$4.0 million	None	Moderate - Requires demonstration that TCE in discharge would not exceed acceptable limits, with subsequent regulatory approval.
Groundwater monitoring program	\$150,000	\$5.0 million	\$15.0 million	Optimize long-term monitoring.	\$100,000 ^{d/} \$113,000 ^{e/}	\$3.3 million ^{d/} \$3.7 million ^{e/}	\$10.0 million ^{d/} \$11.3 million ^{e/}	None	Low - Requires regulatory approval.

^{a/} Estimated costs given in constant 1999 dollars (see Section 4).

^{b/} Assumes that remediation objectives are achieved in year 2033.

^{c/} Assumes that remediation objectives are achieved in year 2100.

^{d/} Monitoring costs using conventional or micropurge techniques.

^{e/} Monitoring costs using diffusion sampling techniques.

Monitoring Program

Recommendation 3 (optimization of groundwater monitoring program) could potentially have the largest long-term cost impact on the operational budget of the remediation system at GAFB OU1 (Table 5.2). The estimated monitoring costs for a 34-well sampling program, assumed to be conducted using conventional or micropurge techniques, are provided in Table 5.3; and the estimated monitoring costs for the same 34-well program, conducted using diffusion sampling techniques, are provided in Table 5.4. Reducing the LTM program by decreasing the sampling frequency, quantity, and number of analytical methods results in estimated cost savings of about \$100,000 per year, or over \$3 million in constant dollars over the remaining 33-year period of operation.

5.2 LONG-TERM OPPORTUNITIES

The RPO evaluation has identified several longer-term optimization opportunities that the Air Force should consider. These include regulatory approaches for establishing realistic clean-up objectives for the site (Section 3) and technical approaches, which could be implemented as alternative ways of managing site remediation. The following long-term opportunities for remedial system optimization have been identified:

Regulatory

Opportunity 1: Establish site-specific risk-based cleanup goals, and proceed with adoption as alternate cleanup goals.

Impact: Current conditions at GAFB OU1 suggest that re-evaluation of cleanup goals for the site may be appropriate -- MCLs established as cleanup goals in the ROD (Montgomery Watson, 1994) are not necessary to protect current human or environmental receptors because no completed exposure pathways exist. Therefore, it is recommended that the Air Force consider an amendment to the ROD (1994) to establish risk-based cleanup goals for groundwater, to be developed using realistic exposure scenarios. Section 3.4 identifies one possible approach for establishing risk-based cleanup goals based on industrial land-use classification.

There are provisions in both federal and state regulations (notably, the Lahontan Basin Plan [Lahontan RWQCB, 1998]) to apply for an exception to the application of MCLs as groundwater ARARs. In making exceptions for water use designation, the Lahontan Basin Plan considers the criteria in the Regional Board Resolution No. 6-89-94. These criteria include conditions for a site where “there is contamination that cannot reasonably be treated for domestic use either by best management practices or best economically achievable practices.” If more realistic risk-based cleanup goals are adopted for groundwater at OU1, a shorter (but currently unknown) period of time than the projected 33-year period would be required to attain those goals. In the absence of site-specific, alternate cleanup goals, the cost impact of implementing this opportunity is difficult to estimate. However, if adoption of risk-based goals resulted in cessation of operation of the pump-and-treat system, together with changes in the monitoring program, annual cost savings on the order of \$170,000 might be realized (Table 5.5).

TABLE 5.3
COST ESTIMATE FOR 34-WELL GROUNDWATER MONITORING PROGRAM
USING CONVENTIONAL OR MICROPURGE SAMPLING TECHNIQUES^{a/}
REMEDIAL PROCESS OPTIMIZATION, OU-1
GEORGE AIR FORCE BASE, CALIFORNIA

Cost type	Quantity	Units	Unit Cost	Cost
Labor for sample collection				
3 people for 11 days at \$60/hr	264	hours	\$ 60.00	\$ 15,840.00
Labor for data validation and data management				
2 people for 5 days at \$60/hr	80	hours	\$ 60.00	\$ 4,800.00
Laboratory Analyses				
Primary samples; VOCs by method SW8260	34	samples	\$ 150.00	\$ 5,100.00
QA/QC samples; VOCs by method SW8260	22	samples	\$ 150.00	\$ 3,300.00
Other Direct Costs				
Equipment rental (PID, pH/Eh, O2/CO2, etc.)	11	days	\$ 400.00	\$ 4,400.00
Vehicle rental (2 vehicles for 11 days)	22	days	\$ 45.00	\$ 990.00
Per Diem (3 people for 11 days at \$110 ea/day)	33	days	\$ 110.00	\$ 3,630.00
Miscellaneous field supplies				\$ 500.00
Reporting				
Labor (at representative labor rate)	120	hours	\$ 65.00	\$ 7,800.00
Miscellaneous and other direct costs				\$ 2,500.00
SUBTOTAL COST (1999 dollars)				\$ 48,860.00
Long-Term Monitoring costs for 33 years of annual sampling				x 33
TOTAL COST (constant 1999 dollars)				\$ 1,612,380.00

^{a/} Estimate by Parsons ES.

TABLE 5.4
COST ESTIMATE FOR 34-WELL GROUNDWATER MONITORING PROGRAM
USING DIFFUSION SAMPLING TECHNIQUES^{a/}
REMEDIAL PROCESS OPTIMIZATION, OU-1
GEORGE AIR FORCE BASE, CALIFORNIA

Cost type	Quantity	Units	Unit Cost	Cost
Labor and direct costs for sample collection				
34 primary samples and 22 QA/QC samples	56	samples	\$ 65.00	\$ 3,640.00
Labor for data validation and data management				
2 people for 5 days at \$60/hr	80	hours	\$ 60.00	\$ 4,800.00
Laboratory Analyses				
Primary samples; VOCs by method SW8260	34	samples	\$ 150.00	\$ 5,100.00
QA/QC samples; VOCs by method SW8260	22	samples	\$ 150.00	\$ 3,300.00
Other Direct Costs				
Equipment rental (PID, pH/Eh, O2/CO2, etc.)	11	days	\$ 400.00	\$ 4,400.00
Vehicle rental (2 vehicles for 11 days)	22	days	\$ 45.00	\$ 990.00
Per Diem (3 people for 11 days at \$110 ea/day)	33	days	\$ 110.00	\$ 3,630.00
Miscellaneous field supplies				\$ 500.00
Reporting				
Labor (at representative labor rate)	120	hours	\$ 65.00	\$ 7,800.00
Miscellaneous and other direct costs				\$ 2,500.00
SUBTOTAL COST (1999 dollars)				\$ 36,660.00
Long-Term Monitoring costs for 33 years of annual sampling				x 33
TOTAL COST (constant 1999 dollars)				\$ 1,209,780.00

^{a/} Estimate by Parsons ES, using unit costs presented in Parsons ES (1999c).

TABLE 5.5
RPO SUMMARY: LONG-TERM OPPORTUNITIES AND POTENTIAL COST SAVINGS
REMEDIAL PROCESS OPTIMIZATION, OU1
GEORGE AIR FORCE BASE, CALIFORNIA

Long-Term Optimization Opportunities	Annual Cost Savings	Cost Savings Over Remaining 33-Year Project Life Cycle ^{a/}	Cost Savings Over Remaining 100-Year Project Life Cycle ^{a/}	Reduction in Time to Meet Cleanup Goals	Difficulty of Implementation
Develop proposal for establishing site-specific, risk-based goals in accordance with requirements of Lahontan Basin Plan. Terminate operation of OU1 pump-and-treat system.	\$170,000	\$5.6 million	\$17 million	> 30 years	High - Requires regulatory approval and negotiation of site-specific, risk-based cleanup goals.
Evaluate monitored natural attenuation option in detail by shutting down system for 12-month period and observing plume migration. If appropriate, terminate operation of OU1 pump-and-treat system.	\$170,000	\$5.6 million	\$17 million	TBD ^{b/}	Moderate - Requires regulatory approval, long-term monitoring, and negotiation of site-specific, risk-based cleanup goals.
Refine conceptual hydrogeologic model, and use to evaluate phytoremediation option. If appropriate, terminate operation of all or part of OU1 pump-and-treat system.	\$150,000	\$5 million	\$15 million	TBD	Moderate – Requires regulatory approval, treatability study, and negotiation of site-specific, risk-based cleanup goals.

^{a/} Costs given in constant 1999 dollars (see Section 4).

^{b/} TBD = to be determined.

Technical Approach

Opportunity 2: Natural attenuation evaluation/implementation.

Impact: Continued migration of the TCE contaminant plume beyond its current extent is undesirable. That is the principal reason for the initial installation of the groundwater pump-and-treat system at GAFB OU1 (Section 4). The natural migration of the TCE plume is a consequence of geochemical conditions in the groundwater, which in general appear to be currently unfavorable to TCE degradation (Section 2.5). However, other attenuation mechanisms (volatilization, dispersion, sorption) act to reduce the mass, concentrations, or mobility of contaminants in groundwater. Because the effects of other attenuation mechanisms can be difficult to distinguish from the effects of groundwater extraction, the potential effectiveness of natural attenuation mechanisms is currently uncertain. If it can be demonstrated that natural attenuation mechanisms can effectively limit the continued migration of TCE at detectable concentrations, the groundwater pump-and-treat system at GAFB OU1 could be shut down.

In addition to evaluating the possible occurrence of natural attenuation mechanisms other than biodegradation, information collected during the shut-down period could be used in an evaluation of whether the existing system is operating “properly and successfully” (OPS evaluation), or whether alternative technologies (e.g., natural attenuation) could eventually operate properly and successfully. The phrase “operating properly and successfully) involves two separate concepts (USEPA, 1996). A remedial measure is operating “properly” if it is performing as designed or intended. The same system is operating “successfully” if its operation or implementation will achieve the cleanup levels or performance goals delineated in the decision document. Additionally, in order to be “successful”, the remedy must be protective of human health and the environment. If the plume expands during the shut-down period, this may provide evidence that the existing extraction system has been effective in limiting migration, and has therefore been operating “properly”. If the plume remains stable or contracts during the shut-down period, this may provide evidence that attenuation measures could provide an equivalent “proper and successful” remedy.

In order to provide sufficient chemical and hydrologic information to evaluate plume conditions, monitoring of groundwater at OU1 should continue on a semi-annual basis through the shut-down period. This would preclude development and implementation of an annual groundwater monitoring program until after the system had been shut down for an appropriate period of time, and the results evaluated. Assuming that annual groundwater monitoring would be implemented after the trial period, and that annual operating and maintenance costs for the system could be eliminated, annual cost savings on the order of \$170,000 could result, with this opportunity could saving over \$5 million (in constant 1999 dollars) over a 33-year period (Table 5.5).

