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FINAL

**Comparison of Predicted and Observed Plume Trends at
Fuel and Solvent Contaminated Sites
Technical Summary Report**



Prepared For

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

July 2001

**FINAL
COMPARISON OF PREDICTED AND OBSERVED PLUME TRENDS AT
FUEL AND SOLVENT CONTAMINATED SITES
TECHNICAL SUMMARY REPORT**

JULY 2001

Prepared for:

**AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE
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EXECUTIVE SUMMARY

This natural attenuation technical summary report was prepared by Parsons Engineering Science, Inc. (Parsons ES) under contract to the Technology Transfer Division of the Air Force Center for Environmental Excellence (AFCEE/ERT). Over 45 natural attenuation treatability studies (TSs) were performed from 1994 to 1999 by Parsons ES for AFCEE/ERT, in conjunction with researchers from the United States Environmental Protection Agency (USEPA) National Risk Management Research Laboratory (NRMRL). Recommendations for remediation of these sites were based, at least in part, on modeling of natural attenuation processes to predict contaminant trends and plume dynamics. Model-based prediction of an extended time frame for remediation of a site by natural attenuation (e.g., greater than 20 years) was frequently the basis for recommending implementation of more expensive engineered remedial alternatives.

Subsequent to the natural attenuation TSs, update data were used to evaluate the effectiveness of natural attenuation at reducing contaminant concentrations in groundwater at 24 selected sites. Discrepancies between observed and predicted contaminant trends and plume behavior suggested that critical model input parameters may be inaccurate; therefore, the influence of natural attenuation processes may not have been accurately simulated. As a result of these observations, contaminant data from various update sites were compared to the initial computer-model-generated predictions of contaminant concentrations presented in the TS reports in order to assess the accuracy of some fundamental model input parameters and assumptions, with a goal of making recommendations to improve the accuracy of natural attenuation model predictions.

The two natural attenuation parameters selected for specific evaluation are solute decay and source weathering rates. Volatile fuel constituents (e.g., benzene, toluene, ethylbenzene, and xylenes [BTEX]) and chlorinated aliphatic hydrocarbons (CAHs, or chlorinated solvents) attenuate under a broad range of environmental conditions. Attenuation mechanisms for BTEX and CAHs include biological and abiotic degradation of dissolved constituents, and nondestructive processes such as dispersion, sorption, and volatilization. In addition, weathering of the contaminant source via biodegradation, volatilization, and leaching can result in reduced concentrations of dissolved constituents in the groundwater. Therefore, the observed effectiveness of natural attenuation was compared to modeling predictions to assess the accuracy of biodegradation and source weathering rates used in the model.

Seven fuel hydrocarbon and five CAH-contaminated sites were evaluated for this study. The BIOPLUME II numerical model code (Rifai *et al.*, 1987) was the primary tool used to predict fuel hydrocarbon plume behavior, and MODFLOW/MT3D (McDonald and Harbaugh, 1988) numerical code was the primary tool used to predict the fate and transport of CAHs, mostly trichloroethene (TCE). In addition, BIOSCREEN is a common analytical tool used to predict the fate and transport of fuel hydrocarbons, and was used for two sites evaluated for this study. Most common solute transport codes for fuel hydrocarbons can simulate biodegradation via instantaneous reactions and/or a first-

order rate. In contrast, most common transport codes for CAHs can only incorporate a first-order rate.

FUEL HYDROCARBON SITES

Most of the calibrated BIOPLUME II and BIOSCREEN models for fuel hydrocarbon sites tended to overestimate plume migration distance, source persistence, and/or the time required for the BTEX or benzene plumes to attenuate to below regulatory guidelines. The conservatism of these models may be attributable to underestimation of natural source weathering rates, overestimation of the mass of contaminant present in the source area, and/or use of overly conservative first-order solute decay rates.

Models that predicted future plume conditions with a reasonable degree of accuracy employed geometric source weathering rates and first-order decay rates ranging from 5 percent per year (%/yr) to 27 %/yr and $1.0\text{E-}3$ per day (day^{-1}) (half-life of 1.9 years) to $7.0\text{E-}3 \text{ day}^{-1}$ (half-life of 0.23 year), respectively. The decay rates used in the more “successful” models are the same order-of-magnitude as geometric mean first-order decay rates for BTEX constituents derived from field studies of combined aerobic/anaerobic sites and presented by Suarez and Rifai (1999) ($1.0\text{E-}3$ to $2.0\text{E-}3 \text{ day}^{-1}$ or half-lives of 1.9 to 9.95 years).

The range of source weathering rates used in the more “successful” models encompasses both average first-order (geometric) weathering rates for BTEX in JP-4 jet fuel derived during a light non-aqueous phase liquid (LNAPL) weathering study (Parsons ES, 1999a) (11 %/yr to 23 %/yr) and the average geometric rate estimated using site-specific dissolved BTEX data (24 %/yr).

Several models proved to be overly conservative. In these cases, natural attenuation processes resulted in greater reductions in plume size and concentrations than were predicted by simulations of engineered remediation. First-order decay rates used in the four of the nine overly-conservative models ranged from $4.9\text{E-}4 \text{ day}^{-1}$ (half-life of 3.9 years) to $5\text{E-}3 \text{ day}^{-1}$ (half-life of 0.38 years). The remaining five models used an instantaneous reaction approach to simulate contaminant decay; three of these five models coupled instantaneous decay with a reaeration rate of $3.0\text{E-}3 \text{ day}^{-1}$.

Models that under-predicted the effects of natural attenuation employed widely-variable source weathering rates that ranged from 0 %/yr (constant source) to complete source removal over a 3-year period. Five of the nine overly-conservative models used source reduction rates that were less than or equal to 4.9 %/yr (geometric rates). Natural source-reduction rates derived using the OILLENS module of the Hydrocarbon Spill Screening Model (HSSM) (USEPA, 1994) did not exceed 4.9 %/yr (geometric rate), suggesting that rates obtained from this model may be overly conservative and should be used with caution.

The accuracy of contaminant fate and transport model input parameters should be discussed so that the limitations of the model are understood. For example, uncertainty regarding source weathering rates often was concluded to be a potentially significant source of error in the model; however, source weathering was often only represented by one rate per scenario for each site. A more realistic and defensible approach in cases

where site-specific weathering rate data are not available would be to present predictive results from the use of a range of potentially realistic source reduction rates.

The results of this comparative study indicate that first-order decay rates for dissolved BTEX that are less than $1.0\text{E-}3 \text{ day}^{-1}$ (half-life of 1.9 years) should be used with caution for predictive modeling purposes. In many, if not most, cases available data suggest that use of dissolved BTEX decay rates equal to or greater than $1.0\text{E-}1 \text{ day}^{-1}$ will result in more accurate fate and transport predictions. The occurrence of decay rates less than this value is certainly feasible; however, in the absence of site-specific data that justify use of lower rates, use of higher rates may be more accurate.

Similarly, unless construction of a conservative model is intended, use of geometric source weathering rates that are less than 5 %/yr should be justified based on site-specific data. Data presented in this report suggest that geometric rates of 8 %/yr to 27 %/yr are realistic for most sites.

CHLORINATED SOLVENT SITES

Models for chlorinated solvents (CAHs) are often intentionally designed to be conservative in order to support decisions regarding whether to implement monitored natural attenuation (MNA) or proceed with engineered remediation. Models for three sites of the five sites studied predicted plume expansion for at least a 10-year period. Monitoring data for two these sites indicate stable plumes (i.e., the model simulations were overly conservative). Overall, plumes at four of the five sites studied are currently thought to be stable or receding. The ability of natural attenuation processes to stabilize chlorinated solvent plumes is not as generally accepted as for fuel hydrocarbon plumes.

TCE decay rates derived using the method of Buscheck and Alcantar (1995) ranged from $5.1\text{E-}5 \text{ day}^{-1}$ (half-life of 37 years) to $5.0\text{E-}4 \text{ day}^{-1}$ (half-life of 3.8 years). Total chlorinated ethene decay rates ranged from $1.9\text{E-}7 \text{ day}^{-1}$ (half-life of 10,210 years) calculated using the method of Moutoux *et al.* (1996) to $3.5\text{E-}3 \text{ day}^{-1}$ (half-life of 0.54 year) calculated using the method of Buscheck and Alcantar (1995). Half-lives calculated using the method of Buscheck and Alcantar (1995) are typically higher than the range of reported field-scale half-lives for TCE (0.32 years to 3.8 years) listed by Wiedemeier, *et al.* (1999).

Model-calibrated rates at four of the five sites were equal to or slightly less than rates calculated using the method of Buscheck and Alcantar (1995). Chlorinated solvent plumes at three of these four sites appear to be either at or near steady-state, satisfying the Buscheck and Alcantar (1995) assumption of a steady-state plume. Decay rates calculated using the method of Moutoux, *et al.* (1996) are too low in many cases. It is therefore recommended that rates calculated using the method of Buscheck and Alcantar (1995) be used as a first approximation for modeling purposes, even if the stability of the plume can not be verified. Use of rates derived using the method of Moutoux, *et al.* (1996) should be limited to CAH plumes or flow paths where strict anaerobic conditions exist and there are significant concentrations of VC and ethene to indicate that CAH mass is being conserved. Loss of DCE and VC due to oxidation reactions is likely a primary source of error in applying this method.

Estimated source-reduction rates for the five chlorinated solvent sites varied from 2 %/yr to 10 %/yr (geometric rates). No documented studies or actual measurements of natural CAH source weathering rates were available for use as the basis for these estimates. Due to the absence of source weathering rate information, rates that were believed to be conservative were often selected for use in the models. The apparent conservatism of several of the models suggest that these rates were overly conservative. Geometric source reduction rates of 6 %/yr to 10 %/yr yielded acceptable model calibrations and predictions for two sites, suggesting that this range of natural weathering rates is an appropriate first approximation for chlorinated ethenes.

As more information regarding the evolution and attenuation of chlorinated solvent plumes is obtained over time, the level of confidence associated with key fate and transport model input parameters such as decay rates and source weathering rates will increase. The necessity for using significantly conservative modeling assumptions due to a lack of information regarding realistic values for these parameters will diminish. Continued monitoring of fuel hydrocarbon and chlorinated solvent sites may provide an empirical basis for application of MNA as opposed to engineered remediation.

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LIST OF ACRONYMS AND ABBREVIATIONS

%/yr	percent per year
µg/L	microgram(s) per liter
µmol/L	micro mole(s) per liter
1-D	1-dimensional
2-D	2-dimensional
3-D	3-dimensional
AFB	Air Force Base
AFCEE/ERT	Air Force Center for Environmental Excellence/Technology Transfer Division
AMC	Air Mobility Command
BTEX	benzene, toluene, ethylbenzene, and xylenes
CAHs	chlorinated aliphatic hydrocarbons
CAS	corrective action study
CCAS	Cape Canaveral Air Station
<i>cis</i> -1,2-DCE	<i>cis</i> -1-2-dichloroethene
day ⁻¹	per day
DCE	dichloroethene
DO	dissolved oxygen
EE/CA	Engineering Evaluation/Cost Analysis
ft/yr	feet per year
HASS	horizontal air sparging system
HSSM	Hydrocarbon Spill Screening Model
KSA	King Salmon Airport
LF-03	Landfill No. 3
LNAPL	light nonaqueous phase liquid
LTM	long-term monitoring
MAROS	Monitoring and Remediation Optimization Software
MCL	maximum contaminant level
mg/L	milligrams per liter
MNA	Monitored Natural Attenuation
MOC	Method of Characteristics
MTBE	methyl tert-butyl ether
NAPL	nonaqueous-phase liquid
NGS	North Gas Station
NRMRL	National Risk Management Research Laboratory
NSGS	North and South Gas Stations
OU	operable unit
Parsons ES	Parsons Engineering Science, Inc.
POL	petroleum, oils, and lubricants
R ²	coefficient of determination
redox	oxidation/reduction
RNA	remediation by natural attenuation
SGS	South Gas Station
TCE	trichloroethene

TEMBs	tetramethylbenzenes
TMBs	trimethylbenzenes
TS	Treatability Study
USEPA	United States Environmental Protection Agency
USGS	United States Geologic Survey
UST	Underground Storage Tank
VC	vinyl chloride

SECTION 1

INTRODUCTION

This natural attenuation technical summary report was prepared by Parsons Engineering Science, Inc. (Parsons ES) under contract to the Technology Transfer Division of the Air Force Center for Environmental Excellence (AFCEE/ERT) through Air Mobility Command (AMC) contract number F11623-94-DO0024, RL71.

Over 45 natural attenuation treatability studies (TSs) were performed from 1994 to 1999 by Parsons ES for AFCEE/ERT, in conjunction with researchers from the United States Environmental Protection Agency (USEPA) National Risk Management Research Laboratory (NRMRL) (Parsons ES, 1999c and 1999d). Recommendations for remediation of these sites were based, at least in part, on modeling of natural attenuation processes to predict contaminant trends and plume dynamics. Model-based prediction of an extended time frame for remediation of a site by natural attenuation (e.g., greater than 20 years) was frequently the basis for recommending implementation of more expensive engineered remedial alternatives.

Subsequent to the initial natural attenuation TSs, update data collected by the NRMRL and data from Base monitoring programs were used to evaluate the effectiveness of natural attenuation at reducing contaminant concentrations in groundwater at 24 selected sites. Discrepancies between observed and predicted contaminant trends and plume behavior suggested that critical model input parameters may be inaccurate; therefore, the influence of natural attenuation processes may not have been accurately simulated. As a result of these observations, AFCEE/ERT initiated this project to compare model-predicted and observed contaminant trends and to evaluate some fundamental parameters that impact the accuracy of natural attenuation predictions, relative to updated field observations.