Opportunity 3: Phytoremediation evaluation/implementation.

Impact: The arroyos that extend from the plateau on which George AFB is situated to the Mojave River floodplain below appear to function as pathways for preferential migration of groundwater containing dissolved TCE from the Upper Aquifer to the Lower Aquifer (Section 2). The saturated thickness and saturated cross-section of alluvial materials within these arroyos is most likely limited. The existence of thriving cottonwood trees in some areas within these arroyos indicates that the depth to groundwater in these areas is probably less than 10 to 20 feet. Therefore, phytoremediation is a candidate technology for extracting contaminated groundwater along targeted migration pathways, thereby limiting the potential for further TCE migration (Section 4.5).

In light of the available information, the subsurface relationships among the Upper and Lower Aquifers, the aquitard, and the potentiometric surfaces in the two units near the edge of the bluffs are not clear. As part of the phytoremediation evaluation, a limited subsurface investigation program should be completed to clarify the stratigraphic and hydraulic relationships, determine the depth to groundwater within the arroyos, and better characterize any preferred migration pathways. The investigation program should be focused on identifying conditions within and adjacent to the arroyos, and would include drilling and logging a number of testholes to clarify the stratigraphic and hydraulic relationships, determine the depth to groundwater within the arroyos, and better characterize any preferred migration pathways. The investigation program should be focused on identifying conditions within and adjacent to the arroyos, and would include drilling and logging a number of boreholes using low-cost technologies (e.g., GeoProbe™) to collect stratigraphic information, and installation of temporary groundwater monitoring wells in selected boreholes to collect water-level and hydrochemical information. Once the nature and extent of pathways for preferential migration have been confirmed, a phytoremediation treatability study could be initiated. At a minimum this would involve evaluating whether the native vegetation is affecting plume migration, identifying native or exotic plant species most likely to thrive in conditions at GAFB OU1, and planting the appropriate species at sufficient density to limit groundwater migration in the arroyos where TCE migration is occurring.

Implementation of a phytoremediation remedy would require some initial capital expenditures (on the order of \$35 to \$280 per tree) and maintenance costs (on the order of \$10 to \$30 per tree, per year), as well as increased frequency of monitoring during the initial implementation period. However, over the long term (10 to 33 years), it is expected that OM&M savings would off-set any capital investment required without sacrificing effectiveness, and could potentially save more than \$150,000 annually in operating costs (Table 5.5).

SECTION 6

IMPLEMENTATION PLAN

6.1 SHORT-TERM RECOMMENDATIONS

As part of this AFCEE RPO initiative, a short-term (6-month) implementation of the recommendations made in Section 5 should be considered and implemented by AFBCA and their primary environmental contractor (Montgomery Watson). After the trial period, an evaluation of the effectiveness of the various recommended approaches can be made:

Based on a review of the data collected to date, it appears that the short-term recommendations made in Section 5.1 can be implemented by the Base contractor with minimal effort. By implementing the changes during regular site visits and maintaining the same level of effort for data collection and reporting, an evaluation of the proposed changes that is consistent with current data collection and reporting techniques can be made. The following is a summary of what is required for implementation:

Recommendation 1: Temporarily (approximately 12 months) discontinue pumping at wells EW-5, EW-6, EW-10, EW-11, EW-12, EW-13, EW-14, EW-15, EW-16, EW-17, and EW-18.

- Well shutdown should be planned to coincide with a scheduled groundwater monitoring event. Prior to cessation of pumping, collect water-level measurements and a round of groundwater samples from each of the listed 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 selected wells.
- Prepare the system for a 12-month shutdown period.
- At the end of the 12-month period, conduct 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 (see Section 6.2).
- 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 4.5,

RNA cannot be fully evaluated during active groundwater extraction because the effects of pumping can mask some natural-attenuation indicators.

Recommendation 2: After pumping has been discontinued at the above-listed wells, conduct a short-term, pilot-scale treatability study to evaluate the concentrations of TCE in groundwater extracted from the remaining on-line wells.

- Concurrently with the shut-down of the wells, collect a sample of extracted groundwater at the influent wet-well and analyze for VOCs to assess the concentration of TCE in extracted groundwater.
- Temporarily route extracted groundwater from influent wet-well directly to the infiltration ponds. Discharge to the ponds should be through a spray mechanism or riffle weir to promote volatilization.
- After at least one pond-volume has been discharged from the influent wet-well, collect a water sample from pond and analyze it for VOCs to assess the concentration of TCE in infiltration water.
- If concentrations of TCE remain within acceptable treatment system effluent limits established in the ROD (see Section 3), continue discharge of water directly to infiltration ponds. Monitor system in accordance with current system monitoring plan.
- Begin evaluation of other candidate sites for discharge of extracted groundwater to eliminate the necessity of pumping water uphill from the influent wet-well.
- Initiate evaluation of feasibility and cost comparison for system discharging water to a POTW (the VVWRA facility).

Recommendation 3: Conduct detailed statistical evaluation of groundwater monitoring system. The objective of the evaluation will be to minimize the number of wells sampled, while maintaining a level of information adequate to support remediation and monitoring decisions. Reduce the frequency of sampling from semi-annual to annual. Modify the GAFB SAP (HydroGeoLogic, Inc., 1998) to incorporate the changes to the groundwater LTM plan. Evaluate

Annual groundwater monitoring probably should not be implemented until the results of the temporary well shut-down period have been evaluated. Results of the 12-month trial period will be reported by the Base contractor in the quarterly OM&M reports. This will 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.

6.2 LONG-TERM OPPORTUNITIES

It is recommended that the Air Force apply for exceptions to the MCL as the TCE cleanup goal for groundwater because the MCL does not reflect current or realistic future exposure scenarios or potential human-health or ecological risks. Non-attainability of the MCL of 5 µg/L for TCE in groundwater could be demonstrated using guidance in the Lahontan RWQCB's (1998) basin plan or CalEPA regulations (CCR). As an alternative to the MCL, the request for

an exception should recommend that the RBCA process be initiated to develop site-specific cleanup goals. The Air Force should begin discussions on this matter with state and federal regulators as soon as possible, because the process of obtaining alternate cleanup goals may require a period of 1 year or longer.

Per the Lahontan Basin Plan (Section 3.4), the following requirements to obtain exceptions to background concentrations or RWQCB cleanup standards must be met:

- Cleanup and abatement must be done in a manner that promotes attainment of background water quality, or the highest water quality which is reasonable if background levels of water quality cannot be restored; and
- The determination of what is reasonable must consider all demands being made and to be made on those waters, and the total values involved, beneficial and detrimental, economic and social, tangible, and intangible.

If cleanup to background is infeasible, cleanup standards will be set at the lowest concentrations for TCE that are technically and economically achievable:

- So as not to exceed the maximum concentrations allowable under applicable statutes and regulations;
- So as not to pose a hazard to health or to the environment; and
- So that the theoretical risks from chemicals associated with the release are considered additive across all media of exposure and are considered additive for those pollutants which cause similar toxicologic effects and for those which are carcinogens.

These requirements are similar to those established by USEPA (1993) for obtaining a TI waiver. In addition to the above-noted requirements, the following information also may be required to obtain an exception to the Lahontan Basin Plan (Lahontan RWQCB, 1998):

- The proximity and withdrawal rates of groundwater users;
- The potential for health risks caused by human exposure to TCE (human-health risk analysis);
- The potential damage to wildlife, crops, vegetation, and physical structures caused by exposure to TCE (ecological risk analysis);
- The persistence and permanence of the potential adverse effects;
- Alternate cleanup goals;
- A demonstration that no other remedial technologies (conventional or innovative) could reliably, logically, or feasibly attain the ROD cleanup level for TCE in site groundwater within a reasonable timeframe; and
- A predictive analysis of the timeframe and cost of groundwater remediation to alternate cleanup goals using the existing or proposed remedial options, including construction and OM&M costs.

The two long-term opportunities identified in Sections 4.5 and 5.2 as possible technical approaches to groundwater remediation (i.e., MNA and phytoremediation) should be evaluated at the pilot scale before proceeding to full-scale implementation. A detailed assessment of the potential for RNA can be conducted using the monitoring data to be collected immediately prior to shutdown of 11 of the 18 extraction wells, and at the conclusion of the 12-month trial operating period for the modified pump-and-treat system. Detailed instructions for conducting MNA evaluations are provided in existing protocol documents (e.g., USEPA, 1998).

To initiate the evaluation of phytoremediation, the Base contractor, in consultation with the Air Force, should prepare an investigation work plan describing sampling locations, samples types, and the methods to be followed in collecting the information necessary to assess the stratigraphic and hydraulic relationships of the soils and water-bearing units along the Mojave River bluffs in the vicinity of the arroyos. The investigation program should be designed primarily to characterize the nature and extent of preferential groundwater migration pathways from the Upper Aquifer to the Lower Aquifer along the arroyos. Once the nature and extent of possible migration pathways have been clarified, a phytoremediation treatability study could be initiated to evaluate if native vegetation is affecting TCE plume migration, by planting appropriate plant species at sufficient density in appropriate locations, and by monitoring plume characteristics in and immediately downgradient from the treatability study area. Parsons ES anticipates that the phytoremediation evaluation could be completed during the 12-month trial period of reduced groundwater pumping.

SECTION 7

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APPENDIX A

**FIELD SAMPLING RECORDS
AND
LABORATORY ANALYTICAL DATA**

(to be provided as CD-ROM in ERPIMS format with final report)

APPENDIX B

**PROPERTIES OF CHEMICALS OF POTENTIAL CONCERN
AND
THEIR MOVEMENT AND FATE IN THE ENVIRONMENT**

APPENDIX B

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.

B1.0 CHEMICAL STRUCTURE AND ITS INFLUENCE ON CHEMICAL PROPERTIES

B1.1 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 B.1.

B1.2 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;
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.

TABLE B.1
PROPERTIES OF SELECTED ORGANIC COMPOUNDS
REMEDIAL PROCESS OPTIMIZATION, OU-1
GEORGE AIR FORCE BASE, CALIFORNIA

Compound ^{b/}	Molecular Weight (g/mol) ^{c/}	Henry's Law Constant (atm-m ³ /mol) ^{d/}	Vapor Pressure (mm Hg @ 20°C) ^{e/}	Density (g/cm ³) ^{f/}	Solubility (mg/L) ^{g/}	Vapor-Air Diffusion Coefficient (cm ² /day) ^{h/}	Water-Liquid Diffusion Coefficient (cm ² /day)	K _{oc} ^{a/} (mL/g) ^{i/}	log K _{oc}	First Order Decay Constant in Water (1/days) ^{j/}
Methane	16.04 ^{k/}	1.83E+01 ^{l/}	2.08E+04 ^{l/}	0.420 ^{m/}	24 ^{m/}	17,680 ^{l/}	1.55 ^{l/}	7.60E+02 ^{l/}	2.88	N/A
Ethane	30.07 ^{k/}	1.92E+01 ^{l/}	2.93E+04 ^{m/}	0.561 ^{m/}	60.4 ^{m/}	11,870 ^{l/}	1.12 ^{l/}	4.58E+02 ^{l/}	2.66	N/A
Ethene	28.05 ^{k/}	8.60E+00 ^{l/}	3.08E+04 ^{l/}	0.566 ^{m/}	131 ^{l/}	12,510 ^{l/}	1.22 ^{l/}	2.99E+02 ^{l/}	2.48	0.006 - 0.17 ^{n/}
1,1-DCA	98.96 ^{k/}	4.32E-03 ^{o/}	1.80E+02 ^{m/}	1.176 ^{k/}	5,500 ^{m/}	7,690 ^{p/}	0.79 ^{p/}	3.00E+01 ^{q/}	1.48	0.002 ^{n/}
PCE	165.83 ^{k/}	1.32E-02 ^{o/}	1.40E+01 ^{m/}	1.623 ^{k/}	150 ^{m/}	6,912 ^{p/}	0.65 ^{p/}	2.63E+02 ^{q/}	2.42	0.0001 - 0.001 ^{n/ s/}
TCE	131.39 ^{k/}	7.19E-03 ^{o/}	6.00E+01 ^{m/}	1.464 ^{k/}	1,100 ^{m/}	7,603 ^{p/}	0.72 ^{p/}	1.07E+02 ^{q/}	2.03	0.0001 - 0.001 ^{n/ s/}
1,1-DCE ^{r/}	96.94 ^{k/}	2.07E-02 ^{o/}	5.00E+02 ^{m/}	1.218 ^{k/}	2,250 ^{q/}	8,122 ^{p/}	0.82 ^{p/}	6.50E+01 ^{q/}	1.81	0.005 ^{n/}
cis-1,2-DCE	96.94 ^{k/}	2.97E-03 ^{o/}	2.00E+02 ^{r/}	1.284 ^{k/}	800 ^{m/}	8,122 ^{p/}	0.82 ^{p/}	4.47E+01 ^{l/}	1.65	0.0001 - 0.004 ^{n/ l/}
1,1,1-TCA	133.40 ^{k/}	1.33E-02 ^{o/}	1.00E+02 ^{m/}	1.339 ^{k/}	4,400 ^{m/}	6,826 ^{p/}	0.69 ^{p/}	1.05E+02 ^{q/}	2.02	0.001 ^{n/}
Vinyl Chloride	62.50 ^{k/}	2.18E-02 ^{o/}	2.66E+03 ^{m/}	0.911 ^{k/}	1,100 ^{m/}	9,245 ^{p/}	0.98 ^{p/}	2.50E+00 ^{q/}	0.40	0.0002 ^{n/ s/}
Toluene	92.14 ^{k/}	5.94E-03 ^{r/}	2.20E+01 ^{m/}	0.867 ^{k/}	515 ^{m/}	7,344 ^{p/}	0.82 ^{p/}	1.51E+02 ^{q/}	2.18	0.001 ^{n/}
o-Xylene	106.17 ^{k/}	5.10E-03 ^{r/}	5.00E+00 ^{m/}	0.880 ^{k/}	175 ^{m/}	6,307 ^{p/}	0.61 ^{p/}	1.29E+02 ^{q/}	2.11	0.002 ^{n/}
m-Xylene	106.17 ^{k/}	7.68E-03 ^{r/}	6.00E+00 ^{m/}	0.864 ^{k/}	146 ^{r/}	5,962 ^{p/}	0.61 ^{p/}	1.59E+03 ^{q/}	3.20	0.01 ^{n/}
p-Xylene	106.17 ^{k/}	7.68E-03 ^{r/}	6.50E+00 ^{m/}	0.861 ^{k/}	198 ^{m/}	5,789 ^{p/}	0.61 ^{p/}	2.04E+02 ^{q/}	2.31	0.01 ^{n/}

^{a/} K_{oc} = Organic carbon partition coefficient.

^{b/} DCA = dichloroethane, DCE = dichloroethene, TCA = trichloroethane, TCE = trichloroethene.

^{c/} grams/mole.

^{d/} atmospheres-cubic meters per mole.

^{e/} millimeters mercury at 20 degrees Centigrade.

^{f/} grams per cubic centimeter.

^{g/} milligrams per liter.

^{h/} square centimeters per day.

^{i/} milliliters per gram.

^{j/} per day.

^{k/} Weast *et al.*, 1989.

^{l/} estimated using: Lyman *et al.*, 1990.

^{m/} Verschueren, 1983.

^{n/} Howard, *et al.*, 1991.

^{o/} Gossett, 1987.

^{p/} Tetra Tech, Inc., 1988.

^{q/} Montgomery and Welkom, 1990.

^{r/} Howard *et al.*, 1990.

^{s/} Wiedemeier *et al.*, 1999.

^{t/} Anthony *et al.*, 1997.

^u Howard *et al.*, 1990.

(1) Weast, R.C., Astle, M.J., and Beyer, W.H., eds., 1989, CRC Handbook of chemistry and physics: CRC Press, Inc., Boca Raton, Florida, 75th ed.

(8) estimated using: Lyman, W.J., Reehl, W.F., and Rosenblatt, D.H., 1990, Handbook of chemical property estimation methods: American Chemical Society, Washington, D.C.

(3) Verschueren, K., 1983, Handbook of environmental data on organic chemicals: Van Nostrand Reinhold Company, New York, 2nd ed., 1310 pp.

(4) Howard, P.H., Boethling, R.S., Jarvis, W.F., Meylan, W.M., and Michalenko, E.M., 1991, Handbook of environmental degradation rates: Lewis Publishers, Inc., Chelsea, Michigan, 725 pp.

(2) Gossett, J.M., 1987, Measurement of Henry's Law constants for C1 and C2 chlorinated hydrocarbons: Environmental Science and Technology, Vol. 21, No. 2, p. 202-208.

(4) Tetra Tech, Inc., 1988, Chemical data for predicting the fate of organic compounds in water, Vol. 2 -- Database: Electric Power Research Institute (EPRI), Palo Alto, California, EPRI Report EA-5818, 411 pp.

(5) Montgomery, J.H., and Welkom, L.M., 1990, Groundwater chemicals desk reference: Lewis Publishers, Inc., Chelsea, Michigan, 640 pp.

(7) Howard, P.H., Sage, G.W., Jarvis, W.F., and Gray, D.A., 1990, Handbook of environmental fate and exposure data for organic chemicals, Vol. II -- Solvents: Lewis Publishers, Inc., Chelsea, Michigan, 546 pp. Wiedemeier *et al.* (1999)

Anthony *et al.* (1997)

(9) Howard, P.H., Sage, G.W., Jarvis, W.F., and Gray, D.A., 1990, Handbook of environmental fate and exposure data for organic chemicals, Vol. I -- Large production and priority pollutants: Lewis Publishers, Inc.,

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.

B1.3 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 B.1. (Note that the literature values, reported by different workers, for a particular chemical property can vary widely. The values listed in Table B.1 represent chemical property values judged to be most representative, or are in the median range of values reported for a particular chemical.)

B1.3.1 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.

B1.3.2 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.

B1.3.3 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):

$$C_{sorbed} = K_d \times C_{dissolved} \quad (B-1)$$

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

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

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 B.1) to evaluate chemical partitioning, using

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

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 B.1), are strongly sorbed to soil particles, and travel only slowly in the dissolved (aqueous) phase.

B2.0 FATE OF CHEMICALS OF POTENTIAL CONCERN IN THE ENVIRONMENT

B2.1 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 B.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.

B2.2 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 B.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.

B2.3 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 B.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**):

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

where

- $V_{groundwater}$ = average groundwater flow velocity [L/T],
- $V_{chemical}$ = average velocity of center of mass of dissolved chemical slug [L/T],
- \mathbf{r} = 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 B1.3.3), ranging from about 45 milliliters per gram (mL/g) for *cis*-1,2-DCE to 107 mL/g (TCE; Table B.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.

B3.0 CHEMICAL AND BIOLOGICAL DEGRADATION

B3.1 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).

B3.2 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):

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

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:

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

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:

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

where

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

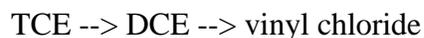
B3.3 Degradation of Halogenated Compounds

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.

B3.3.1 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 B.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



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 B.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 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).

- (Cl)** Chlorine Atom
- (C)** Carbon Atom
- (H)** Hydrogen Atom
- Single Chemical Bond
- = Double Chemical Bond