1.1 PROJECT OBJECTIVES

The objectives of this study were to compare contaminant data from various update sites to the initial computer-model-generated predictions of contaminant concentrations presented in the natural attenuation TS reports in order to assess the accuracy of some fundamental model input parameters and assumptions, with a goal of making recommendations to improve the accuracy of natural attenuation model predictions.

The two natural attenuation parameters selected for specific evaluation are solute decay and source weathering rates. Volatile fuel constituents (e.g., benzene, toluene, ethylbenzene, and xylenes [BTEX]) dissolved in groundwater naturally attenuate under a broad range of environmental conditions (AFCEE, 1995 and USEPA, 1998). Chlorinated aliphatic hydrocarbons (CAHs) may also attenuate when certain geochemical conditions

prevail. Attenuation mechanisms for BTEX and CAHs include biological and abiotic degradation of dissolved constituents, and nondestructive processes such as dispersion, sorption, and volatilization. In addition, weathering of the contaminant source via biodegradation, volatilization, and leaching can result in reduced concentrations of dissolved constituents in the groundwater (Parsons ES, 1999a). An attempt is made in this study to compare the observed effectiveness of natural attenuation relative to predictions based on analytical or numerical modeling, and to assess the accuracy of biodegradation and source weathering rates used in the model.

1.2 PROJECT SCOPE

In order to meet these objectives, the following tasks were performed:

- Evaluate trends in contaminant concentrations and plume stability (i.e., change in plume dimensions) for 12 sites with groundwater contaminated with BTEX, CAHs, or both. Evaluation methods included qualitative evaluation of plume dynamics and statistical analyses of contaminant trends;
- Summarize biodegradation and source decay rates used for previous model predictions;
- Compare predicted versus observed contaminant concentrations and plume extent; and
- Evaluate the accuracy of two key model input parameters (i.e., biodegradation and source decay rates) that influence computer model predictions of contaminant concentrations and plume extent.

1.3 REPORT ORGANIZATION

This report contains seven sections, including this introduction, and two appendices. Site selection criteria and the sites included in this study are presented in Section 2. Section 3 presents an overview of methodologies used to evaluate natural attenuation, and upon which predictions of natural attenuation processes are based. Evaluations of observed versus predicted contaminant trends for selected fuel hydrocarbon and CAH/mixed sites are presented in Sections 4 and 5, respectively. Section 6 presents conclusions based on the site-specific evaluations described in Sections 4 and 5, along with recommendations for improving the accuracy of natural attenuation modeling. References cited are listed in Section 7. Appendix A Contains historical plume maps for each of the selected study sites. Appendix B contains responses to comments on the draft report.

SECTION 2

SITE SELECTION

Sites included for evaluation in this study were selected from a database of over 20 sites for which a natural attenuation TS was performed, and for which subsequent follow-up data were collected.

2.1 SITE SELECTION CRITERIA

Sites were selected for this study based on the following criteria:

- Lack of Engineered Remediation. Sites with little or no active engineered remediation (e.g., bioventing, air sparging, pump and treat) were desired to discern the effectiveness of natural attenuation alone at reducing contaminant concentration and mass.
- Modeling of Natural Attenuation. Required for comparison to observed conditions.
- Time-Span for Monitoring Data. The accuracy of model-predicted trends is more evident in cases where several years have elapsed since the modeling was performed.
- Monitoring Frequency. A minimum of four sampling events was desired to provide a meaningful statistical basis for trend analyses.
- Calculated Biodegradation Rates. Sites with well-documented biodegradation rates were desired.
- Source-Reduction Rates. Sites with well-documented source reduction terms were desired.
- Variety of Modeling Techniques. Both analytical and numerical models were selected for evaluation.

Identification of a sufficient number of sites that fulfilled all these criteria was problematic, and all criteria were not always met. However, model predictions often took into account such items as source reduction by a specific remedial action, or a previously implemented remedial action, thus providing a baseline for comparison of predicted versus observed natural attenuation behavior.

2.2 FUEL HYDROCARBON SITES

The seven fuel hydrocarbon sites evaluated for this study are listed in Table 2.1. The fate and transport of total BTEX was modeled for six of the seven sites; benzene was the modeled constituent for the seventh site. The BIOPLUME II numerical model code (Rifai *et al.*, 1987) was the primary tool used to predict plume behavior; the BIOSCREEN analytical model code (USEPA, 1996) was used for Langley Air Force Base (AFB) Site SS-04. The elapsed time between modeling and the most recent available monitoring data ranged from 3 to 7 years.

2.3 CHLORINATED SOLVENT AND MIXED CONTAMINANT SITES

The five CAH-contaminated sites evaluated for this study are listed in Table 2.2. Chlorinated ethenes were the primary contaminants at each of the sites, with the fate and transport of trichloroethene (TCE) being modeled at four sites and *cis*-1,2-dichloroethene (*cis*-1,2-DCE) modeled at the remaining site. Because chlorinated solvent sites were generally evaluated during the last half of the AFCEE natural attenuation initiative, the elapsed time between calibration and the most recent available monitoring data ranged from only 1 to 4 years.

Table 2.1
Fuel Hydrocarbon Site Selection Summary

Site Identification	Contaminant Modeled^{a/}	Primary Modeling Method	Secondary Modeling Method^{b/}	Degradation Rate Calculations^{c/}	Model Calibration Date	Last Monitoring Event
Fuel Hydrocarbon Sites						
North and South Gas Stations, Travis AFB, CA	BTEX	BIOPLUME II	HSSM	B&A, TMB	September 1995	August 2000
POL Yard, Myrtle Beach AFB, NC	BTEX	BIOPLUME II	HSSM	B&A, TMB	January 1995	February 2000
Site 870, Hill AFB, UT	BTEX	BIOPLUME II	--	--	August 1993	March 2000
Site ST-41, Elmendorf AFB, AK	BTEX	BIOPLUME II	--	TMB	June 1994	October 2000
Upper Naknek Site, King Salmon Airport, AK	BTEX	BIOPLUME II	--	--	September 1994	June 2000
Site SS-04, Langely AFB, VA	Benzene	BIOSCREEN	--	--	October 1997	June 2000
Site SS27/XYZ, Dover AFB, DE	BTEX	BIOPLUME II	van Genuchten and Alves	TMB	April 1994	February 1999

^{a/} BTEX = benzene, toluene, ethylbenzene, and xylenes.

^{b/} HSSM = Hydrocarbon Spill Screening Method (USEPA, 1994); van Genuchten and Alves (1982).

^{c/} B&A = Method of Buscheck and Alcantar, 1995; Moutoux = Method of Moutoux et al., 1996.

Table 2.2
Chlorinated Solvent Site Selection Summary

Site Identification	Contaminant Modeled^{a/}	Primary Modeling Method^{b/}	Degradation Rate Calculations^{c/}	Model Calibration Date	Last Monitoring Event
Primary Chlorinated Solvent/Mixed Sites					
Site LF-03, F.E. Warren AFB, WY	TCE	MODFLOW/MT3D	B&A, Moutoux	May 1999	April 2000
Site OU5, Hill AFB, UT	TCE	MODFLOW/MT3D	B&A, Moutoux	August 1996	Spring 2000
Site FTA-2, Tinker AFB, OK	TCE	MODFLOW/MT3D	B&A	August 1997	October 1999
Site LF-06, Columbus AFB, MS	Various	van Genuchten and Alves	B&A	November 1996	July 2000
Site FT-17, Cape Canaveral Air Station, FL	Total CAHs	MODFLOW/MT3D	B&A, Moutoux	January 1996	April 2000

^{a/} TCE = trichloroethene, CAHs = chlorinated aliphatic hydrocarbons.

^{b/} MODFLOW (McDonald and Harbaugh, 1988) and MT3D (Zheng, 1990); van Genuchten and Alves (1982).

^{c/} B&A = Method of Buscheck and Alcantar, 1995; Moutoux = Method of Moutoux *et al.*, 1996.

SECTION 3

METHODOLOGIES TO EVALUATE NATURAL ATTENUATION

Various methods have been developed to estimate fundamental parameters used to evaluate and predict the impacts of natural attenuation processes on dissolved contaminant plumes. An exhaustive description of the available parameter estimation methods and an evaluation of the technical merit of these methods is beyond the scope of this project. The accuracy of numerical model simulations performed for selected fuel- and solvent-contaminated sites is evaluated in Sections 4 and 5. The evaluations focus specifically on biodegradation and source reduction rates. Information regarding how values for these two model input parameters were derived, and a description of the model codes used, are provided in the remainder of this section.

3.1 BIODEGRADATION RATE CALCULATION METHODS

Estimation of biodegradation rate constants is necessary to accurately simulate the fate and transport of contaminants dissolved in groundwater. Several methods, including instantaneous reaction and first- and second-order approximations, may be used to estimate biodegradation rates for fuel hydrocarbons. First- and second-order approximations also may be used to estimate biodegradation rates for chlorinated compounds. The preferred methods by which contaminant biodegradation rates are determined use actual field data.

Use of a first-order approximation can be appropriate to estimate biodegradation rates for chlorinated compounds where the rate of biodegradation is assumed to be controlled solely by the concentration of the contaminant. However, the use of a first-order approximation may not be appropriate when more than one substrate is limiting microbial degradation rates or when microbial mass is increasing or decreasing. For example, use of a first-order rate for CAHs may not provide the best approximation of the dechlorination rate of CAH compounds in the presence of an electron donor such as BTEX. In such cases, a second- or higher-order approximation may provide a more accurate estimate of biodegradation rates.

Most common transport codes for fuel hydrocarbons (including BIOSCREEN and BIOPLUME II) can simulate biodegradation via instantaneous reactions and/or a first-order rate. In contrast, most common transport codes for CAHs (including MT3D) can only incorporate a first-order rate. This may impact model calibration and constrain the usefulness of predictions, but at this time there is no feasible alternative for simulating CAH transport under the influence of biodegradation. Provided that conservative values are used for other input parameters and a sensitivity analysis is performed, simulations incorporating a first-order rate constant will still be useful and meaningful.

3.1.1 Instantaneous Reactions

Instantaneous reactions may be used in models to compute fuel hydrocarbon biodegradation based on the availability of electron acceptors. For example, in the BIOSCREEN analytical model, site-specific data for available oxygen are used to compute aerobic degradation of dissolved hydrocarbons, and site-specific data for nitrogen, sulfate, ferrous iron, and methane are used to compute anaerobic degradation. On the basis of the work of Borden and Bedient (1986), the BIOPLUME II model assumes a reaction between dissolved oxygen (DO) and BTEX that is instantaneous relative to the advective groundwater velocity, and allows for use of a user-specified first-order decay rate for anaerobic degradation.

3.1.2 First-Order Decay Rates

Use of first-order kinetics can be appropriate to estimate field-scale biodegradation rates for compounds where the rate of biodegradation is assumed to be controlled solely by the concentration of the contaminant. In order to calculate first-order field biodegradation rate constants, the apparent degradation rate must be normalized for the effects of dilution, sorption, and volatilization. Several methods were used to estimate first-order biodegradation rates in the TS reports evaluated as part of this study. These methods included:

- Use of a biologically recalcitrant compound, which acts as a conservative tracer (AFCEE, 1995 and USEPA, 1998).
- Use of the one-dimensional (1-D), steady-state analytical solution to the advection-dispersion equation presented by Bear (1979) (Buscheck & Alcantar, 1995).
- Computation of field-scale reductive dechlorination rates using the method of Moutoux *et al.* (1996).

3.1.2.1 Conservative Tracer Method

Recalcitrant compounds, such as trimethylbenzenes (TMBs), tetramethylbenzenes (TEMBs), or methyl tertiary-butyl ether (MTBE), are often present in sufficient quantities in fuel mixtures to be readily detectable when dissolved in groundwater. Under suitable conditions, these recalcitrant compounds can be used as conservative tracers to calculate decay rates for other fuel compounds (e.g., BTEX) that are undergoing biodegradation. TMBs and TEMBs are generally recalcitrant to biodegradation under anaerobic conditions, while MTBE is generally recalcitrant to biodegradation under both aerobic and anaerobic conditions. The degree of recalcitrance is site-specific, and the use of any compound as a conservative tracer must be evaluated on a case-by-case basis.

An ideal tracer would have Henry's Law and soil sorption coefficients identical to the contaminant of interest. Therefore, it is advisable to account for the difference in contaminant and tracer velocity resulting from the higher or lower soil sorption capacities and consequent differences in retardation relative to BTEX.

3.1.2.2 Method of Buscheck and Alcantar

Buscheck and Alcantar (1995) derive a relationship that allows calculation of first-order biodegradation rate constants for steady-state plumes. This method involves coupling the regression of contaminant concentration (plotted on a logarithmic scale) versus distance downgradient (plotted on a linear scale) to an analytical solution for one-dimensional, steady-state, contaminant transport that includes advection, dispersion, sorption, and biodegradation (Bear, 1979). For an expanding plume, this first-order approximation can be viewed as an upper bound on the biodegradation rate. In this case, use of this method may result in an overestimation of the rate of biodegradation because a typical expanding plume exhibits decreasing source area concentrations, increasing downgradient concentrations, or both. Over time, these changes result in a decreasing slope on a log-linear plot, and consequently a decreasing biodegradation rate.

3.1.2.3 Moutoux Method for Chlorinated Ethenes

A method for estimating reductive dechlorination rates of CAHs is described by Moutoux *et al.* (1996). This method can be used to estimate the theoretical contaminant concentration resulting from reductive dechlorination alone for every point along a flow path on the basis of the measured contaminant concentration at the point of plume origin and the contaminant/tracer ratios between consecutive points along the flow path. This series of points can then be used to estimate a first-order rate of biodegradation. The carbon core of the CAH compounds, which is subject to the same non-destructive attenuation mechanisms that act on the larger chlorinated molecule, but is unaffected by biologically mediated reductive dechlorination, is used as the tracer.