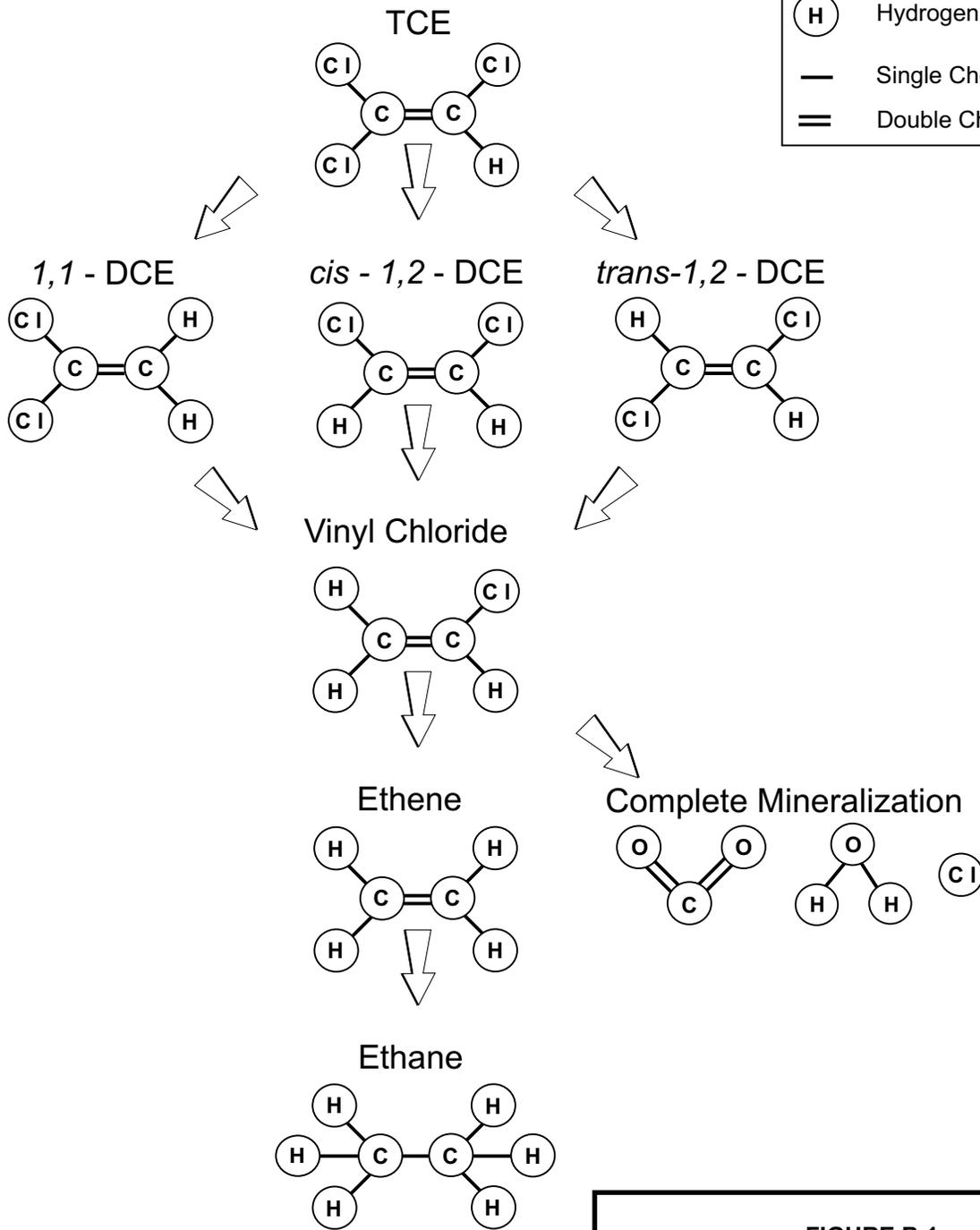


FIGURE B.1
REDUCTIVE
DEHALOGENATION OF
CHLORINATED ETHENES

Remedial Process Optimization
George AFB, California

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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).

B3.3.2 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.

B3.3.3 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 B.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.

B3.4 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.

B3.4.1 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:

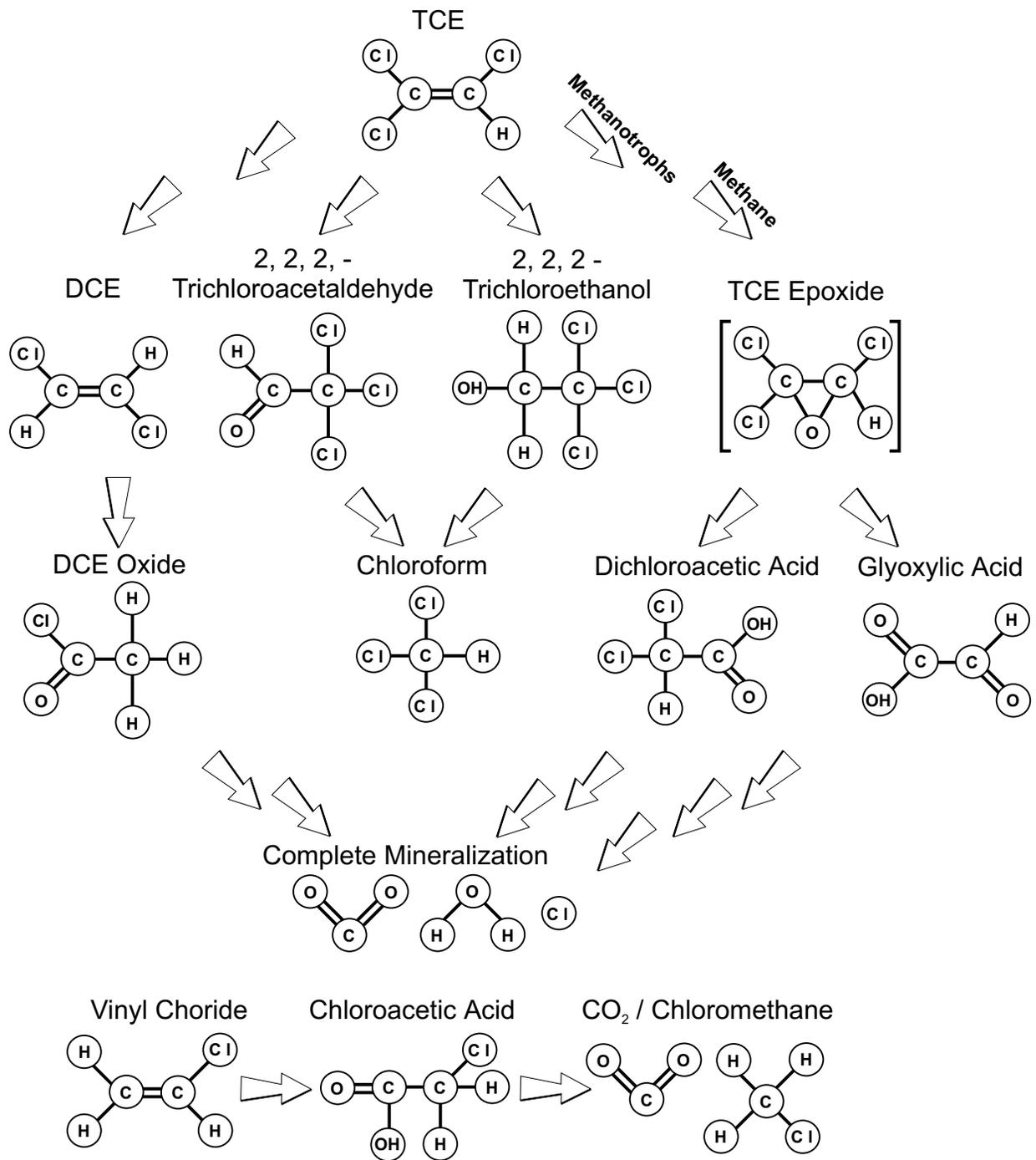


FIGURE B.2
AEROBIC
DEGRADATION PATHWAYS

Remedial Process Optimization
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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.

B3.4.2 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.

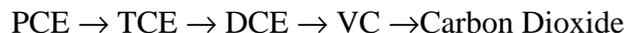
B3.4.3 Type 3 Behavior

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.

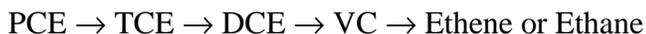
B3.4.4 Mixed Behavior

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:



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

B3.5 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 C

EXAMPLE CALCULATIONS FOR RISK-BASED CLEANUP LEVELS

APPENDIX C

Example Risk-Based Groundwater Cleanup Levels

Example risk-based concentrations (RBCs) for trichloroethene (TCE) in groundwater (GW) were derived based on an industrial groundskeeper dermal-exposure scenario at George Air Force Base (AFB), California. For information purposes only, these RBCs (dermal exposure scenario) were compared with RBCs based on RBCs developed using an industrial drinking-water (DW) scenario, and federal DW maximum contaminant levels (MCLs).

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

- A groundskeeper may be dermally exposed to contaminants in groundwater while watering grounds on the Base (e.g., lawn, flowerbeds, etc.);
- The dermal contact exposure route is the only significant, completed exposure route for the groundskeeper;
- An on-site well will be used to supply the water used by the groundskeeper;
- As a consequence of particular clothing and work requirements, the hands, forearms, and lowerlegs are the dermally exposed body parts;
- 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 for TCE than noncancer effects).

The results of the dermal-based GW RBC calculations are presented in Table C.1. Supporting calculations are provided as an Attachment. As shown in Table C.1, RBCs based on potential dermal contact with contaminated GW ranged from 1,130 micrograms per liter ($\mu\text{g/L}$; reasonable maximum exposure -- RME) to 11,130 $\mu\text{g/L}$ (central tendency; CT) for TCE. For comparison purposes, drinking water-based RBCs for TCE ranged from 5 to 26 $\mu\text{g/L}$ (Table C.1).

**TABLE C.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
TCE	1,130	11,130	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

APPENDIX C: RISK CALCULATION SHEETS
CALCULATION OF SCREENING LEVEL PRELIMINARY REMEDIATION GOALS - GROUNDWATER^{a/}
INDUSTRIAL LAND USE ASSUMPTIONS
REMEDIAL PROCESS OPTIMIZATION REPORT, GEORGE AIR FORCE BASE

Exposure Assumptions		
Receptor		Industrial Worker
Site-specific screening level preliminary remediation goal for combined exposure routes (PRG)		chem.-specific μg/L ^{b/}
Site-specific screening level preliminary remediation goal based on incidental ingestion of groundwater (PRG _{ing})		chem.-specific μg/L
Site-specific preliminary remediation goal based on dermal contact with groundwater (PRG _{derm})		chem.-specific μg/L

PRG Equation (combined exposure routes)

$$PRG = \frac{1}{\frac{1}{PRG_{ing}} + \frac{1}{PRG_{derm}}}$$

Contaminant	CAS Number ^{c/}	RME SCENARIO ^{d/}					CT SCENARIO ^{e/}			
		PRG _{ing} (μg/L)	PRG _{derm} (μg/L)	PRG _{RME} (μg/L)	PRG _{RME} Based on: ^{e/}	Screening Level PRG _{RME} (mg/kg) ^{f/}	PRG _{ing} (μg/L)	PRG _{derm} (μg/L)	PRG _{CT} (μg/L)	PRG _{CT} Based on: ^{e/}
Volatile Organic Compounds										
Trichloroethene	79-01-6	2.60E+01	1.26E+03	2.55E+01	C	2.55E+01	1.48E+02	1.26E+04	1.47E+02	C

^{a/} PRG calculations based on combining the following exposure routes: ingestion and dermal contact.

^{b/} μg/L = micrograms per liter

^{c/} CAS = Chemical Abstracts Service number.

^{d/} RME = reasonable maximum exposure

^{e/} "N" = PRG based on noncarcinogenic effects; "C" = PRG based on carcinogenic effects.

^{f/} Screening level PRG_{RME} equals PRG_{RME} for carcinogenic contaminants and 1/10 PRG_{RME} if PRG_{RME} is based on noncarcinogenic effects.