This method provides a total dechlorination rate for all dechlorination steps. All rates (including the more-rapid TCE to DCE rate and the slower vinyl chloride [VC] to ethene rate) are averaged using the Moutoux *et al.* (1996) method. Because abiotic reactions and reactions that involve CAH compounds in the role of an electron donor are not included in this rate, the rate should be considered a lower bound on the destructive attenuation rate. Consequently, these rates are often more than an order of magnitude lower than the rates computed for the same site using the Buscheck and Alcantar (1995) or conservative tracer method.

3.2 NATURAL ATTENUATION MODEL DESCRIPTIONS

Partial differential equations that describe groundwater flow and/or solute transport can be solved analytically or numerically. The type of model selected to simulate site conditions depends on the complexity of the problem, the amount of available data, the importance of the decisions that will be based upon the model, and project scope. Analytical methods provide exact, closed-form solutions, and numerical methods provide approximate solutions.

Analytical models are the simplest to set up and solve, allowing the user to evaluate many scenarios in a relatively short time. Numerical methods are more efficient for those systems that are too complex for analytical methods. Analytical models are restricted in the nature of the problems for which they can be used, and for some transport problems they may become so complex and unwieldy that the use of numerical methods may be more efficient. Theoretically, there are no limits on the characteristics of the

hydrogeological system and the properties of the solute(s) that can be simulated using a numerical model code. There are, however, practical limits on the ways in which the system and any reactions within it can be represented.

The basic parameters for both types of models typically include groundwater seepage velocity, hydraulic conductivity, saturated thickness of the aquifer, porosity, source area configuration, source area contaminant concentrations, leakage rates, dispersion coefficients, retardation values, and decay rates.

3.2.1 Analytical Models

Two analytical models were used in the TSs to simulate contaminant plume behavior. The method of van Genuchten and Alves (1982) was used for both fuel hydrocarbon and CAH sites, while BIOSCREEN (USEPA, 1996) was utilized at fuel hydrocarbon sites only.

3.2.1.1 Van Genuchten and Alves

The analytical model developed by van Genuchten and Alves (1982) provides first-order solute decay solutions for a semi-infinite system with a constant point source. The 1-D model assumes a homogeneous, isotropic aquifer; a uniform, constant-velocity flow field in the x-direction only; a constant longitudinal hydrodynamic dispersion; a first-order rate of decay for biodegradation; and a linear sorption rate. In general, this model was used to provide a conservative estimate of maximum contaminant concentration or plume length where adequate site-specific data were not available for more complex modeling codes.

3.2.1.2 BIOSCREEN

BIOSCREEN is a public domain, screening-level computer model, which can be used to simulate remediation of dissolved hydrocarbons at petroleum release sites due to natural attenuation (USEPA, 1996). The software consists of a Microsoft[®] Excel spreadsheet based on an implementation of the Domenico (1987) analytical solute transport model. The model can simulate the processes of advection, dispersion, adsorption, first-order decay reactions, and aerobic and anaerobic instantaneous decay reactions.

BIOSCREEN can be used to evaluate three different general cases of solute transport either separately or combined (USEPA, 1996):

- Solute transport due to advection and dispersion with no decay or retardation (No Biodegradation Model).
- Solute transport with solute biodegradation modeled as a first-order decay process (single, lumped parameter approach) (First-Order Decay Model); and
- Solute transport with solute biodegradation modeled as an instantaneous oxidation/reduction (redox) reaction (Instantaneous Reaction Model).

- The first general model type is appropriate for predicting the movement of a conservative (non-degrading) solute such as chloride, and was not used for simulating the migration and persistence of fuel hydrocarbons dissolved in groundwater

The first-order decay model assumes that the solute degradation rate is proportional to the solute concentration (“first-order” conditions). This is the conventional method for simulating biodegradation of dissolved hydrocarbon plumes. All methods of hydrocarbon removal are lumped together in a single calibration parameter (the first-order rate constant) when using the First-Order Decay model. The First-Order Decay model does not account for site-specific information such as the availability of electron acceptors.

The Instantaneous Reaction model in BIOSCREEN computes solute biodegradation based on availability of electron acceptors. Site-specific data for available oxygen are used to compute aerobic degradation of dissolved hydrocarbons, and site-specific data for nitrogen, sulfate, ferrous iron, and methane are used to compute anaerobic degradation. For sites where electron acceptor and metabolic byproduct concentration data are available, the Instantaneous Reaction model is preferred, either alone or in conjunction with the First-Order Decay Model (USEPA, 1996).

3.2.2 Numerical Models

Two numerical model codes were used in the TSs to simulate contaminant plume behavior. BIOPLUME II was used for fuel hydrocarbon sites and MODFLOW/ MT3D was used for CAH-contaminated sites.

3.2.2.1 BIOPLUME II

The BIOPLUME II model incorporates advection, dispersion, sorption, and biodegradation to simulate BTEX plume migration and degradation. The finite difference model is based upon the United States Geological Survey (USGS) Method of Characteristics (MOC) two-dimensional (2-D) solute transport model of Konikow and Bredehoeft (1978). The model was modified by researchers at Rice University to include a biodegradation component that is activated by a superimposed DO plume. On the basis of the work of Borden and Bedient (1986), the model assumes a reaction between DO and BTEX that is instantaneous relative to the advective groundwater velocity.

BIOPLUME II solves the USGS 2-D solute transport equation twice, once for hydrocarbon concentrations in the aquifer and once for a DO plume. The two plumes are combined using superposition at every particle move to simulate the instantaneous, biologically-mediated reaction between hydrocarbons and oxygen. The BIOPLUME II model allows the use of a first-order decay coefficient to account for anaerobic BTEX degradation processes.

3.2.2.2 MODFLOW/MT3D

MODFLOW is a three-dimensional (3-D) groundwater flow simulation computer program published by the USGS (McDonald and Harbaugh, 1988). MODFLOW solution techniques are based on a 1-, 2-, or 3-D, block centered, finite difference grid, which is superimposed on the model area. The aquifer properties can be heterogeneous

and anisotropic, and aquifer layers can be simulated as confined, unconfined, or a combination of both.

The MT3D code incorporates advection, dispersion, sorption, and biodegradation to simulate plume migration and degradation. MT3D uses solution routines based on the MOC solute transport model [e.g., as developed by Konikow and Bredehoeft (1978) for the USGS 2-D MOC model code]. The MOC model was modified by Zheng (1990) to allow 3-D solutions, and to allow use of a modified MOC that reduces numerical dispersion; the modified model is called MT3D.

3.3 SOURCE TERM CONTAMINANT LOADING AND REDUCTION

Zones of mobile or residual nonaqueous-phase liquid (NAPL) represent a significant, continuing source of contaminant mass to groundwater. Transport models use boundary conditions to express the influence of contaminant sources such as NAPL bodies and dissolved mass entering through recharge, injection wells, surface water bodies, and leaking structures. Sources such as NAPL bodies may be represented as specified-concentration boundaries (limited by solubility constraints or observed maximum concentrations) or as specified-flux boundaries (for which the chemical loading rate must be known or estimated).

3.3.1 Source Loading

In many cases, only the effects of the source are measured, not the source characteristics (Spitz and Moreno, 1996). The source must therefore be represented as a “black box” that produces appropriate contaminant concentrations or fluxes at selected points in the model. The source may be misrepresented under such a scenario, but there is often little choice in the matter. Estimating contaminant flux into groundwater from NAPL is difficult and is dependent upon several parameters, most of which cannot be measured (Feenstra and Guiguer, 1996; Abriola, 1996). The location and strength of the contaminant source in the numerical models constructed for natural attenuation treatability studies was typically varied, along with other model input using a trial and error approach during model calibration until the simulated and observed plumes were reasonably similar. This approach was used for both fuel- and solvent-contaminated sites. Experience modeling contaminated sites as part of the AFCEE Natural Attenuation Initiative has suggested that this is the best method for reproducing observed plumes.

3.3.2 Source Reduction Rates

Natural source reduction rates were estimated using a variety of approaches including:

- Use of the OILENS module of USEPA’s (1994) Hydrocarbon Spill Screening Model (HSSM) (fuel sites only);
- Use of actual weathering-rate information available for the study site or another, similar site (however, such information was rarely available); and
- Variation of simulated source-reduction rates during model calibration to determine which rate(s) best facilitated model calibration.

In cases where none of the above-listed approaches was used, rates that were thought to be reasonably conservative based on all available information were typically used in the models.

Geometric (first-order) source reduction rates result in lower reductions in source concentration or mass per year over time because the current reduction is dependent on the previous time-period concentration or mass. Because processes such as volatilization, dissolution, or biodegradation are thought to be concentration dependent, geometric (first-order) rates are typically used to simulate natural weathering rates. Linear (zero-order) source reduction rates result in a fixed reduction of the initial source concentration or mass per time-period, and are generally used to simulate engineered source reduction.

As indicated above, the OILENS module of the USEPA's HSSM was used for some sites to quantify the dissolution of contaminant mass from mobile and residual light non-aqueous phase liquid (LNAPL) into the groundwater over time. The HSSM code was developed by the USEPA NRMRL to aid in estimating the impacts of LNAPL releases on groundwater quality. The areal extent of suspected zones, or pockets, of mobile LNAPL are used to estimate the mass transfer of chemical constituents in the LNAPL into the groundwater via infiltrating rainfall and dissolution caused by flowing groundwater. To simplify calculations, OILENS assumes that mobile LNAPL plumes are circular in shape. OILENS calculates the mass loading to groundwater from infiltrating rainfall based on volume flux (Darcy velocity) of the precipitation influx and the equilibrium concentration for the chemical in contact with water. OILENS calculates the mass loading to groundwater from dissolution based on equilibrium between the base of the circular mobile LNAPL lens and the migrating groundwater.

Less contaminant mass will be available to act as a continuing source to groundwater as mobile LNAPL weathers over time. To account for these source weathering effects, OILENS can be used to estimate decreasing mass loading rates over time. The subsequent mass of contaminants in the LNAPL can be sequentially reduced by the mass that had already partitioned from and dissolved into groundwater. As the LNAPL weathers, lower mass loading rates are expected.

The total weathering rate estimated using the HSSM is conservative because the effects of biodegradation and volatilization are not accounted for. Under favorable site conditions these two processes can account for significant LNAPL degradation.

SECTION 4

FUEL HYDROCARBON SITES

4.1 SITE 1 – TRAVIS AFB NORTH AND SOUTH GAS STATIONS

Travis AFB is located in Solano County, California, approximately 3 miles east of the town of Fairfield, midway between the cities of San Francisco and Sacramento. A Monitored Natural Attenuation (MNA) TS for the North and South Gas Stations (NSGS) was performed in 1994/1995 (Parsons ES, 1996b).

4.1.1 Model Setup and Predictions

4.1.1.1 Model Codes and Predictive Scenarios

The BIOPLUME II code was used to estimate the potential for dissolved BTEX migration and degradation by naturally occurring mechanisms operating at the NSGS site. Three scenarios were simulated. The first scenario, model TRV1, assumes only natural physical weathering of the LNAPL, and that mobile LNAPL would persist near the two source areas. The second scenario, model TRV2, assumed that the mobile LNAPL source was removed via bioslurping. Although bioslurping was not implemented, TRV2 appears to be most representative of the actual conditions present at the site because mobile LNAPL has not been detected since October 1995. No engineered remediation has occurred at the NSGS site since the TRV1 and TRV2 models were created. Underground storage tanks (USTs) and associated piping at the North and South Gas Stations were excavated in 1988 and July/August 1994, respectively, prior to the MNA TS.

4.1.1.2 Calculated and Model-Calibrated Biodegradation Rates

First-order biodegradation rates for BTEX were calculated using the conservative tracer method (AFCEE, 1995) and the method of Buscheck and Alcantar (1995). The calculated first-order biodegradation rates are presented in Table 4.1. The first-order decay rate initially input in the BIOPLUME II model represents the average of the two calculated decay rates. The coefficient of anaerobic decay had a significant effect on limiting plume migration in the model, and was also important in controlling dissolved BTEX concentrations at the fringes of the plume. This coefficient was not changed during the model calibration process.

TABLE 4.1
BIODEGRADATION RATES PRESENTED IN MNA TS FOR THE NSGS SITE
TRAVIS AFB CALIFORNIA

Contaminant	Buscheck and Alcantar		TEMB-Tracer ^{a/}		Model-Calibrated Rate	
	First-Order (day ⁻¹) ^{b/}	Half-Life (years)	First-Order (day ⁻¹)	Half-Life (years)	First-Order (day ⁻¹)	Half-Life (years)
BTEX	4.4E-4	4.3	5.4E-4	3.5	4.9E-4	3.9

^{a/} Rate computed using tetramethylbenzene (TEMB) as a conservative tracer.

^{b/} day⁻¹ = per day.

As discussed in Section 3.1.2.2, the method of Buscheck and Alcantar (1995) assumes that the plume has reached steady-state conditions. The rate calculated using this method is very similar to the rate calculated using the conservative tracer method (AFCEE, 1995), which is not dependent upon the presence of steady-state conditions, suggesting that the dissolved BTEX plume may have been at or near steady-state equilibrium.

4.1.1.3 Source Reduction Terms

To estimate the persistence and weathering of the BTEX source for Models TRV1 and TRV2, the USEPA's (1994) HSSM was used to quantify the dissolution of BTEX from LNAPL over time. Each of the simulations was calibrated utilizing a BTEX weathering rate (geometric) derived from the HSSM of 2.3 percent per year (%/yr) and 4.9 %/yr for the North Gas Station (NGS) and South Gas Station (SGS), respectively.

Model TRV1 assumed that the geometric source weathering rate would gradually decrease over time due to an anticipated decrease in source size and changes in the source composition. The geometric weathering rates were reduced from 2.3 %/yr and 4.9 %/yr in 1996 to 1.2 %/yr and 1.7 %/yr in 2036 for the NGS and SGS source areas, respectively. By the end of the model predictive period in 2036, the simulated source concentrations were approximately 44 percent and 25 percent of the initial source concentrations at the NGS and SGS, respectively.

Model TRV2 assumed that a bioslurping system began operating in 1996 and ended in 2000, having removed all of the mobile LNAPL. Dissolution of BTEX from LNAPL was assumed to be zero starting in 2000, and further mass removal and changes in the dissolved BTEX plume geometry resulted solely from natural attenuation. The geometric BTEX weathering rates for the NGS and SGS were simulated to be 2.3 and 4.9 percent from 1996 to 1997, respectively; 50 percent from 1997 to 1998; and 100 percent from 1998 to 1999 at both the NGS and SGS.

4.1.1.4 Predicted Plume Behavior

Model TRV1 assumed that BTEX dissolution into the aquifer would continue while the LNAPL source is being physically weathered. The results of the BIOPLUME II modeling suggested that the dissolved BTEX plume would expand until a steady-state configuration is reached by 2025. Because mobile LNAPL was assumed to persist in simulation TRV1, the dissolved BTEX plume was estimated to require over 50 years to completely degrade. Model TRV2 predicted that the BTEX plume would continue to expand until 2021, at which time it would reach a steady state condition with a maximum

BTEX concentration of approximately 1,500 micrograms per liter ($\mu\text{g/L}$). The dissolved BTEX plume was predicted to be completely degraded by 2031.

In the MNA TS, the lengthy remediation timetable for each scenario was attributed primarily to the low background concentrations of DO in the groundwater, the low hydraulic conductivity of the aquifer, and the low anaerobic decay rate used in the model (relative to common literature values).

4.1.2 Historical Contaminant Trends Compared to Predicted Plume Behavior

A summary of predicted versus observed plume conditions for the NSGS is provided in Table 4.2. Total BTEX isopleth maps for September 1998, June 1999, and August 2000 are included in Appendix A. Model predictions for the year 2006 are also included in Appendix A. Comparison of the observed BTEX plume with model-simulated plumes presented in the Final TS (Parsons ES, 1996b) indicates that model simulations TRV1 and TRV2 are overly conservative. TRV1 predicted that maximum total BTEX concentrations in the plume would exceed 10,000 $\mu\text{g/L}$ at least until the year 2006. TRV2 predicted that the maximum BTEX concentrations in 2006 would be between 5,000 and 10,000 $\mu\text{g/L}$, and by 2021 the maximum BTEX concentration would be approximately 1,500 $\mu\text{g/L}$. The model predicted that this minimum concentration would be located downgradient from the source area (i.e., the plume center of mass was predicted to detach from the source area).

The maximum BTEX concentration detected at the site in August 2000 was 4,960 $\mu\text{g/L}$. In addition to lower-than-predicted maximum concentrations, BTEX concentrations along the plume flow path exhibit a decreasing or a statistically stable trend, as evidenced by results obtained using the Monitoring and Remediation Optimization Software (MAROS) (AFCEE, 2000). The results of the AFCEE MAROS evaluation for plume stability indicated that the BTEX plume is stable or shrinking (Parsons ES, 2001a).

The source weathering rates used to simulate the reduction in source concentrations at the NSGS sites, presented in Section 4.1.1.3, were 2.3 %/yr and 4.9 %/yr (geometric rates) for the NGS and SGS, respectively. Assuming that dissolved BTEX concentrations in the source area are reflective of the source strength, the actual source reduction rate between 1994 and 2000 was estimated by comparing monitoring data collected in August 2000 to results of the baseline groundwater sampling event performed in August/September 1994. The average dissolved BTEX reduction rates calculated in this manner were 35.5 %/yr and 60.2 %/yr (geometric rates) for the NGS and SGS, respectively, indicating that the simulated source weathering rates were biased low. Free product at the site has not been detected since October 1995, although weathered residual LNAPL is probably still present. As stated in Section 4.1.1.1, model TRV1 assumed that mobile LNAPL would persist. This assumption contributed to the conservatism of this model.

Sensitivity analyses performed for the model simulations (Parsons ES, 1996b) indicated that the first-order decay coefficient and the aquifer transmissivity had the most significant effects on the model predictions. The source weathering rate was not changed during the model calibration process, and the sensitivity of the model to variations in this parameter was not evaluated. TRV2 predicted that the BTEX plume would continue to

TABLE 4.2
SUMMARY OF PREDICTED VERSUS OBSERVED CONDITIONS FOR THE NSGS SITE
TRAVIS AFB, CALIFORNIA

	Condition at Model Calibration Date (1995)	Predicted Condition – TRV1	Predicted Condition – TRV2	Observed Condition
Plume Dynamics	Unknown	Expanding BTEX Plume	Expanding BTEX Plume	Stable or Receding Plume
Maximum BTEX Concentration at Source Area Well(s)	NGS September 1995: 11,700 g/L ^{a/} SGS September 1995: 23,500 g/L	NGS 2006 and 2021: >1,000 and <10,000 g/L SGS: 2006 and 2021 >10,000 and <100,000 g/L	NGS 2006: >1000 and < 5,000 g/L 2021: not detected SGS 2006: ~5,000 g/L 2021: Slightly > 1 g/L	NGS August 2000: 725 g/L SGS August 2000: 412 g/L
Maximum BTEX Concentration at Plume Toe Well(s) (same well for NGS and SGS)	August 1995: 96 g/L	2006 and 2021: >1,000 and <10,000 g/L	2006: 5,000 g/L 2021: 100 g/L	August 2000: 8.1 g/L

^{a/} µg/L = micrograms per liter.

expand after the BTEX source had completely weathered, which indicates that other model input parameters, such as the first-order decay rate, were too conservative. The first-order decay rate used in the model ($4.9\text{E-}4$ per day [day^{-1}]) (half-life of 3.9 years) is an order-of-magnitude lower than the range of geometric mean first-order decay rates for the BTEX constituents derived from field studies of combined aerobic/anaerobic sites ($1.0\text{E-}3$ to $2.0\text{E-}3$ day^{-1}) (half-lives of 1.9 to 0.95 years) presented by Suarez and Rifai (1999).

4.2 SITE 2 – MYRTLE BEACH AFB POL BULK FUEL STORAGE AREA

Myrtle Beach AFB is located on a strip of land in South Carolina bounded by the Atlantic Ocean on the southeast and the Intracoastal Waterway on the northwest. The petroleum, oils, and lubricants (POL) Bulk Fuel Storage area is located approximately 1.7 miles from the Atlantic Ocean. A corrective action study (CAS) was completed for the POL area in 1995 (Parsons ES, 1997a).

4.2.1 Model Setup and Predictions

4.2.1.1 Model Codes and Predictive Scenarios

The BIOPLUME II code was used to estimate the potential for dissolved BTEX migration and degradation by naturally occurring mechanisms operating at the POL. Three model simulations were created. Model MB1 was created to simulate natural weathering of the contaminant source. Model MB2 simulated engineered source reduction by utilizing a greater source reduction rate than was utilized in model MB1. Model MB3 assumed that the source was removed instantaneously, one year after the model calibration date, via excavation. In 1997, a bioslurping system pilot test was performed, however, implementation of this technology was determined to be impractical for the site. Model predictions are compared to groundwater quality data collected in February 2000.

4.2.1.2 Calculated and Model-Calibrated Biodegradation Rates

First-order decay rates were calculated for BTEX using the conservative tracer method (USEPA, 1995) and the method of Buscheck and Alcantar (1995) (Table 4.3). The first-order rate calculated using the method of Buscheck and Alcantar, $2.1\text{E-}3$ day^{-1} (half-life of 0.90 years) was selected for use in the model simulations because it had a coefficient of determination (R^2) closer to one. Values of R^2 closer to unity indicate a better fit to the first-order rate. The first-order decay rate was not varied during the model calibration process.

TABLE 4.3
CALCULATED BIODEGRADATION RATES FOR THE POL YARD
MYRTLE BEACH AFB, SOUTH CAROLINA

Contaminant	Buscheck and Alcantar		Conservative Tracer ^{a/}	
	First-Order Rate (day^{-1}) ^{b/}	Half-Life (years)	First-Order Rate (day^{-1})	Half-Life (years)
BTEX	$2.1\text{E-}3$	0.90	$1.4\text{E-}3$	1.4

^{a/} Rate computed using TEMB as a conservative tracer.

^{b/} day^{-1} = per day.

Dissolved BTEX migrates downgradient from the source area at the POL area along multiple flow paths. The path used to calculate the first-order decay rates was not the preferred or optimal flow path for the methods used. However, the primary flow path for BTEX migration could not be used because of 1) the lack of three data points between the source area and the downgradient creek into which the plume discharges, and 2) the source area (mobile LNAPL) extends to within 350 feet of a creek. Therefore, the first-order decay rates were calculated using data collected along a secondary flow path.

4.2.1.3 Source Reduction Terms

To estimate partitioning rates for dissolution of BTEX from free and residual product at the POL Area, the OILENS module of the HSSM (USEPA, 1994) was used. Model MB1 assumed that only physical weathering was responsible for reductions in source area BTEX concentrations. Physical weathering was estimated to reduce the mass of BTEX partitioning into the groundwater at a geometric rate of approximately 1 %/yr for the first 50 years of the model. After 50 years of weathering, the source strength would be approximately 66 percent of the 1995 source strength.

Simulation MB2 assumed that bioslurping was implemented to remove the free product at the POL. MB2 assumed that free product would be removed by 2005 (10 years of simulation), and the remaining BTEX source (residual product) would be completely removed by 2015 (20 years of simulation). The BTEX weathering/reduction rate was simulated to be linear rather than geometric, and varied from 12 %/yr to 37 %/yr for the first 10 years of simulation and from 14 %/yr to 60 %/yr for the 9 years after free product was removed.

4.2.1.4 Predicted Plume Behavior

The CAS (Parsons ES, 1997a) presented model predictions for MB1 for the years 2005 (10 years of simulation), 2015 (15 years of simulation) and 2045 (50 years of simulation). After 10 years of natural weathering, the simulated plume was still similar to the calibrated plume. Dissolved BTEX isoconcentration contours remained in approximately the same locations, although the simulated source area concentrations were approximately 9 percent lower than 1995 concentrations. The model-predicted BTEX plume for 2015 had the same overall areal extent as the calibrated plume (1995); however the 10,000-µg/L and 15,000-µg/L isoconcentration contours were simulated to have receded toward the source area. The simulated plume for 2045 also had the same areal extent as the calibrated plume (1995); however the source area BTEX concentrations were approximately 65 percent of the 1995 concentrations, and the simulated locations of the 10,000-µg/L and 15,000-µg/L isoconcentration lines had receded significantly.

Model simulation MB2 predicted that after 1 year of bioslurping (1997), the BTEX plume would have approximately the same overall areal extent as the calibrated plume (1995), although the source area concentrations would be approximately 11 percent lower than in the calibrated plume, and the higher concentrations would have been more localized in the source area. The simulated plume for 2008 was predicted to have the same areal extent as the calibrated plume, however, the simulated source area concentrations were approximately 85 percent lower than in the calibrated model. MB2 predicted that the areal extent of the BTEX plume in 2021 would be greatly reduced, and

that remaining dissolved BTEX concentrations would be approaching the detection limits.

4.2.2 Historical Contaminant Trends Compared to Predicted Plume Behavior

A summary of predicted versus observed plume conditions for the POL area is provided in Table 4.4, and historical BTEX isopleth maps for January 1995 and February 1999 are included in Appendix A. Predicted plume migration for models MB1 and MB2 are also included in Appendix A. Although full-scale bioslurping was not implemented at the POL area, measured BTEX concentrations at the site appear to be better approximated by model MB2 than by model MB1. Model MB1 predicted that dissolved BTEX concentrations in the source area would remain the same order of magnitude for over 50 years, while actual BTEX concentrations detected in the source area in 2000 are similar to concentrations predicted by model MB2 for years 1997 and 2006. Because models MB1 and MB2 were equivalent except for the source reduction rates, the conservatism of the MB1 simulation is attributed to the 1%/yr source reduction input term.

The source reduction terms utilized in the MB1 and MB2 simulations were calculated using the OILENS module of the HSSM (USEPA, 1994) rather than actual measured decreases in BTEX concentrations in LNAPL at the site (such data were not available). As reported in *LNAPL Weathering at Various Fuel Release Sites* (Parsons ES, 1999a), average measured first-order weathering rates for BTEX in JP-4 ranged from 11 to 23 %/yr. The source weathering rates used for the MB2 simulation (12 %/yr to 37 %/yr) are comparable to or higher than the natural source weathering rates reported in this document. These data support the observation that the conservatism of MB1 is likely directly attributable to the source weathering rate. The first-order decay rate for BTEX used in both MB1 and MB2, $2.1\text{E-}3 \text{ day}^{-1}$ (half-life of 0.90 year), compares well to mean first-order decay rates for the BTEX constituents ($1.0\text{E-}2$ to $2.0\text{E-}3 \text{ day}^{-1}$ or half-lives of 1.9 to 0.95 years) presented by Suarez and Rifai (1999).

4.3 SITE 3 – HILL AFB UST SITE 870

Hill AFB is located in Ogden, Utah, approximately 30 miles northwest of Salt Lake City. An Engineering Evaluation/Cost Analysis (EE/CA) was completed for UST Site 870 in 1995 (Parsons ES, 1995a).