^{g/} CT = central tendency

APPENDIX C: RISK CALCULATION SHEETS
CHEMICAL PROPERTIES
INDUSTRIAL LAND USE ASSUMPTIONS
REMEDIAL PROCESS OPTIMIZATION REPORT, GEORGE AIR FORCE BASE

Contaminant	CAS Number ^{b/}	Type ^{c/}	Chemical Properties ^{a/}															
			t* (hr) ^{d/}	Ref ^{e/}	K _p (cm/hr) ^{f/}	Ref	t _{event} (hr/event) ^{g/}	Ref	B (unitless)	Ref	OAF (unitless)	Ref	Sf _{oral} (mg/kg-day) ^{-1 h/}	Ref	SF _d (mg/kg-day) ⁻¹	RfD _{oral} (mg/kg-day)	Ref	RfD _d (mg/kg-day)
Volatile Organic Compounds																		
Trichloroethene	79-01-6	o	1.30E+00	D	1.60E-02	D	5.50E-01	D	2.60E-02	D	1	Lee, 1997, Green, 1985, & Dekant, 1986	1.10E-02	W	1.10E-02	6.00E-03	E	6.00E-03

^{a/} Chemical Properties are defined as follows: t* = time it takes to reach steady state, K_p = Permeability coefficient from water, t_{event} = lag time per event, B = Relative contribution of permeability coefficients, OAF = oral absorption factor, SForal = oral slope factor, SF_d = dermal slope factor (i.e., oral slope factor adjusted for gastrointestinal absorption), RfD_{oral} = oral reference dose, RfD_d = dermal reference dose (i.e., oral reference dose adjusted for gastrointestinal absorption).

^{b/} CAS = Chemical Abstracts Service number.

^{c/} "o" indicates an organic compound, "i" indicates an inorganic compound

^{d/} hr = hour

^{e/} Ref = References as defined below.

^{f/} cm/hr = centimeters per hour

^{g/} hr/event = hours per event

^{h/} mg/kg-day = milligrams per kilogram-day

References:

D = USEPA (1992) *Dermal Exposure Assessment: Principles and Applications*. EPA/600/7-91/011B.

I = USEPA (1999), *Integrated Risk Information System (IRIS)*.

E = USEPA National Center for Environmental Assessment per USEPA Region 3 (1998). *Risk-Based Concentration Table*. October 1, 1998

W = Withdrawn from IRIS or HEAST.

X = Based on route-to-route extrapolation per USEPA Region IX (1998) PRG Table.

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APPENDIX C: RISK CALCULATION SHEETS
CALCULATION OF SCREENING LEVEL PRELIMINARY REMEDIATION GOALS - GROUNDWATER ^{a/}
INDUSTRIAL LAND USE - RME SCENARIO
REMEDIAL PROCESS OPTIMIZATION REPORT, GEORGE AIR FORCE BASE

Exposure Assumptions	DA _{event} Equations	
Receptor	Groundskeeper: RME Scenario	Carcinogenic:
Dose absorbed per unit area per event (DA _{event})	chemical-specific mg/cm ² -event ^{a/}	$DA_{event\ carc} = \frac{(TR)(BW)(AT_c)(365day/year)}{(SF_d)(EF)(ED)(EV)(EC)(SA)}$
Target cancer risk level (TR)	1.00E-06 unitless	
Body Weight (BW)	70 kg	$where\ SF_d = \frac{(SF_o)}{(OAF)} \text{ and: } OAF = \text{Oral GI absorption factor (chemical-specific; unitless)}$
Averaging Time, Carcinogens (AT _c)	70 yrs	
Dermal Slope Factor (SF _d) (i.e., SF _o adjusted for GI absorption)	chemical-specific (mg/kg-day) ⁻¹ ^{b/}	Noncarcinogenic:
Exposure Frequency (EF)	50 days/yr ^{c/}	$DA_{event\ nc} = \frac{(THQ)(BW)(RfD_d)(AT_{nc})(365day/year)}{(EF)(ED)(EV)(EC)(SA)}$
Exposure Duration (ED)	25 yr	
Event Frequency (EV)	1 events/day	$where\ RfD_d = (RfD_o)(OAF)$
Fraction of Estimated Time in Contact with Water (EC)	1 unitless	
Exposed Body Surface Area (SA)	4450 cm ²	
Target hazard quotient (THQ)	1 unitless	
Dermal Reference Dose (RfD _d) (i.e., RfD _o adjusted for GI absorption)	chemical-specific mg/kg-day	
Averaging Time, Noncarcinogens (AT _{nc})	25 yr	

Contaminant	CAS Number ^{d/}	SF _o (mg/kg-day) ⁻¹	RfD _o (mg/kg-day)	OAF (unitless)	SF _d (mg/kg-day) ⁻¹	RfD _d (mg/kg-day)	DA _{event} _{carc} (mg/cm ² -event)	DA _{event} _{nc} (mg/cm ² -event)	DA _{event} (mg/cm ² -event)	COPC Classification for DA _{event} ^{d/}
Volatile Organic Compounds										
Trichloroethene	79-01-6	1.10E-02	6.00E-03	1.00E+00	1.10E-02	6.00E-03	2.92E-05	6.89E-04	2.92E-05	C

^{a/} mg/cm² = milligram per square centimeter.
^{b/} mg/kg-day = milligram per kilogram-day
^{c/} days/yr = days per year
^{d/} CAS = Chemical Abstracts Service number.
^{e/} -- = toxicity data not available.

APPENDIX C: RISK CALCULATION SHEETS
CALCULATION OF SCREENING LEVEL PRELIMINARY REMEDIATION GOALS - GROUNDWATER ^{a/}
INDUSTRIAL LAND USE - RME SCENARIO
REMEDIAL PROCESS OPTIMIZATION REPORT, GEORGE AIR FORCE BASE

Input Parameters	PRG Equations	
Receptor	Groundskeeper: RME Scenario	For inorganics:
Site-specific preliminary remediation goal based on dermal contact with groundwater (PRG _{derm})	chemical-specific μg/L ^{a/}	$PRG_{derm-inorg} = \frac{(DA_{event})(CF)}{(K_p)(t_{event})}$
Dose absorbed per unit area per event (DA _{event})	chemical-specific mg/cm ² -event ^{b/}	
Conversion Factor (CF)	1.00E+06 (ml/L) x (μg/mg) ^{c/}	For organics:
Permeability coefficient from water (K _p)	Chemical-specific cm/hr ^{d/}	
Duration of event (t _{event})	0.5 hr/event ^{e/}	
Time it takes to reach steady state (t*)	Chemical-specific hr/event	If t _{event} < t*, then:
Lag time per event (t _{event})	Chemical-specific hr/event	
Relative contribution of permeability coefficients in stratum corneum and viable epidermis (B)	Chemical-specific unitless	$PRG_{derm-org} = \frac{(DA_{event})(CF)}{2K_p \sqrt{\frac{6t_{event} t_{event}}{p}}}$
		If t _{event} > t*, then: $PRG_{derm-org} = \frac{(DA_{event})(CF)}{K_p \left[\frac{t_{event}}{1+B} + 2t_{event} \left(\frac{1+3B+3B^2}{(1+B)^2} \right) \right]}$

Contaminant	Type ^{f/}	K _p (cm/hr)	t* (hr/event)	t _{event} (hr/event)	B (unitless)	DA _{event} (mg/cm ² -event)	PRG _{derm-inorg} (μg/L)	PRG _{derm-organic} (μg/L)	PRG _{derm} (μg/L)	COPC Classification for PRG _{derm} ^{a/}
Volatile Organic Compounds										
Trichloroethene	o	1.60E-02	1.30E+00	5.50E-01	2.60E-02	2.92E-05		1.26E+03	1.26E+03	C

^{a/} μg/L = micrograms per liter

^{b/} mg/cm²-event = milligrams per centimeter-event

^{c/} (ml/L) x (μg/mg) = milliliter per liter times microgram per milligram

^{d/} cm/hr = centimeters per hour

^{e/} hr/event = hours per event

^{f/} "o" indicates an organic compound, "i" indicates an inorganic compound

APPENDIX C: RISK CALCULATION SHEETS
CALCULATION OF SCREENING LEVEL PRELIMINARY REMEDIATION GOALS - GROUNDWATER ^{a/}
INDUSTRIAL LAND USE - CT SCENARIO
REMEDIAL PROCESS OPTIMIZATION REPORT, GEORGE AIR FORCE BASE

Exposure Assumptions	DA _{event} Equations	
Receptor	Groundskeeper: CT Scenario	Carcinogenic:
Dose absorbed per unit area per event (DA _{event})	chemical-specific mg/cm ² -event ^{a/}	$DA_{event\ care} = \frac{(TR)(BW)(AT_c)(365day/year)}{(SF_d)(EF)(ED)(EV)(EC)(SA)}$
Target cancer risk level (TR)	1.00E-06 unitless	
Body Weight (BW)	70 kg	
Averaging Time, Carcinogens (AT _c)	70 yrs	
Dermal Slope Factor (SF _d) (i.e., SF _o adjusted for GI absorption)	chemical-specific (mg/kg-day) ⁻¹ ^{b/}	
Exposure Frequency (EF)	25 days/yr ^{c/}	where $SF_d = \frac{(SF_o)}{(OAF)}$ and: OAF = Oral GI absorption factor (chemical-specific; unitless)
Exposure Duration (ED)	5 yr	Noncarcinogenic:
Event Frequency (EV)	1 events/day	$DA_{event\ nc} = \frac{(THQ)(BW)(RfD_d)(AT_{nc})(365day/year)}{(EF)(ED)(EV)(EC)(SA)}$
Fraction of Estimated Time in Contact with Water (EC)	1 unitless	
Exposed Body Surface Area (SA)	4450 cm ²	
Target hazard quotient (THQ)	1 unitless	
Dermal Reference Dose (RfD _d) (i.e., RfD _o adjusted for GI absorption)	chemical-specific mg/kg-day	
Averaging Time, Noncarcinogens (AT _{nc})	5 yr	where $RfD_d = (RfD_o)(OAF)$

Contaminant	CAS Number ^{d/}	SF _o (mg/kg-day) ⁻¹	RfD _o (mg/kg-day)	OAF (unitless)	SF _d (mg/kg-day) ⁻¹	RfD _d (mg/kg-day)	DA _{event} _{care} (mg/cm ² -event)	DA _{event} _{nc} (mg/cm ² -event)	DA _{event} (mg/cm ² -event)	COPC Classification for DA _{event} ^{d/}
Volatile Organic Compounds										
Trichloroethene	79-01-6	1.10E-02	6.00E-03	1.00E+00	1.10E-02	6.00E-03	2.92E-04	1.38E-03	2.92E-04	C

^{a/} mg/cm² = milligram per square centimeter.

^{b/} mg/kg-day = milligram per kilogram-day

^{c/} days/yr = days per year

^{d/} CAS = Chemical Abstracts Service number.

^{e/} -- = toxicity data not available.

APPENDIX C: RISK CALCULATION SHEETS
CALCULATION OF SCREENING LEVEL PRELIMINARY REMEDIATION GOALS - GROUNDWATER ^{a/}
INDUSTRIAL LAND USE - CT SCENARIO
REMEDIAL PROCESS OPTIMIZATION REPORT, GEORGE AIR FORCE BASE

Input Parameters			PRG Equations	
Receptor	Groundskeeper: CT Scenario		For inorganics:	
Site-specific preliminary remediation goal based on dermal contact with groundwater (PRG _{derm})	chemical-specific	μg/L ^{a/}	$PRG_{derm-inorg} = \frac{(DA_{event})(CF)}{(K_p)(t_{event})}$	
Dose absorbed per unit area per event (DA _{event})	chemical-specific	mg/cm ² -event ^{b/}		
Conversion Factor (CF)	1.00E+06	(ml/L) x (μg/mg) ^{c/}	For organics:	
Permeability coefficient from water (K _p)	Chemical-specific	cm/hr ^{d/}		
Duration of event (t _{event})	0.5	hr/event ^{e/}	If t _{event} < t*, then: $PRG_{derm-org} = \frac{(DA_{event})(CF)}{2K_p \sqrt{6t_{event} t_{event}}}$	
Time it takes to reach steady state (t*)	Chemical-specific	hr/event		
Lag time per event (t _{event})	Chemical-specific	hr/event	If t _{event} > t*, then: $PRG_{derm-org} = \frac{(DA_{event})(CF)}{K_p \left[\frac{t_{event}}{1+B} + 2t_{event} \left(\frac{1+3B+3B^2}{(1+B)^2} \right) \right]}$	
Relative contribution of permeability coefficients in stratum corneum and viable epidermis (B)	Chemical-specific	unitless		

Contaminant	Type ^{f/}	K _p (cm/hr)	t* (hr/event)	t _{event} (hr/event)	B (unitless)	DA _{event} (mg/cm ² -event)	PRG _{derm-c} (μg/L)	PRG _{derm-nc} (μg/L)	PRG _{derm} (μg/L)	COPC Classification for PRG _{derm} ^{d/}
Volatile Organic Compounds										
Trichloroethene	o	1.60E-02	1.30E+00	5.50E-01	2.60E-02	2.92E-04		1.26E+04	1.26E+04	C

^{a/} μg/L = micrograms per liter

^{b/} mg/cm²-event = milligrams per centimeter-event

^{c/} (ml/L) x (μg/mg) = milliliter per liter times microgram per milligram

^{d/} cm/hr = centimeters per hour

^{e/} hr/event = hours per event

^{f/} "o" indicates an organic compound, "i" indicates an inorganic compound

APPENDIX C: RISK CALCULATION SHEETS
CALCULATION OF SCREENING LEVEL PRELIMINARY REMEDIATION GOALS - GROUNDWATER ^{a/}
INDUSTRIAL LAND USE - RME SCENARIO
REMEDIAL PROCESS OPTIMIZATION REPORT, GEORGE AIR FORCE BASE

Exposure Assumptions		PRG Equations
Receptor	Groundskeeper: RME Scenario	Carcinogenic:
Site-specific preliminary remediation goal based on incidental ingestion of groundwater (PRG _{ing})	chemical-specific µg/L ^{a/}	$PRG_{ing-c} = \frac{(TR)(BW)(AT_c)(365day/year)}{(SF_o)(IR_w)(EF)(ED)(CF)}$
Target cancer risk level (TR)	1.00E-06 unitless	
Body Weight (BW)	70 kg	
Averaging Time, Carcinogens (AT _c)	70 yrs	Noncarcinogenic: $PRG_{ing-nc} = \frac{(THQ)(BW)(RfD_o)(AT_{nc})(365day/year)}{(IR_w)(EF)(ED)(CF)}$
Oral Slope Factor (SF _o)	chemical-specific (mg/kg-day) ⁻¹ ^{b/}	
Water Ingestion Rate (IR _w)	1 L/day	
Exposure Frequency (EF)	250 days/yr	
Exposure Duration (ED)	25 yr	
Conversion Factor (CF)	0.001 mg/µg	
Target hazard quotient (THQ)	1 unitless	
Oral Reference Dose (RfD _o)	chemical-specific mg/kg-day	
Averaging Time, Noncarcinogens (AT _{nc})	25 yr	

Contaminant	CAS Number ^{c/}	SF _o (mg/kg-day) ⁻¹	RfD _o (mg/kg-day)	PRG _{ing-c} (µg/L)	PRG _{ing-nc} (µg/L)	PRG _{ing} (µg/L)	COPC Classification ^{d/} for PRG _{ing} ^{d/}
Volatile Organic Compounds							
Trichloroethene	79-01-6	1.10E-02	6.00E-03	2.60E+01	6.13E+02	2.60E+01	C

^{a/} µg/L = microgram per liter

^{b/} mg/kg-day = milligram per kilogram-day

^{c/} CAS = Chemical Abstracts Service number.

^{d/} -- = toxicity data not available.

APPENDIX C: RISK CALCULATION SHEETS
CALCULATION OF SCREENING LEVEL PRELIMINARY REMEDIATION GOALS - GROUNDWATER ^{a/}
INDUSTRIAL LAND USE - CT SCENARIO
REMEDIAL PROCESS OPTIMIZATION REPORT, GEORGE AIR FORCE BASE

Exposure Assumptions		PRG Equations
Receptor	Groundskeeper: CT Scenario	Carcinogenic:
Site-specific preliminary remediation goal based on incidental ingestion of groundwater (PRG _{ing})	chemical-specific µg/L ^{a/}	$PRG_{ing-c} = \frac{(TR)(BW)(AT_c)(365day/year)}{(SF_o)(IR_w)(EF)(ED)(CF)}$
Target cancer risk level (TR)	1.00E-06 unitless	
Body Weight (BW)	70 kg	
Averaging Time, Carcinogens (AT _c)	70 yrs	
Oral Slope Factor (SF _o)	chemical-specific (mg/kg-day) ⁻¹ ^{b/}	Noncarcinogenic:
Water Ingestion Rate (IR _w)	1 L/day	$PRG_{ing-nc} = \frac{(THQ)(BW)(RfD_o)(AT_{nc})(365day/year)}{(IR_w)(EF)(ED)(CF)}$
Exposure Frequency (EF)	219 days/yr	
Exposure Duration (ED)	5 yr	
Conversion Factor (CF)	0.001 mg/µg	
Target hazard quotient (THQ)	1 unitless	
Oral Reference Dose (RfD _o)	chemical-specific mg/kg-day	
Averaging Time, Noncarcinogens (AT _{nc})	5 yr	

Contaminant	CAS Number ^{c/}	SF _o (mg/kg-day) ⁻¹	RfD _o (mg/kg-day)	PRG _{ing-c} (µg/L)	PRG _{ing-nc} (µg/L)	PRG _{ing} (µg/L)	COPC Classification for PRG _{ing} ^{d/}
Volatile Organic Compounds							
Trichloroethene	79-01-6	1.10E-02	6.00E-03	1.48E+02	7.00E+02	1.48E+02	C

^{a/} µg/L = microgram per liter

^{b/} mg/kg-day = milligram per kilogram-day

^{c/} CAS = Chemical Abstracts Service number.

^{d/} -- = toxicity data not available.

APPENDIX D

**COMMENTS AND RESPONSES ON THE DRAFT FINAL RPO REPORT
FOR OU1, NORTHEAST DISPOSAL AREA, GEORGE AFB,
CALIFORNIA**

**RESPONSE TO COMMENTS ON THE DRAFT FINAL REMEDIAL PROCESS OPTIMIZATION REPORT
FOR OPERABLE UNIT 1, NORTHEAST DISPOSAL AREA,
GEORGE AIR FORCE BASE (AFB), CALIFORNIA
FROM MR. JAMES CHANG, USEPA REGION IX**

Item	Page	Section	Comments	Responses
1			<p>Short Term Recommendations. Recommendation No. 1 proposes discontinuing pumping at eleven of the eighteen extraction wells at OU 1. This recommendation has essentially already been put into place. As noted in the Draft Final RPO Report five extraction wells (EW-6, EW-14, EW-15, EW-16, and EW-17) were taken off-line earlier this year, thus, only six of the extraction wells proposed for deletion are currently on-line (EW-5, EW-10, EW-11, EW-12, EW-13 and EW-18). However, five of the six on-line extraction wells proposed for removal (EW-5, EW-10, EW-11, EW-12, and EW-13), account for less than six gallons per minute (gpm) of flow to the treatment system. These five extraction wells also only account for a combined TCE removal rate of approximately 0.45 pounds per year. U.S. EPA had previously recommended shutting off extraction well EW-18, however, it was decided by the RPMs to leave this well operational because of the RWQCB's concerns that there were no other extraction wells in this area provide hydraulic containment of the groundwater plume.</p>	<p>Comment noted.</p>
2			<p>The revised extraction scenario should be based on modeling data to ensure that the extraction wells left on line can adequately capture the TCE in groundwater plume while minimizing the volume of groundwater extracted. The report should be revised to provide modeling data to assure that capture of the TCE in groundwater plume is maintained.</p>	<p>Modeling activities are not part of the scope of the current RPO evaluation. Site-specific scope and objectives of the RPO project at the Northeast Disposal Area (NEDA), George Air Force Base (GAFB) are provided in Section 1.2 of the Draft Final report.</p> <p>Furthermore, Parsons is uncertain as to the degree of defensibility that might be associated with a numerical model of groundwater flow and contaminant transport, constructed to represent a hydrologic system as heterogeneous as that at GAFB. In our opinion, until</p>