4.3.1 Model Setup and Predictions

4.3.1.1 Model Codes and Predictive Scenarios

The BIOPLUME II model was used to predict the potential for dissolved BTEX migration and degradation by naturally occurring mechanisms operating at UST Site 870. Three scenarios were simulated. Model Hill-A assumed that no engineered remediation or intrinsic source weathering occurred at the site. Models Hill-B and Hill-C assumed that the LNAPL source area was reduced by a combination of engineered remediation and natural weathering processes. Since the summer of 1994, source removal activities at the site have included limited LNAPL recovery with skimmer pumps and sorbent wicks, and bioventing for remediation of fuel hydrocarbons in vadose zone soils. However,

TABLE 4.4
SUMMARY OF PREDICTED VERSUS OBSERVED CONDITIONS FOR THE POL YARD
MYRTLE BEACH AFB, SOUTH CAROLINA

	Condition at Model Calibration Date	Predicted Condition - MB1	Predicted Condition - MB2	Observed Condition
Plume Dynamics	Unknown	Stable	Stable	Stable
Maximum BTEX Concentrations in Source Area	1995: 18,270 µg/L ^{a/}	2005: ~20,000 µg/L 2015: ~15,000 µg/L 2045: ~15,000 µg/L	1997: 17,000 µg/L 2006: 3,000 µg/L 2021: ~1 µg/L	2000: ~5,000 µg/L
Maximum Concentration in Plume Toe	1995: ~5,000 µg/L	2005: ~5,000 µg/L 2015: ~5,000 µg/L 2045: >1,000 and <5,000 µg/L	1997: ~5,000 µg/L 2006: ~1,000 µg/L 2021: ~3 µg/L	2000: 4,920 µg/L

^{a/} µg/L = micrograms per liter.

after the EE/CA for Site 870 was completed, additional releases of fuel hydrocarbons occurred and mobile LNAPL was still present at the site as of the March 2000 groundwater sampling event.

4.3.1.2 Calculated and Model-Calibrated Biodegradation Rates

The model simulations for Site 870 assumed that dissolved BTEX concentrations were reduced via instantaneous redox reactions rather than first-order decay. In addition to instantaneous decay of BTEX via oxygen reduction, the anaerobic process of nitrogen reduction was assumed to occur instantaneously by mathematically converting nitrate concentrations to equivalent concentrations of oxygen. Nitrate concentrations were modeled as having an instantaneous reaction capacity equivalent to 64.6 percent of the instantaneous reaction capacity of oxygen.

A first-order reaeration rate of $3.0\text{E-}3 \text{ day}^{-1}$ was used to simulate dissolved BTEX degradation by the oxygen introduced into the groundwater via soil gas diffusion and rainwater infiltration. The first-order rate of $3.0\text{E-}3 \text{ day}^{-1}$ was intended to be conservative, and was based on first-order decay rates calculated for other contaminant plumes at Hill AFB (Wiedemeier *et al.*, 1994).

4.3.1.3 Source Reduction Terms

Model Hill-A assumed that no source removal or weathering occurred at Site 870. Models Hill-B and Hill-C were identical to Hill-A, except that the BTEX source was assumed to decline at geometric rates of 5 %/yr and 15 %/yr, respectively.

4.3.1.4 Predicted Plume Behavior

Predictive simulation results generated using model Hill-A were presented for 1, 4, and 10 years after the model calibration date (1993). The model simulation for 10 years (2003) is included in Appendix A. Model Hill-A predicted that the plume would first expand slightly, and then reach steady-state equilibrium within 4 years. The steady-state plume was predicted to have approximately the same footprint as the calibrated plume. The simulated dissolved BTEX plume for 2003 (10 years of simulation) had a similar footprint to the plume predicted for year 4.

Predictive simulation results generated with model Hill-B were presented for 1, 4, and 7 years after the model calibration date (1993). The model simulation for 7 years (2000) is included in Appendix A. The plume predicted by model Hill-B for simulation year 1 (1994) was nearly identical to that predicted by model Hill-A for the same year. By simulation year 4 however, the plume was predicted to have receded significantly and maximum source-area concentrations were reduced by approximately 2,000 $\mu\text{g/L}$. By simulation year 7, the plume was predicted to encompass only approximately 10 percent of its original area, and the maximum BTEX concentration in the source area was predicted to be 300 $\mu\text{g/L}$. Although BTEX partitioning from the source LNAPL into groundwater was simulated to occur for 20 years (1993-2013), after 7 years of geometric weathering at a simulated geometric rate of 5 %/yr, the influx of BTEX into the groundwater was exceeded by the biodegradation capacity of the electron acceptors, and the dissolved BTEX plume was almost completely degraded.

Model predictions generated using Hill-C were presented for 1 and 3 years after the calibration date (1993). Model Hill C assumed a 15-percent annual geometric source weathering rate. The magnitude and extent of the predicted plume for simulation year 1 (1994) were similar to that predicted by models Hill-A and Hill-B for the same year. By simulation year 4, the dissolved BTEX plume was predicted to have completely degraded.

4.3.2 Historical Contaminant Trends Compared to Predicted Plume Behavior

A summary of predicted versus observed plume conditions for Site 870 is presented in Table 4.5. Historical BTEX isopleth maps from 1993 to 1998 are included in Appendix A. After groundwater data were collected in 1994, additional fuel hydrocarbons were released at Site 870. The date(s) of the release(s) are not known with certainty, but the release(s) likely occurred in the 1993-1999 time frame. Therefore, models Hill-B Hill-C overestimate the rate at which the dissolved BTEX will attenuate at Site 870. Of the three models, Hill-A appears to be the most representative of site conditions. Although bioventing and mobile LNAPL recovery was implemented at Site 870, LNAPL persists, and source area BTEX concentrations have not significantly decreased.

Model Hill-A appears to adequately represent the measured BTEX plume extent and concentrations. The observed plume in 1999 compares well to the predicted plume for year 2004. Because the Hill-A model did not simulate any source weathering, the magnitude and extent of the simulated plume did not change after steady-state conditions were reached. Because of the additional release of fuel hydrocarbons at Site 870, the effect of any source weathering that may have occurred since 1993 are apparent from temporal BTEX concentrations detected in groundwater samples collected beneath the LNAPL.

4.4 SITE 4 – ELMENDORF AFB SITE ST41

Elmendorf AFB is located in Anchorage, Alaska. An Intrinsic Remediation TS was performed for Site ST41 in 1994 (Parsons ES, 1995b).

4.4.1 Model Setup and Predictions

4.4.1.1 Model Codes and Predictive Scenarios

The BIOPLUME II code was used to estimate the potential for dissolved BTEX migration and degradation by naturally occurring mechanisms operating at Site ST41. Three distinct models were created. Model ST41A simulated a worst-case scenario because it assumed that a constant BTEX source would persist, without undergoing weathering. Model ST41C assumed that the existing groundwater recovery system would continue to operate for 5 years and reduce the BTEX source by 70 percent. The remaining BTEX source was assumed to weather at a geometric rate of 8 %/yr after the groundwater recovery system was turned off. Model ST41D assumed that only natural weathering (8 %/yr rate) acted to reduce the source loading of BTEX. Since the Intrinsic Remediation TS was performed the groundwater extraction system at the site was turned off because it was determined to be ineffective. The results of model ST41D are presented for comparison with long-term monitoring (LTM) BTEX data.

TABLE 4.5
SUMMARY OF PREDICTED VERSUS OBSERVED CONDITIONS FOR UST SITE 870
HILL AFB, UTAH

	Condition at Model Calibration Date (1993)	Predicted Condition – Hill-A	Predicted Condition – Hill-B	Predicted Condition – Hill-C	Observed Condition
Plume Dynamics	Unknown	Plume expands before reaching steady-state within 4 years (1997)	Plume expands for 2 years and has receded by year 4	Plume expands in year 1 and completely degrades in 4 years	Probably Stable
Maximum BTEX Concentrations in Source Area	8,000 µg/L ^{a/}	1994: 8,000 µg/L 2004: 7,000 µg/L	1994: 5,000 µg/L 1997: 5,000 µg/L 2000: 300 µg/L	1994: 1,000 to 3,000 µg/L 1998: Not detected	1994: 6,020 to 13,300 µg/L 1999: 7,200 to 10,200 µg/L
Maximum BTEX Concentration at Plume Toe	Not detected	1994: ~1 µg/L 2004: <1 µg/L	1994: ~1 µg/L 1997: <1 µg/L 2000: Not detected	1994: ~1 µg/L 1996: Not detected	1994: Not detected 1999: 66 µg/L

^{a/} µg/L = micrograms per liter.

4.4.1.2 Calculated and Model-Calibrated Biodegradation Rates

First-order decay rates for BTEX constituents were calculated for Site ST41 using the conservative tracer method (USEPA, 1995) (Table 4.6). The calculated rates range from $3.0\text{E-}3 \text{ day}^{-1}$ (half-life of 0.6 year) to $3.0\text{E-}2 \text{ day}^{-1}$ (half-life of 0.06 year). The first-order decay rates were calculated using a flow path that extended from a source area well with the maximum detected BTEX concentration at the site to a down-gradient well located along the approximate plume axis. Each model simulation used a calibrated first-order anaerobic decay rate of $5.0\text{E-}3 \text{ day}^{-1}$ (half-life of 0.4 year). In addition to the anaerobic decay rate, the model simulations used a reaeration coefficient. A reaeration coefficient of $2.0\text{E-}3 \text{ day}^{-1}$ was used to simulate the replenishment of oxygen into groundwater by soil-gas diffusion and rainwater infiltration.

TABLE 4.6
CALCULATED BIODEGRADATION RATES FOR SITE ST41
ELMENDORF AFB, ALASKA

Contaminant	Conservative Tracer ^{a/}		Model-Calibrated Rate	
	First-Order (day^{-1}) ^{b/}	Half-Life (years)	First-Order (day^{-1})	Half-Life (years)
Benzene	$3.0\text{E-}2$	0.06	NA ^{c/}	NA
Toluene	$4.0\text{E-}2$	0.05	NA	NA
Ethylbenzene	-- ^{d/}	--	NA	NA
Xylene	$3.0\text{E-}3$	0.6	NA	NA
BTEX	NA	NA	$5.0\text{E-}3$	0.4

^{a/} Rate calculated using 1,3,5- 1,2,4- and 1,2,3-trimethylbenzene as conservative tracers.

^{b/} day^{-1} = per day.

^{c/} NA = Not applicable.

^{d/} "--" = Rate calculated but determined to be invalid because it was negative.

4.4.1.3 Source Reduction Terms

The natural source weathering rate of 8 %/yr (geometric) used in models ST41C and ST41D was based on a calculated weathering rate for a gasoline site at Eglin AFB (AFCEE, 1995), where natural weathering appeared to have decreased the BTEX loading capacity of the source by approximately 80 percent in 5 years. The observed reduction at the Eglin site is equivalent to 15 percent of the original concentration per year (27 %/yr geometric reduction rate). At the time, this rate was considered to be an upper limit to potential source weathering rate. A lower geometric rate of 8 %/yr was used in the Elmendorf model simulations as a conservative estimate of source weathering.

4.4.1.4 Predicted Plume Behavior

Model ST41A (no source weathering) predicted that the BTEX plume would continue to expand for several years. The predicted plumes for 2 and 5 years of simulation time (1996 and 1999) were approximately 250 feet and 350 feet longer than the model-calibrated plume (1994), respectively.

Model output for simulation ST41D was compiled for 15, 25, and 29 years of simulation time (i.e., years 2009, 2019, and 2023, respectively). After simulation year 15 (2009), the plume was predicted to shrink considerably relative to the calibrated plume, and the simulated maximum BTEX concentrations decreased by 72 percent. Further simulation indicated that the plume would continue to shrink.

4.4.2 Historical Contaminant Trends Compared to Predicted Plume Behavior

A summary of model-predicted and actual site conditions is presented in Table 4.7. Total BTEX isopleth maps for June 1994 and October 2000 are included in Appendix A. LTM data for groundwater are available for November 1999 and October 2000. BTEX concentration trends indicate that the areal extent of the BTEX plume has remained relatively unchanged from 1994 to 1999/2000 as defined by the inferred location of the 1- $\mu\text{g/L}$ isoconcentration line. However, BTEX concentrations within the plume have decreased, as evidenced by lower BTEX concentrations in the source area and along the plume axis (Parsons ES, 2001c).

Single-well, first-order degradation rates were computed for a source area well and a plume toe well by fitting first-order trend lines to BTEX data collected in 1994, 1999, and 2000. A first-order decay rate of $3.0\text{E-}4 \text{ day}^{-1}$ (half-life of 6.3 years) was approximated using data collected from the two wells. Because model prediction output for 1999 or 2000 was not presented in the TS report, these calculated first-order decay rates were used to predict future dissolved BTEX concentrations for comparison to the ST41D model predictions. The projected source area and plume toe concentrations for 2009, assuming a first-order decay rate of $3.0\text{E-}4 \text{ day}^{-1}$, were approximately 9,000 $\mu\text{g/L}$ and 400 $\mu\text{g/L}$, respectively. In contrast, the 2009 BTEX concentrations predicted by model ST41D for the source area and plume toe were approximately 5,000 $\mu\text{g/L}$ and 1,000 $\mu\text{g/L}$, respectively. This comparison suggests that while model ST41D may underestimate the BTEX concentrations in the source area for year 2009, the model predicts concentrations at the plume toe with a reasonable degree of accuracy. The areal extent of the predicted 2009 BTEX plume is approximately the same as the observed BTEX plume in 2000 (Parsons ES, 2001c).

During the model calibration process it was noted that simulated concentrations were lower than measured concentrations at the site. For example, the observed concentration at a source-area well was 43,300 $\mu\text{g/L}$, while the simulated concentration for the model cell representing the well was 17,700 $\mu\text{g/L}$. It was noted that increasing the BTEX loading rates sufficiently to produce concentrations in excess of 25,000 $\mu\text{g/L}$ in the source area resulted in a simulated plume that was much longer than the observed plume. Additionally, the simulated 5,000- $\mu\text{g/L}$ and 10,000- $\mu\text{g/L}$ isoconcentration lines encompassed a larger area than the isoconcentration lines inferred from measured concentrations. Because it was known from the model calibration process that the model would underpredict the source area BTEX concentrations, the lower-than-predicted magnitude of the observed concentrations are not unexpected. The modeling results for this site may be appropriate for estimating future plume extent, but may not provide an accurate forecast of BTEX persistence in the source area.

TABLE 4.7
SUMMARY OF PREDICTED VERSUS OBSERVED CONDITIONS FOR SITE ST41
ELMENDORF AFB, ALASKA

	Condition at Model Calibration Date (1994)	Predicted Condition – ST41C	Observed Condition
Plume Dynamics	Unknown	Stable	Shrinking or Stable
Maximum BTEX Concentration in Source Area	43,300 µg/L ^{a/}	2009: ~4,000 µg/L 2019: ~1,500 µg/L	1999: 34,400 2000: 15,900 µg/L
Maximum BTEX Concentration at Plume Toe	1,830 µg/L	2009: ~1,000 µg/L 2019: <100 µg/L	1999: 1,020 µg/L 2000: 819 µg/L

^{a/} µg/L = micrograms per liter.

Assuming that dissolved BTEX concentrations in the source area are reflective of the actual source strength, the actual geometric source reduction rate between 1994 and 2000 of 11 %/yr was slightly greater than the model input value of 8 %/yr. Geometric weathering rates for BTEX in LNAPL, reported by Parsons ES (1999a), ranged from 11 %/yr to 23 %/yr. The first-order decay rate used in the model ($5.0\text{E-}3 \text{ day}^{-1}$, half-life of 0.4 year) is the same order-of-magnitude as the range of mean first-order decay rates for the BTEX constituents ($1.0\text{E-}3$ to $2.0\text{E-}3 \text{ day}^{-1}$) presented by Suarez and Rifai (1999).

4.5 SITE 5 – KING SALMON AIRPORT SITE SS-12

King Salmon Airport (KSA) is situated on 216 acres on the upper, northwestern side of the Alaskan Peninsula. Anchorage, Alaska is 280 miles to the northeast. The Upper and Lower Naknek Sites (collectively referred to as Site SS-12) are located on the northern bank of the Naknek River, approximately 0.7 mile west of the town of King Salmon, Alaska. A TS in Support of Intrinsic Remediation was finalized in 1999 (Parsons ES, 1999e).

4.5.1 Model Setup and Predictions

4.5.1.1 Model Codes and Predictive Scenarios

Two simulations were performed using the BIOPLUME II code to estimate the potential for dissolved BTEX migration and degradation by naturally occurring mechanisms operating at Site SS-12. Model NaknekA simulated a worst-case scenario because it assumed that a constant BTEX source would persist, without weathering. Model NaknekB assumed that the BTEX source would weather due to natural attenuation.

4.5.1.2 Calculated and Model-Calibrated Biodegradation Rates

Calculated first-order decay rates for BTEX constituents were not used in the model simulations for Site SS-12. Instead, a reaeration coefficient of $1.0\text{E-}3 \text{ day}^{-1}$ was used to simulate the vertical exchange of oxygen from the vadose zone by soil-gas diffusion and rainwater infiltration. The magnitude of the reaeration rate was determined by trial and error during the model calibration process.

4.5.1.3 Source Reduction Terms

Simulation NaknekA assumed that the BTEX source was not weathered during the predictive modeling, and that conditions used to calibrate the model were assumed to continue. Simulation NaknekB utilized a 10 %/yr linear source weathering rate for a 5-year predictive simulation period (i.e., the source strength was reduced by 50 percent over 5 years).

4.5.1.4 Predicted Plume Behavior

Output for model NaknekA was compiled for 10 years of predictive simulation time following the calibration period, although model results indicated that the simulated plume had reached stability within the first year of simulation. Model NaknekB predicted that the areal extent of the BTEX plume would remain relatively unchanged

from 1994 to 1997 (3 years of simulated source weathering). By 1999 (5 years of simulation), the maximum simulated plume concentration was only 18 percent of the calibrated maximum concentration, and the plume was noticeably smaller.

4.5.2 Historical Contaminant Trends Compared to Predicted Plume Behavior

A summary of model-predicted and actual site conditions is presented in Table 4.8. Total BTEX isopleth maps from 1994 to 2000 are included in Appendix A. The predicted BTEX plume for model NAKNEKA after 4 years (1998) and for model NAKNEKB after 5 years (1999) are included in Appendix A. LTM groundwater data are available for September 1998 and June 2000. Because wells at the BTEX plume toe were not sampled, it is not possible to confirm whether the plume has expanded, receded, or remained stable. However, sufficient data have been collected to evaluate changes in source area concentrations.

Assuming that dissolved BTEX concentrations in the source area are reflective of the source strength, actual geometric source reduction rates of $1.6\text{E-}3 \text{ day}^{-1}$ (11 %/yr) and $1.4\text{E-}3 \text{ day}^{-1}$ (9 %/yr) were calculated using BTEX concentrations collected from two wells near the source area at Site SS-12 over a 6-year period. The calculated rates are similar to the linear rate of 10 %/yr (equivalent to a 11 %/yr geometric rate) used in the model simulations, and are at or near the low end of the 11 %/yr to 23 %/yr range for geometric BTEX weathering rates in LNAPL reported by Parsons ES (1999a).

The maximum BTEX concentration detected in the source area in June 2000 was 447 µg/L. The maximum concentration predicted by the NaknekB simulation for 1999 was 1,400 µg/L. The NaknekB simulation appears to be slightly conservative; however, as described above, the source reduction rate used in the model appears to correlate to the actual source weathering conditions at the site reasonably well. Although the detected concentrations at the site are lower than predicted by the model, the measured BTEX concentrations at the site may not represent the highest BTEX concentrations present in source area groundwater. Although a first-order aerobic biodegradation rate was not used, the first-order reaeration rate of $1.0\text{E-}3 \text{ day}^{-1}$ is comparable to first-order decay rates for the BTEX constituents ($1.0\text{E-}3$ to $2.0\text{E-}3 \text{ day}^{-1}$) presented by Suarez and Rifai (1999).

4.6 SITE 6 – LANGLEY AFB SITE SS-04

Langley AFB is located in Hampton in southeastern Virginia. Parsons ES completed a Remediation by Natural Attenuation (RNA) TS for Site SS-04, a former UST site, in 1999 (Parsons ES, 1999b).

4.6.1 Model Setup and Predictions

4.6.1.1 Model Codes and Predictive Scenarios

The BIOSCREEN analytical model (USEPA, 1996) was used to evaluate natural attenuation of the dissolved benzene plume at Site SS-12. The objectives of the BIOSCREEN modeling effort were defined in the RNA TS report as: 1) determine the maximum migration distance of the benzene plume; 2) determine the time required for benzene concentrations to attenuate to concentrations below the federal maximum

TABLE 4.8
SUMMARY OF PREDICTED VERSUS OBSERVED CONDITIONS FOR SITE SS-12
KING SALMON AIRPORT, ALASKA

	Condition at Model Calibration Date (1994)	Predicted Condition NaknekB (1999)	Observed Condition
Plume Dynamics	Unknown	Steady-State through 1997, then Receding	Unknown
Maximum BTEX Concentrations in Source Area	5,260 µg/L ^{a/}	1999: 1,400 µg/L	2000: 447 µg/L
Maximum BTEX Concentration in Plume Toe	6 µg/L	Downgradient plume extent is relatively unchanged, although the overall footprint of the plume has been reduced.	Unknown

^{a/} µg/L = micrograms per liter.

contaminant level (MCL) of 5 µg/L; and 3) determine how source remediation will affect dissolved benzene plume concentrations. To meet these objectives, simulations were created to model both natural attenuation and engineered remediation via biosparging.

4.6.1.2 Calculated and Model-Calibrated Biodegradation Rates

The Instantaneous Reaction option of the BIOSCREEN model was used rather than a first-order biodegradation rate. The simulation used sulfate, ferrous iron, and methane in the model input for instantaneous reaction. Data for oxygen and nitrate were not used because aerobic biodegradation and nitrate reduction were determined to be insignificant processes at the site. As recommended in the BIOSCREEN user's manual (USEPA, 1996), the total biodegradation capacity was reduced to account for electron acceptor utilization by other constituents in the plume due to the fact that only benzene was simulated. Benzene was estimated to comprise an average of 50 percent of the total BTEX dissolved in groundwater at the site based on laboratory analytical results for groundwater samples.

4.6.1.3 Source Reduction Terms

The benzene source for the RNA simulation was modeled as finite and decaying. The model calculated the source reduction rate to be 3.5 %/yr (geometric) by assuming that the mass of contaminant in the source area slowly dissolved into the uncontaminated groundwater migrating through the source area from upgradient; the model simulated this to be a first-order process. The simulated biosparging scenario assumed that the source concentration would geometrically decrease by 50 %/yr for two years, and then continue to weather at a first-order rate of 3.5 %/yr throughout the remainder of the simulation period.

4.6.1.4 Predicted Plume Behavior

The BIOSCREEN model was calibrated to match benzene concentrations along the plume centerline. The model was used to predict plume conditions for 10, 15, 20, and 23 years of simulation time (i.e. 2007, 2012, 2017, and 2020, respectively). The RNA simulation predicted that after 10 years (2007), the maximum benzene concentration in the source area would be 81 µg/L and the plume length would be approximately 300 feet. The maximum benzene concentration in the source area after 20 years (2017) was 18 µg/L (reduced by 88 percent), and the predicted plume length was less than 100 feet.

The biosparging simulation predicted that in 2004 (7 years of simulation) the source concentration would be reduced by 97 percent and the maximum benzene concentrations would be less than the 5-µg/L MCL.

4.6.2 Historical Contaminant Trends Compared to Predicted Plume Behavior

A summary of model-predicted and actual site conditions is presented in Table 4.9. A BTEX isopleth map for shallow groundwater in October 1997 is included in Appendix A. In both June 1999 and June 2000, samples from only one of the 12 wells sampled during each event had detectable concentrations of benzene above the 5-µg/L MCL. The benzene concentrations exceeding the MCL in June 1999 and 2000 were 4,400 µg/L and

TABLE 4.9
SUMMARY OF PREDICTED VERSUS OBSERVED CONDITIONS FOR SITE SS04
LANGLEY AFB, VIRGINIA

	Condition at Model Calibration Date (1997)	Predicted Condition - RNA Scenario	Predicted Condition - Biosparging Scenario	Observed Condition
Plume Dynamics	Unknown	Expanding	Expanding	Shrinking
Maximum BTEX Concentrations in Source Area Well(s)	170 µg/L ^{a/}	2000: 140 µg/L 2007: 80 µg/L	2000: 90 µg/L 2007: not detected	2000: not detected
Maximum BTEX Concentration at Plume Toe Well(s)	43 µg/L	2007: 25 µg/L	Unknown	2000: 1,200 µg/L (not incorporated into model simulations)

^{a/} µg/L = micrograms per liter.

1,200 µg/L, respectively. In November 1996 and October 1997, analytical results for benzene from the same well were 1,300 µg/L and 0.4U µg/L (i.e., not detected), respectively. The BIOSCREEN models were calibrated to the analytical results of the October 1997 sampling event, and did not consider the 1,300-µg/L benzene concentration detected in November 1996, because it was believed to result from another source unrelated to the plume being modeled.

Apart from the single benzene MCL exceedances in June 1999 and June 2000, the RNA model over-predicted by 21 years the time required for natural attenuation to degrade benzene concentrations to below 5 µg/L. The biosparging scenario predicted that benzene would decrease below the MCL after 7 years (2004) in this case, a scenario that was intended to represent remediation of the source over-predicted the time necessary for benzene concentrations to reach the MCL.

The model simulation of RNA intentionally used conservative input parameters, and results were thought to represent the maximum time frame for meeting the groundwater standards (Parsons ES, 1999b). The RNA simulation was believed to be conservative because it did not account for benzene biodegradation via nitrogen fixation or for biodegradation of the source. In addition, the model-calculated source weathering rate is low compared to average literature values (Parsons ES, 1999a).

4.7 SITE 7 – DOVER AFB SITE SS27/XYZ

Dover AFB is located in Kent County, Delaware. Site SS27/XYZ is a former aircraft refueling location with contamination suspected to derive from subsurface fuel lines and/or ancillary equipment. An Intrinsic Remediation EE/CA was completed for the site in January 1996 (Parsons ES, 1996a).

4.7.1 Model Setup and Predictions

4.7.1.1 Model Codes and Predictive Scenarios

The BIOPLUME II model was used to predict the future extent and concentration of the dissolved BTEX plume, and to assess the potential for downgradient receptors to be exposed to BTEX concentrations that exceed regulatory levels intended to be protective of human health and the environment. Three remedial scenarios were simulated using the BIOPLUME II model, and the same three scenarios also were modeled using an analytical groundwater fate and transport model (van Genuchten and Alves, 1982). Model CAL assumed no source weathering or removal, Models SR8 and SR6 assumed linear weathering rates of 12.5 %/yr and 17 %/yr, respectively. Since the field work for the EE/CA was completed, a mobile LNAPL recovery and remediation pilot study using bioslurping was conducted in 1995, and a product skimmer was installed in one well. Full-scale bioslurping has not been implemented at the site, and free product was detected during a 1999 sampling event.