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				<p>the understanding of the nature of hydraulic communication between the Upper and Lower Aquifers at GAFB has been refined, construction of a numerical model to simulate that system would be a futile exercise.</p> <p>Construction of a numerical model is probably also unnecessary. Groundwater flow velocity calculations provided by Montgomery Watson, Inc. (1999b) indicate that in the absence of any hydraulic controls, a period of at least one year would be required for TCE to migrate from the current, distal edge of the plume in the Lower Aquifer to potential receptor exposure points. This is sufficient time to re-institute hydraulic control of the plume, in the event that plume expansion or migration begins following the cessation of pumping. The current groundwater monitoring network surrounding, and downgradient of the TCE plume in the Lower Aquifer is adequate to detect possible increases in downgradient concentrations of TCE, which would be indicative of expansion or migration of the TCE plume. Therefore, it is our opinion that collection and interpretation of real chemical concentration data through time, rather than numerical simulation of an incompletely-understood hydrologic system, is the means by which the performance of the system under reduced pumping conditions should be evaluated.</p>
3			Short Term Recommendation No. 2 recommends termination of the air-stripping treatment of the extracted groundwater. This	Refer to Section 4.2.2 of the RPO report. The results of recent and historical monitoring indicate that extracted

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			<p>recommendation is not acceptable. This option may be considered after the extraction system has been modified and extraction rates and influent concentrations have been established. However, under current conditions, it will likely result in the discharge of groundwater contaminated with TCE to the percolation ponds. The OU 1 Record of Decision (ROD) states that TCE in treated groundwater effluent must meet the enforceable level of 2.5 µg/l TCE on a median basis with a maximum discharge level of 5 µg/l. Furthermore, since discharge to the percolation ponds is causing the migration of TCE in groundwater to areas that are not captured by the extraction system, alternative discharge points for the treated effluent should be explored. The RPO Report should also address alternative discharge points that reuse or recycle the treated effluent, such as irrigation of the golf course at George Air Force Base.</p>	<p>groundwater influent to the treatment system probably contains TCE at concentrations at or below the Maximum Contaminant Level (MCL) concentration for TCE (5 micrograms per liter [µg/L]). Because TCE by nature is a <i>volatile</i> organic chemical, it is entirely possible that the simple fact of introducing extracted groundwater to a discharge point could cause sufficient TCE to volatilize so that the remaining concentrations would be below detection limits. However, this hypothesis can only be tested at field scale – the point of our recommendation. Refer to Recommendation No. 2 (Section 6 of the RPO report):</p> <p><i>“After pumping has been discontinued at the above-listed wells, conduct a short-term, pilot-scale treatability study to evaluate the concentrations of TCE in groundwater extracted from the remaining on-line wells.</i></p> <p><i>“Concurrently with the shut-down of the wells, collect a sample of extracted groundwater at the influent wet-well and analyze for VOCs to assess the concentration of TCE in extracted groundwater.</i></p> <p><i>“Temporarily route extracted groundwater from influent wet-well directly to the infiltration ponds. Discharge to the ponds should be through a spray mechanism or riffle weir to promote volatilization.</i></p> <p><i>“After at least one pond-volume has been discharged</i></p>

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				<p><i>from the influent wet-well, collect a water sample from pond and analyze it for VOCs to assess the concentration of TCE in infiltration water.</i></p> <p><i>“If concentrations of TCE remain within acceptable treatment system effluent limits established in the ROD (see Section 3), continue discharge of water directly to infiltration ponds. Monitor system in accordance with current system monitoring plan.”</i></p> <p>The discharge requirements in the ROD were established after considering then-current “applicable or relevant and appropriate standard(s), requirement(s), criteria, or limitation(s)” (ARARs). Evaluation of the requirements of the ROD indicates that groundwater beneath, and down-gradient of the NEDA, GAFB OU1, has “existing or potential beneficial uses as a source of drinking water” (Lahontan RWQCB, 1998). Thus, the action-specific ARAR governing effluent discharge was apparently the necessity of meeting drinking-water MCLs in groundwater beneath the NEDA. However, if drinking-water MCLs in groundwater are an appropriate ARAR for effluent discharge concentrations, the point at which the ARAR is applied should be the groundwater table, rather than the infiltration ponds. The depth to the water table of the Upper Aquifer beneath the infiltration ponds is currently on the order of 100 feet. Even if TCE is introduced to the percolation ponds at a concentration that exceeds the MCL concentration, it is unlikely to</p>

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				<p>migrate to the groundwater table at detectable concentrations, through a 100-foot-thick vadose zone.</p> <p>Refer to Recommendation No. 2 (Sections 5 and 6) of the RPO report. Included in this recommendation was the suggestion that the publicly-owned treatment works (POTW), operated by the Victor Valley Water Reclamation Authority (VWVRA) be considered as an alternate discharge point.</p> <p><i>“Begin evaluation of other candidate sites for discharge of extracted groundwater to eliminate the necessity of pumping water uphill from the influent wet-well.</i></p> <p><i>“Initiate evaluation of feasibility and cost comparison for system discharging water to a POTW (the VWVRA facility).”</i></p>
4			<p>Recommendation No. 3 of the Short-Term Recommendations presented in Section 6.1 suggests reducing the sampling frequency from semi-annual to annual. In light of recent groundwater sampling results at OU 1 which indicate that the upper aquifer TCE plume is not being captured by the current groundwater extraction system (for instance in the vicinity of monitoring well NZ-55), it would not be appropriate to reduce the frequency of groundwater monitoring.</p>	<p>Long-term groundwater monitoring programs have two primary objectives¹:</p> <ol style="list-style-type: none"> 1. To evaluate the extent to which contaminant migration is occurring, particularly if a point of potential exposure of a susceptible population to the contaminant exists (<i>spatial evaluation</i>); and

¹ Gibbons, R.D. 1994. *Statistical Methods for Groundwater Monitoring*. John Wiley & Sons, Inc. New York, NY.

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				<p>2. To evaluate long-term temporal trends in contaminant concentrations at one or more points (<i>temporal evaluation</i>).</p> <p>Most authorities (c.f., USEPA²) concur that groundwater monitoring at a frequency shorter than annually is probably not necessary to evaluate long-term temporal trends. Therefore, the apparent reason for conducting semi-annual groundwater monitoring, rather than annual monitoring, is to evaluate the possible migration of TCE in groundwater to potential receptors. Given the range of hydraulic conductivity values reported³ for the Lower Aquifer (about 4 to 80 feet per day [ft/day]), and a northeasterly hydraulic gradient of about 0.001 feet per foot (ft/ft), we estimate that the pore velocity of groundwater (“groundwater flow velocity”) in the Lower Aquifer northeast of the bluffs ranges from about 0.02 to 0.5 ft/day. The nearest currently-active groundwater production wells of which Parsons is aware are located near the Mojave River, about one mile north of the VVWRA facility. However, for illustrative purposes, we assume that active groundwater extraction is currently occurring at regional observation well OW-6, near the northern boundary of</p>

2 USEPA. 1998. *Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Ground Water*. U.S. Environmental Protection Agency, Office of Research and Development. EPA/600/R-98/128.

3. Montgomery Watson, Inc. 1995. *Installation Restoration Program, Operable Unit 1 Pre-Design Study, George Air Force Base, California*. January.

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				<p>the VVWRA facility, about 2,350 feet north of the distal edge of the TCE plume. Under the current hydrologic regime, an unreactive (“non-retarded”) constituent, moving at the flow velocity of groundwater, would require a period of time ranging from 20 to about 400 years to migrate from the distal edge of the TCE plume to the vicinity of well OW-6. A reactive constituent such as TCE is sorbed to earth materials to a certain degree, and travels more slowly than groundwater. Consequently, it is our opinion that groundwater monitoring conducted annually should be sufficient to detect TCE migration from the current plume location to potential downgradient receptors.</p>
5			<p>Long Term Opportunities. Long Term Opportunity No. 1 proposed the development of site-specific, risk-based goals in accordance with the requirements of the Lahontan Basin Plan. The use of risk-based goals at George Air Force Base is not appropriate at this time as ARARs, such as the State Water Resources Control Board’s Nondegradation Policy and Drinking Water Policy, will require cleanup of TCE in groundwater to the maximum contaminant level (MCL). Thus, Long Term Opportunity No. 1 should not be included in the RPO Report.</p>	<p>The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) establishes a systematic approach for conducting environmental investigation and remediation activities at sites on the National Priority List (NPL sites). This includes the framework within which regulatory decisions regarding cleanup objectives, cleanup mechanisms, and cleanup timeframes are made. The CERCLA process specifically requires periodic review of regulatory decisions, as expressed in the Record of Decision (ROD) for a site, and provides mechanisms for modifying or deleting regulatory decisions that are found to be unworkable or inappropriate. As discussed in Section 3 of the RPO report, mechanisms established</p>

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				<p>in Federal law include modifications to RODs, adoption of alternate cleanup goals, and declaration of technical impracticability (“TI waivers”). Similar mechanisms for modifying the regulatory decision framework are available in California State law, including adoption of risk-based standards and site-specific modification of the Lahontan RWQCB Basin Plan (27 CCR). As noted in Section 3 of the RPO report, groundwater beneath, and immediately downgradient of the NEDA at GAFB is not currently used as a drinking-water supply; no current pathway for potentially-exposed populations is complete; and institutional controls can effectively prevent exposure to groundwater containing TCE in the future. Evaluation of risk-based cleanup standards is therefore entirely appropriate; and the U.S. Air Force should consider the mechanisms available to adopt such goals.</p>
6			<p>Long-Term Opportunity No. 2 indicates that monitored natural attenuation should be evaluated, then if appropriate, operation of the OU 1 pump and treat system could be terminated. Since the current network of monitoring wells is not adequate to determine the extent of contamination in the upper and lower aquifers, it is not appropriate to conduct this evaluation across the entire OU 1 site. Section 4.2.1.2, Plume Containment, of the Draft Final RPO</p>	<p>In general, two primary remediation objectives are associated with conventional groundwater extraction (“pump-and-treat”) systems⁴ – removal of contaminant mass from the subsurface, and establishing or maintaining hydraulic control to restrict or prevent continued migration of dissolved contaminants. The ineffectiveness of the current groundwater pump-and-</p>

4 National Research Council, Committee on Ground Water Cleanup Alternatives. 1994. Alternatives for Ground Water Cleanup. National Academy of Sciences, National Academy Press. Washington, D.C.

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			<p>Report states that “In some locations, in particular near the bluffs along the Mojave River, TCE concentrations in groundwater have not been well defined: For instance the extent of contamination has not been defined to the north and east of monitoring well NZ-39. Also, the TCE groundwater plume is poorly defined in the area to the northeast of monitoring well NZ-55 and between monitoring wells NZ-13 and NZ-74. The Air Force is planning to install additional wells to fill these data gaps. A monitored natural attenuation study across the entire OU 1 site is not appropriate until the TCE groundwater plume has been adequately defined and the hydraulic connection between the upper and lower aquifer is better understood. Thus, revise the report to indicate that natural attenuation will only be evaluated in areas at the site where the nature and extent of TCE contamination is well-defined.</p> <p>Since the Draft Final RPO report indicates that biodegradation rates are very slow at the site, then the Air Force will have to focus on other lines of evidence, including decreasing concentrations, stability of the groundwater plume, and modeling of dispersivity.</p>	<p>treat system at GAFB OU1 in removing contaminant mass from groundwater is a recurrent theme of the RPO report. In fact, an accumulating body of evidence (see, for example, National Research Council, 1994) indicates that nearly all groundwater extraction systems are ineffective at removing contaminant mass. Generally speaking, hydraulic control of contaminant migration is the only realistic remediation goal for groundwater pump-and-treat systems.</p> <p>Hydraulic control may also be difficult or impossible to achieve in low-permeability materials, or at sites having complex hydrogeology or extreme heterogeneity in the subsurface⁴. The heterogeneity noted in numerous borehole logs at GAFB OU1 is a consequence of the depositional environment of the sediments (alluvial fan deposits interfingering with bajada and braided-fluvial sediments). This depositional environment produced subsurface hydrostratigraphy of great complexity, with numerous distinct, interbedded strata, of limited areal extent and varying thickness, grading laterally and vertically into finer- or coarser-grained materials. In this situation, it is unlikely that <u>any</u> groundwater extraction system will be able to effect complete hydraulic control of the groundwater system.</p> <p>The point made in Long-Term Recommendation No. 2 is that establishing hydraulic control of groundwater at GAFB OU1 may not be necessary. We are not</p>

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				<p>suggesting that additional monitoring wells are unnecessary, or would not be helpful in defining the potential for natural attenuation (Also refer to our response to Comment No. 4). It is not clear to us that TCE would continue to migrate, at detectable concentrations, to currently uncontaminated parts of the groundwater system. The first phase of the groundwater extraction system at GAFB OU1 was placed in service in 1991, well before the full extent of TCE in groundwater had been defined. Given the available information, it is therefore not possible under current (pumping) conditions, to evaluate whether TCE was originally present in groundwater at greater distances downgradient from the NEDA than at the present time, or to evaluate whether the vertical and lateral extent of TCE in groundwater has increased or decreased since groundwater extraction was initiated. In our opinion, the only means of evaluating whether plume expansion or migration will continue is to temporarily cease all groundwater extraction, and monitor TCE concentrations in groundwater at downgradient locations.</p> <p>The United States Environmental Protection Agency² defines natural attenuation as:</p> <p style="padding-left: 40px;"><i>“Naturally-occurring processes in soil and groundwater environments that act without human intervention to reduce the mass, toxicity, mobility,</i></p>

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				<p><i>volume, or concentration of contaminants in these media. These in-situ processes include biodegradation, dispersion, dilution, adsorption, volatilization, and chemical or biological stabilization or destruction of contaminants.”</i></p> <p>Note that biodegradation is only one of several natural attenuation processes that may reduce or prevent continued migration of contaminants, at detectable concentrations, from GAFB OU1. It is our opinion that evaluation of the occurrence of natural attenuation does not require that the concentrations of TCE be determined at every point in the groundwater system. Rather, identification and evaluation of long-term temporal trends in concentrations, and assessing the continued and future migration of contaminants and/or plume expansion, are the most important aspects of defining the nature and extent of groundwater contamination, and of evaluating the occurrence of natural attenuation processes.</p>
7			<p>Phytoremediation is considered as a remedial alternative in Long-Term Opportunity No. 3. Phytoremediation as a remedial alternative will not be able to be adequately evaluated until the hydraulic connection between the upper and lower aquifers is better understood. The Air Force observed cottonwood trees growing in some of the arroyos indicating the depth to groundwater may be relatively shallow. However, it is likely that significant flow of TCE-contaminated groundwater is occurring at</p>	<p>We concur that the nature of the hydraulic connection between the Upper and Lower Aquifers is not completely understood, and for that reason recommended that a targeted investigation should be conducted to better define that relationship, prior to initiating phytoremediation or phytostabilization. Refer to Section 6 of the RPO report:</p>

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			<p>depths greater than could be reached by phytostabilization trees. The phytoremediation option would likely have to be combined with a groundwater extraction system providing containment of the TCE plume. The Draft Final RPO report should be revised to indicate that phytoremediation will likely not provide full containment of the TCE plume.</p>	<p><i>“The two long-term opportunities identified in Sections 4.5 and 5.2 as possible technical approaches to groundwater remediation (i.e., MNA and phytoremediation) should be evaluated at the pilot scale before to proceeding to full-scale implementation ...</i></p> <p><i>“To initiate the evaluation of phytoremediation, the Base contractor, in consultation with the Air Force, should prepare an investigation work plan describing sampling locations, sample types, and the methods to be followed in collecting the information necessary to assess the stratigraphic and hydraulic relationships of the soils and water-bearing units along the Mojave River bluffs in the vicinity of the arroyos. The investigation program should be designed primarily to characterize the nature and extent of preferential groundwater migration pathways from the Upper Aquifer to the Lower Aquifer along the arroyos. Once the nature and extent of possible migration pathways have been clarified, a phytoremediation treatability study could be initiated to evaluate if native vegetation is affecting TCE plume migration, by planting appropriate plant species at sufficient density in appropriate locations, and by monitoring plume characteristics in and immediately downgradient from the treatability study area.”</i></p>

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				<p>Phytostabilization is not intended to fully contain the TCE plume downgradient of GAFB, but rather is intended to restrict or prevent further migration of more concentrated TCE from the Upper Aquifer to the Lower Aquifer, and thence further off-Base. Refer to our discussion of the refined conceptual hydrogeologic model, in Section 2.7.3 of the RPO report:</p> <p><i>“The Upper and Lower Aquifers are in hydraulic communication only at relatively discrete points along the base of the bluffs that border the Mojave River floodplain. Points of groundwater movement out of the Upper Aquifer occur where surface drainage (arroyo) erosion has breached the aquitard, enabling groundwater to move out of the Upper Aquifer into unconsolidated alluvium along the ephemeral channels. Groundwater then moves through the alluvium to the base of the bluffs, and percolates into the Lower Aquifer via unsaturated-flow mechanisms.”</i></p> <p>According to this conceptualization, if the Upper and Lower Aquifers are only in hydraulic communication in those areas where arroyos have incised the aquitard, interception of groundwater movement along the relatively narrow saturated section beneath the arroyos should effectively restrict further migration of TCE in groundwater.</p>

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8			<p>No active remedial options to improve the removal of the TCE mass in groundwater are presented in the Draft Final RPO Report. It is possible that improved understanding in the hydraulic connection between the upper and lower aquifer could indicate preferential pathways that could be targeted for additional extraction wells. Also, the viability of alternative remedial options such as dual-phase extraction which could potentially enhance the removal of VOCs from the low-permeability upper aquifer should be presented.</p>	<p>We concur that the earth materials comprising the Upper Aquifer can be characterized as “low permeability” – this is precisely the reason that groundwater extraction efforts at GAFB OU1 have been unsuccessful, and will continue to be unsuccessful. Refer to our response to Comment No. 6, above, for additional information regarding groundwater extraction systems.</p> <p>In the context of Comment No. 8, “<i>dual-phase extraction</i>” presumably means combining active groundwater extraction (“pump-and-treat”), which will lower the groundwater table in the Upper Aquifer, with soil vapor extraction (SVE), to move air through dewatered soil, formerly below the water table, thereby improving volatilization of TCE. It is our experience that SVE is an effective remediation technology for volatile constituents only in those situations in which a concentrated source of volatile contaminants can be identified. No such source of TCE has been identified during nearly 20 years of characterization activities at GAFB OU1. The TCE remaining in the subsurface at GAFB OU1 is likely widely dispersed, and is probably present primarily as a dissolved phase in groundwater. In addition, SVE generally is not normally effective in low permeability soils.</p>
9		2-4 to 2-6	<p>Specific Comments: Figures 2.2, 2.3, and 2.4, Cross Sections. The cross-sections do not include the screened intervals of wells, the location of the aquitard, or TCE concentrations in</p>	<p>Screened intervals will be indicated on the depictions of wells in Figures 2.2, 2.3, and 2.4. Because the aquitard apparently consists of several heterogeneous, low-</p>

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			<p>groundwater. Since one of the major conclusions of the Draft Final RPO Report is that the hydrogeologic model needs to be revised, it would be appropriate to include this additional information on the cross-sections. This information which could provide valuable insight into the migration of TCE in groundwater from the upper aquifer to the lower aquifer. Revise the cross-sections to include the screened intervals of the wells, to indicate the location of the aquitard, and to include TCE concentrations in groundwater for the wells.</p> <p>There is also a concern on cross-section A-A' that sediments in the lower aquifer dip to the north. The dipping sediments could influence the vertical migration of contaminants in the lower aquifer, but the dipping beds are not mentioned in the text of the report. Cross-section A-A' should be extended to the north to extraction well EW-14 to determine the influence of the dipping strata on the movement of the TCE in groundwater in the lower aquifer.</p>	<p>permeability strata, of differing lateral extent and thickness, assigning the role of "the aquitard" to an individual stratum is not appropriate.</p> <p>As noted in the RPO report, and in responses to Comments Nos. 2 and 6 (above), the stratigraphy of the subsurface at GAFB OU1 is complex, as a consequence of the nature of the depositional system. Any representation of the subsurface at GAFB OU1, including the referenced cross-sections, must be regarded as a simplification of an extremely heterogeneous system. In general, it is not possible to depict on a cross-section, at the scale that would be required, the heterogeneities that are likely to most strongly influence contaminant migration.</p> <p>Note that the cross-sections have been presented at a vertical exaggeration of 5 to 1. In reality, therefore, the supposed "dipping" strata are more nearly flat-lying, or very gently dipping to the north. The different stratigraphic intervals presented in the cross-sections are based on examination of relatively limited borehole data, with added geologic interpretation based on knowledge of the depositional environment during the period that sediments were being laid down. Little or no additional geologic information is available north of well EW-8 (the northernmost point presented on the cross-sections); and extension of the section to the north would be speculative, at best. Furthermore,</p>

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				<p>stratigraphic dip is likely to affect groundwater movement and contaminant migration only if there are significant differences in hydraulic or chemical properties between different strata, and if those strata are areally extensive and laterally continuous. Given the complex heterogeneities of the subsurface at GAFB OU1, and the discontinuous and intercalating nature of the strata, it is unlikely that stratigraphic dip will have much effect on groundwater movement or contaminant migration, other than in very localized areas.</p>