4.7.1.2 Calculated and Model-Calibrated Biodegradation Rates

First-order anaerobic decay rates for BTEX in groundwater at Site SS27/XYZ were calculated using the conservative tracer method (USEPA, 1995). Calculated rates for the

site ranged from $3.0\text{E-}4 \text{ day}^{-1}$ (half-life of 6 years) to $2.0\text{E-}3 \text{ day}^{-1}$ (half-life of 0.09 year) along the primary flow path (Table 4.10), and from $8.0\text{E-}4 \text{ day}^{-1}$ (half-life of 2.4 years) to $4.0\text{E-}3 \text{ day}^{-1}$ (half-life of 0.5 year) along secondary flow paths. However, first-order anaerobic decay rates were not used in the simulations for Site SS27/XYZ. Instead, BIOPLUME II model simulations assumed that dissolved BTEX concentrations were reduced via instantaneous redox reactions similar to the model constructed for the Hill AFB Site 870 (Section 4.3). In addition to instantaneous decay of BTEX via oxygen reduction, the anaerobic process of nitrogen reduction was assumed to occur instantaneously by mathematically converting nitrate concentrations to equivalent concentrations of oxygen. Nitrate concentrations were modeled as having an instantaneous reaction capacity equivalent to 64.6 percent of the instantaneous reaction capacity of oxygen.

A first-order reaeration rate of $3.0\text{E-}3 \text{ day}^{-1}$ was used to simulate dissolved BTEX degradation via oxygen introduced into the groundwater by soil gas diffusion and rainwater infiltration. Varying the reaeration rate during the model calibration process suggested that the selected rate adequately simulated the site conditions. The use of this first-order rate was based on other documented BIOPLUME II modeling efforts (Rifai *et al.*, 1988, referenced in Parsons ES, 1996a).

TABLE 4.10
CALCULATED BIODEGRADATION RATES FOR SITE SS27/XYZ
DOVER AFB, DELAWARE

Contaminant	Conservative Tracer ^{a/}		Model-Calibrated Reaeration Rate	
	First-Order (day^{-1}) ^{b/}	Half-Life (years)	First-Order (day^{-1})	Half-Life (years)
BTEX	0.0003 to 0.002	6 to 0.09	0.003	0.6

^{a/} Rate computed using TEMB as a conservative tracer.

^{b/} day^{-1} = per day.

4.7.1.3 Source Reduction Terms

Model CAL assumed that the conditions specified to calibrate the model were continued, and that no source weathering or removal occurred. Model SR8 assumed that natural weathering and implementation of bioslurping and bioventing would reduce source concentrations by 12.5 percent of the original source concentrations per year for 8 years. Model SR6 simulated an annual 17-percent reduction in source BTEX concentrations over a 6-year period. These reductions were assumed to result from natural weathering and implementation of a comprehensive remedial system that removed soil gas, skimmed free-product, and reoxygenated oxygen-depleted soils.

4.7.1.4 Predicted Plume Behavior

Simulated BTEX plumes for 2000 and 2012, derived using Model CAL, were presented in the EE/CA (Parsons ES, 1996a). The model predicted that the plume would migrate downgradient at a rate of 100 ft/yr between the model calibration date (1994) and

2000. The migration rate was predicted to decrease to 22 feet per year (ft/yr) between 2000 and 2012. The model results indicated that the plume would stabilize within 17 years (2012). The simulated maximum BTEX concentration in the plume in 1995 was 21,900 µg/L; the predicted maximum concentration increased to a steady-state value of 24,500 µg/L by 2012.

Simulated BTEX plumes derived using model SR8 were presented for 2000, 2008, and 2012. SR8 predicted that, after five years of source removal (2000), the plume extent would change only slightly compared to the Model CAL results, but the maximum BTEX concentration was predicted to be reduced to 10,200 µg/L. After 13 years of simulated source removal and weathering (2008), the simulated plume was reduced to approximately 40 percent of its original area, and the maximum simulated BTEX concentration in the plume was reduced to 3,100 µg/L. After 17 years of simulated source removal (2012), the simulated plume size was reduced to an even greater extent, and the maximum BTEX concentration decreased to 2,400 µg/L. The plume was predicted to completely attenuate by 2020.

Simulated BTEX plumes derived using model SR6 were presented for 2000, 2008, and 2012. After five years of simulated source removal (2000), the predicted plume configuration changed only slightly compared to the SR8 model results, but the maximum BTEX concentration was 5,300 µg/L. After 13 years of simulated source removal (2000) the plume was approximately 40 percent of its original size, and the maximum simulated BTEX concentration was 3,800 µg/L. Seventeen years after the simulated source removal was initiated (2012), the maximum BTEX concentration was predicted to be 3,100 µg/L. Similar to the results of Model SR8, the BTEX plume was completely attenuated by year 2020.

4.7.2 Historical Contaminant Trends Compared to Predicted Plume Behavior

BTEX analytical data for September 1997 and February 1999 provide evidence that the BTEX plume is shrinking and attenuating more quickly than predicted by the BIOPLUME II models. A summary of the model-predicted and actual site conditions is presented in Table 4.11, and total BTEX isopleth maps are included in Appendix A. Maximum BTEX concentrations detected at the site in 1997 and 1999 were 12,300 µg/L and 5,300 µg/L, respectively. BTEX concentrations at a downgradient monitoring well decreased from 89 µg/L in 1994 to below the analytical detection limit in 1999.

Model CAL was intentionally conservative and indicative of a worst-case scenario to determine the maximum plume extent and time required for the plume to stabilize. Models SR8 and SR6 were intended to provide conservative predictions of the effects of engineered source remediation as opposed to a natural attenuation scenario. Although very limited source-area dissolved BTEX data were collected in 1997 and 1999, the measured BTEX concentrations in groundwater suggest that the source is weathering at a rate similar to that simulated by Model SR6 (17 %/yr).

TABLE 4.11
SUMMARY OF PREDICTED VERSUS OBSERVED CONDITIONS FOR SITE SS27/XYZ
DOVER AFB, DELAWARE

	Condition at Model Calibration Date (1994)	Predicted Condition – CAL	Predicted Condition – SR8	Predicted Condition – SR6	Observed Condition
Plume Dynamics	Unknown	Expanding	Expanding	Expanding	Shrinking
Maximum BTEX Concentration in Source Area Well(s)	22,900 µg/L ^{a/}	1994: 21,900 µg/L 2012: 24,500	2000: 10,200 µg/L 2008: 3,100 µg/L 2012: 2,400 µg/L	2000: 5,300 µg/L 2008: 3,800 µg/L 2012: 3,100 µg/L	1997: 12,300 µg/L 1999: 5,300 µg/L
Maximum BTEX Concentration at Plume Toe Well(s)	89 µg/L	2000: 100 to 1,000 µg/L 2012: 100 to 1,000 µg/L	2000: 100 to 1,000 µg/L 2008: 10 to 100 µg/L 2012: 10 to 100 µg/L	2000: 100 to 1,000 µg/L 2008: 10 to 100 µg/L 2012: 10 to 100 µg/L	Not detected

^{a/} µg/L = micrograms per liter.

The data suggest that the conservatism of the models is not entirely due to the source reduction rate, but also may be attributable to use of a low reaeration rate. Each of the models predicted that the BTEX plume would expand at a similar rate for the first 5 years; however, site data indicate that the plume is shrinking. Although the first-order reaeration rate of $3.0\text{E-}3 \text{ day}^{-1}$ used in the model is similar to the maximum first-order decay rate calculated using site-specific data ($2.0\text{E-}3 \text{ day}^{-1}$ or half-life of 0.95 year), and to geometric mean first-order decay rates for the BTEX constituents derived from field studies of combined aerobic/anaerobic sites presented by Suarez and Rifai (1999) ($1.0\text{E-}3$ to $2.0\text{E-}3 \text{ day}^{-1}$), the monitoring data suggest that the rate is conservative.

As described in the EE/CA (Parsons ES, 1996a), additional reasons for the apparent conservatism of the models may include the following:

1. Aerobic respiration, denitrification, iron reduction, and sulfate reduction are all likely occurring at this site; however, only DO and nitrate are considered as electron acceptors during model simulations.
2. Redox potentials suggest that methanogenesis is probably occurring; however, analytical results for methane were not of sufficient quality to evaluate this degradation pathway.
3. The highest DO concentration observed at the site was 8.3 milligrams per liter (mg/L). The highest DO concentration assumed during model simulations was 5.0 mg/L. In addition, the highest observed nitrate concentration observed at the site was 18.4 mg/L (as nitrogen). The highest nitrate concentration assumed during model simulations was 5 mg/L.

SECTION 5

CHLORINATED SOLVENT SITES

Five chlorinated solvent and mixed solvent/fuel hydrocarbon sites were selected to evaluate the accuracy of natural attenuation predictions for chlorinated solvents (Table 2.2). Sites with both solvents and fuel hydrocarbons were included because fuel hydrocarbons provide an organic substrate (electron donor) for reductive dechlorination of chlorinated compounds. Therefore, the five sites represent both Type III (aerobic, oxidizing environments) and Type I (anaerobic, reducing environments) as described in USEPA (1998).

5.1 SITE 8 - F.E. WARREN AFB SITE LF-03

Landfill 3 (LF-03) encompasses approximately 7 acres near the southern boundary of F.E. Warren AFB, in Cheyenne, Wyoming. A MNA TS was completed for LF-03 in 1999 (Parsons ES, 1999f), with an addendum to the TS completed in 2001 (Parsons ES 2001b). Primary contaminants at the site include TCE and *cis*-1,2-DCE; a TCE plume is present in shallow groundwater that is approximately 2,000 feet in length. Isopleth maps for TCE in groundwater from 1993 to 2000 are included in Appendix A.

5.1.1 Model Setup and Predictions

5.1.1.1 Model Codes and Predictive Scenarios

MODFLOW and MT3D96 were used in the MNA TS (Parsons ES, 1999f) to evaluate three remedial alternatives for the dissolved TCE plume at the LF-03 site. Alternative 1 assumed the use of institutional controls (such as land-use restrictions) and LTM with no engineered remediation. Alternatives 2 and 3 included partial and total source removal (i.e., landfill excavation), respectively. Subsequent to the modeling effort, source removal activities were initiated in April 2000, and all landfilled material at LF-03 was removed by the end of June 2000.

5.1.1.2 Calculated and Model-Calibrated Biodegradation Rates

The method of Buscheck and Alcantar (1995) was used to estimate first-order biodegradation rate constants for TCE, *cis*-1,2-DCE, and total chlorinated ethenes in groundwater at LF-03. The flow path used to calculate first-order decay rates extends from the source area downgradient to the toe of the TCE plume, and is representative of the entire plume axis. The results of the attenuation rate calculations are summarized in Table 5.1.

TABLE 5.1
CALCULATED BIODEGRADATION RATES FOR SITE LF-03
F.E. WARREN AFB, WYOMING

Contaminant	Buscheck and Alcantar (1995)		Model-Calibrated Rate	
	First-Order (day ⁻¹) ^{a/}	Half-Life (years)	First-Order (day ⁻¹)	Half-Life (years)
TCE	5.14E-5	37.0	7.6E-5	25
<i>cis</i> -1-2-DCE	1.03E-4	18.5	NA ^{b/}	NA
Total Chlorinated Ethenes	6.96E-5	27.3	NA	NA

^{a/} day-1 = per day.

^{b/} NA = not applicable (i.e., only TCE was simulated).

An attempt was made to compute a lower-bound reductive dechlorination rate along the same flow path using the method of Moutoux *et al.* (1996). However, the corrected chlorinated solvent concentrations along the selected plume flow path increased in the downgradient direction, indicating that critical assumptions underlying the use of this method were violated (e.g., conservation of daughter products produced along the flow path). Therefore, the calculated reductive dehalogenation rate was not used.

The decay rate was varied during plume calibration, and was important in controlling plume length and concentration distributions. For simulation of TCE transport at the LF-03 site, it was not necessary to simulate a spatially variable decay rate to obtain acceptable calibration results. The calibrated rate used in the model to simulate the fate and transport of TCE is shown in Table 5.1. Because of the inability of the MT3D96 transport code to simulate complex biodegradation reactions, the rate obtained from the calibration process should be viewed as a spatial and temporal average over the calibration period.

5.1.1.3 Source Term Modeling and Assumptions

Rather than using various calculations to attempt to estimate TCE partitioning from NAPL into groundwater, the “black-box” source approach described in Section 3.3.1 was used for this application. At LF-03, TCE was assumed to enter groundwater dissolved in leachate over relatively large areas, through point sources related to spills or dumping, and through contact between groundwater and residual NAPL at or below the water table.

For predictive modeling (after 1999) for Alternative 1, it was assumed that the source would continue to weather (lose mass) due to processes such as volatilization, dissolution, and biodegradation, and that the mass of contaminants entering groundwater would continue to decline. It was found that a geometric weathering rate of 7.3 %/yr was most consistent with observed TCE concentrations given the source configuration obtained through calibration. Thus, the model assumed that source loading rates decreased geometrically by 7.3 %/yr (in practice, five-year loading periods were assigned with 7.3 %/yr reductions compounded to yield a 32% reduction every five years).

The geometric source reduction rate for the Alternative 2 simulation was 50 %/yr in 1999 and 2000, and then 7.3 %/yr thereafter as in Alternative 1. The source term for Alternative 3 was assumed to be zero as of 1999 to simulate total source removal.

5.1.1.4 Predicted Plume Behavior

All three model simulations predicted that the plume would expand between 1999 and 2009. Model simulations of remedial Alternatives 2 and 3 (Section 5.1.1.1) predicted that in the year 2009, maximum TCE concentrations in the source area would be less than 50 µg/L and less than 10 µg/L, respectively. The Alternative 3 (complete removal of the source area) simulation predicted that the plume would detach and move downgradient from the suspected source area within a 20-year time period. The results of the simulation for Alternative 2 indicated that the TCE plume would not detach from the source area within a 30-year period, and that concentrations in the source area in 2029 would range from 1 to 5 µg/L.

5.1.2 Comparison of Observed and Predicted Plume Behavior

Due to the short time span between the model simulations and the most recent sampling event, it is difficult to conclude whether the model is accurately predicting TCE plume behavior at the site. Table 5.2 presents both predicted and observed plume conditions. Groundwater model simulations were completed for the years 2009, 2019, and 2029. Model output for a 1-year simulation (year 2000) was not compiled, but there is no obvious discrepancy between the observed plume and the predicted trends. Future monitoring results should be compared with the Alternatives 2 and 3 simulation results for a better perspective on the accuracy of the model.

Concentrations of TCE detected in five source area wells in 1999 and 2000 were compared to evaluate the source reduction term used in the model simulations. TCE concentrations in the source area ranged from 23 µg/L to 93 µg/L and from 28 µg/L to 76 µg/L in 1999 and 2000, respectively (Appendix A). The concentrations detected in the source area were similar from 1999 to 2000. As was presented in Section 5.1.1, a 7.3 %/yr geometric weathering rate was used in the model. Because a significant mass of TCE had already migrated downgradient from the source area by the time the model was created, the source reduction simulated for Alternatives 2 and 3 had little near-term effect on the downgradient migration and persistence of the TCE plume.

Compared to the source weathering rate, the decay constant was a relatively significant parameter in the model calibration process. During the model calibration and sensitivity analysis processes, the decay constant was found to be important in controlling plume length and concentration distributions. Doubling the decay rate resulted in more rapid degradation of dissolved contaminants, producing a smaller plume with lower concentrations outside the source area. Uniformly halving the degradation rate resulted in a slightly larger plume with higher concentrations outside the source area.

Reported field scale half-lives for TCE listed in Wiedemeier, *et al.* (1999) range from 0.32 year to 3.8 years. The first-order decay rate for TCE used in the model, $7.6\text{E-}05\text{ day}^{-1}$ (half-life of 25 years) is low compared to this range of values.

TABLE 5.2
SUMMARY OF MODEL PREDICTIONS VERSUS OBSERVED CONDITIONS FOR SITE LF-03
F.E. WARREN AFB, WYOMING

	Conditions at Model Calibration Date (1999)	Predicted Condition - Alternative 1	Predicted Condition - Alternative 2	Predicted Condition – Alternative 3	Observed Condition
Plume Dynamics	Appears Stable	Expanding	Expanding	Expanding	Plume is statistically stable.
Maximum TCE Concentration at Source Area Wells	23 to 93 µg/L ^{a/}	2009: >10 and <100 µg/L 2019: >10 and <50 µg/L 2029: ~10 µg/L	2009: >10 and <50 µg/L 2019: >5 and <10 2029: <5 µg/L	2009 <5 µg/L 2019 and 2029: Not detected	June 2000: 28 to 76 µg/L
Maximum TCE Concentration at Plume Toe Well	TCE not detected in April 1999	2009: >1 and <5 µg/L 2019 and 2029: ~5 µg/L	2009: >1 and <5 µg/L 2019 and 2029: ~5 µg/L	2009: >1 and < 5 µg/L 2019 and 2029: ~5 µg/L	June 2000: 1.7 µg/L

^{a/} µg/L = micrograms per liter.

Plume stability was evaluated using AFCEE MAROS software. Specifically, the chlorinated solvent plume at LF-03 was evaluated for stability using Mann-Kendall and Linear Regression analyses of historical TCE and *cis*-1,2-DCE concentrations obtained from 1993 to 1999 at the site. The statistical analyses indicated that the chlorinated solvent plume at the LF-03 site is stable (Parsons ES, 2001b). The results of the MAROS evaluation contradict the plume behavior predicted in the MODFLOW simulations in that the simulations indicated that the plume will expand for at least the next 10 years.

The MAROS results suggest that the actual TCE attenuation rate may be higher than the rates calculated for the MNA TS and used in the model. Assuming that the results of the MAROS evaluation prove to be correct over a longer monitoring period and the plume does not expand, the first-order decay rate used in the model may be biased low, contributing to the conservatism of the model.

5.2 SITE 9 - HILL AFB OU5

Hill AFB is located in Ogden Utah, approximately 30 miles northwest of Salt Lake City. A TCE plume with a total length of approximately 5,000 feet has migrated off-Base beneath a mixed residential and commercial area; this plume has been designated as Operable Unit (OU) 5. Groundwater sampling for a RNA TS for OU5 was conducted in August 1996, and the TS was completed in December 1997 (Parsons ES, 1997d). A TCE isopleth map for August 1996 is included in Appendix A. Data collected by the Base from 1997 to Spring 2000 was used as the basis for comparison to model predictions.

5.2.1 Model Setup and Predictions

5.2.1.1 Model Codes and Predictive Scenarios

The model codes MODFLOW and MT3D96 were used to accomplish three primary objectives: 1) predict the future extent and concentrations of the dissolved contaminant plume by modeling the combined effects of advection, dispersion, sorption, and biodegradation; 2) assess the potential for downgradient receptors to be exposed to contaminants at concentrations above regulatory levels of concern; and 3) if applicable, provide technical support for the natural attenuation remedial option at post-modeling regulatory negotiations. Because interim remedial systems were being installed at the site during the natural attenuation evaluation, natural attenuation was not evaluated as a sole remedial alternative.

Three model scenarios were created for the TCE plume at OU5. Model OU5-A was created to simulate only natural attenuation and was used as a baseline for comparison for the other two simulations. Model OU5-B incorporated natural attenuation and the effects of existing and planned remediation systems including an existing air sparging trench and a planned groundwater extraction system in a plume hotspot. Model OU5-C incorporated the assumptions of simulation OU5-B plus the effects of an 800-foot-long groundwater extraction trench located between the plume hotspot and the downgradient toe of the plume.

5.2.1.2 Calculated and Model-Calibrated Biodegradation Rates

Two methods were used to calculate first-order biodegradation rates for CAHs in groundwater at OU5. Because TCE accounts for over 90 percent of the total CAH contaminant plume mass, the total CAH decay rates are substantially equivalent to TCE decay rates. Multiple decay rates were calculated using various flow paths and two portions of the plume separated by a storm water drain that locally influences contaminant concentrations (herein referred to as upgradient and downgradient areas along the plume axis) using the methods of Buscheck and Alcantar (1995) and Moutoux *et al.* (1996). Calculated decay rates ranged from $1\text{E-}7 \text{ day}^{-1}$ (half-life of 19,000 years calculated using the Moutoux method) to $5.3\text{E-}4 \text{ day}^{-1}$ (half-life of 3.6 years calculated using the Buscheck and Alcantar method). Geometric mean decay rates for the various paths are listed in Table 5.3.

TABLE 5.3
CALCULATED BIODEGRADATION RATES FOR OU5
HILL AFB, UTAH

Contaminant	Buscheck and Alcantar (1995)		Moutoux <i>et al.</i> (1996)		Model-Calibrated Rate	
	First-Order (day^{-1}) ^{a/}	Half-Life (years)	First-Order (day^{-1})	Half-Life (years)	First-Order (day^{-1})	Half-Life (years)
Total Chlorinated Ethenes – Upgradient ^{b/}	7.4E-5	26	1.3E-6	1,500	NA ^{c/}	NA
Total Chlorinated Ethenes – Downgradient ^{b/}	3.8E-4	5.0	-- ^{d/}	--	NA	NA
TCE	--	--	--	--	6.0E-6	317

^{a/} day^{-1} = per day.

^{b/} First-order rates presented are geometric means of rates calculated for various flow paths.

^{c/} NA = not applicable (i.e., only TCE was simulated).

^{d/} “--” = rate not calculated.

5.2.1.3 Source Term Modeling and Assumptions

The TCE source in the model was simulated using the “black box” approach (Section 3.3.1), with source loading simulated by recharge of TCE at specified concentrations. A linear source weathering rate of 3 %/yr was utilized for both the model calibration and predictive periods for model OU5-A. Model OU5-B simulated a 400-foot-long air sparging trench across the plume approximately 400 feet downgradient of the source, and a local groundwater extraction system in a downgradient plume hotspot. Model OU5-C was similar to OU5-B, with the addition of an 800-foot-long groundwater extraction trench located approximately 2,000 feet downgradient of the source area. Therefore, the source terms used in models OU5-B and OU5-C were the same as for OU5-A (3 %/yr), with the remedial systems capturing plume mass at selected model cell locations.

5.2.1.4 Predicted Plume Behavior

Simulations OU5-A, OU5-B, and OU5-C predicted that the TCE plume would continue to expand throughout the 100-year simulation period, primarily because a significant mass of dissolved TCE had migrated past the proposed downgradient remedial system locations. The models predicted that this mass would persist and migrate downgradient. Source area concentrations would gradually decrease due to the modeled source reduction rate of 3 %/yr.

Model OU5-B best simulates actual remedial activities at the site, because the 400-foot-long air sparging curtain simulated by this model was being installed during the 1996 TS (calibration) sampling event, and the startup of the sparge curtain was simulated to occur in 1997. From the model calibration year (1996) to 2002, the TCE plume simulated by OU5-B was predicted to expand by approximately 500 feet. This model predicted that the plume would migrate an additional 3 miles during the 100-year predictive simulation period, with maximum TCE concentrations of greater than 100 µg/L persisting throughout the 100 years. The simulated expansion and persistence of the plume was primarily a result of the low total organic carbon content of the aquifer matrix (i.e., minimal contaminant retardation) and a low biodegradation rate.

5.2.2 Comparison of Observed and Predicted Plume Behavior

The most recent available groundwater monitoring data for TCE at OU5 was collected in September 1999, approximately 3 years after the model calibration date. Table 5.4 presents predicted and observed TCE plume concentrations and trends. The TCE concentration detected in a plume toe well (MW169) in 1996 and 1999 was 35.8 µg/L and 40 µg/L, respectively, indicating relatively uniform TCE concentrations at the leading edge of the plume over time. However, TCE concentrations at monitoring wells further downgradient remained very low or below detection limits, suggesting that the plume is stable. Evaluation of the extent of the plume as far back as 1993 supports the observation that the leading edge of the plume has not migrated to a significant extent.

The TCE concentrations detected in a source area well in 1996 and 1999 were 259 µg/L and 1,300 µg/L, respectively. These values suggest that the source of TCE has not weathered significantly, and that the simulated source weathering rate of 3 %/yr is not overly conservative.

Subsequent to the MNA TS (Parsons ES, 1997d), the TCE plume was again modeled using MODFLOW/MT3DMS and a slightly different interpretation of the conceptual site model (higher distribution coefficient for sorption and higher hydraulic conductivity). In order to calibrate the revised model, the biodegradation rate was increased to 5.3E-4 (half-life of 3.6 years). This value is within the range of reported field-scale half-lives for TCE listed in Wiedemeier, *et al.* (1999) (0.32 year to 3.8 years). However, use of this biodegradation rate is not consistent with the aerobic groundwater environment and lack of biodegradation daughter products (DCE and VC) in OU5 groundwater.

The revised modeling effort and associated statistical analysis of plume stability concluded that the OU5 TCE plume stabilized 20 years after the initial contaminant release, estimated to have occurred in 1943. The results of the revised model agree well

TABLE 5.4
SUMMARY OF MODEL PREDICTED VERSUS OBSERVED CONDITIONS FOR OU5
HILL AFB, UTAH

	Condition at Model Calibration Date (August 1996)	Predicted Condition - Model OU5-A	Predicted Condition - Model OU5-B	Observed Condition (To September 1999)
Plume Dynamics	Unknown	Expanding	Expanding	Stable
Maximum TCE Concentration at Source Area Well	1996: 259 µg/L ^{a/}	2002: ~ 500 µg/L 2012: ~ 400 µg/L 2047: ~ 100 µg/L 2097: ~ 10 µg/L	2002: ~ 500µg/L 2012: ~ 400 µg/L 2047: ~ 100 µg/L 2097: ~ 10 µg/L	1997: 155 µg/L 1998: 2,170 µg/L 1999: 1,300 µg/L
Maximum TCE Concentration at Plume Toe Well	1996: 36 µg/L	2002: ~60 µg/L 2012: ~100 µg/L 2047: ~ 200 µg/L 2097: ~ 50 µg/L	2002: ~60 µg/L 2012: ~100 µg/L 2047: ~ 200 µg/L 2097: ~ 50 µg/L	1997: 54 µg/L 1998: 60 µg/L 1999: 40 µg/L

^{a/} µg/L = micrograms per liter.

with plume data obtained from 1993 to 1999. This agreement suggests that the decay rate used for the MNA TS modeling effort (Parsons ES, 1997d) was too conservative, and that the use of lower decay rates than those calculated using the method of Buscheck and Alcantar (1995) was not appropriate.

5.3 SITE 10 - TINKER AFB SITE FTA-2

Site FTA-2 is a former fire training area at Tinker AFB, located near Oklahoma City, Oklahoma. Primary contaminants at the site include TCE and DCE. Groundwater sampling for a RNA TS for groundwater at Site FTA-2 was conducted from July to August 1997, and the Final TS report was completed in December 1999 (Parsons ES, 1999g). Data collected by the USEPA and the Base from 1997 to October 1999 were used as the basis for comparison to modeling predictions. Concentrations of TCE in groundwater for August 1997 and April 1999 are shown in Appendix A.

5.3.1 Model Setup and Predictions

5.3.1.1 Model Codes and Predictive Scenarios

MODFLOW and MT3D96 were used to evaluate the fate and transport of TCE dissolved in groundwater at Site FTA-2. Three remedial alternatives were simulated for Site FTA-2. Alternative 1 assumed that no engineered remediation would occur at the site. Alternative 2 assumed that additional sources were present at the site and that source removal was completed. Alternative 3 assumes that groundwater extraction was implemented at the site. Engineered remediation has not occurred since the modeling was performed. Therefore, the Alternative 1 simulation is used for comparison of modeling predictions to LTM results.

5.3.1.2 Calculated and Model-Calibrated Biodegradation Rates

First-order decay rates were calculated using the methods of Buscheck and Alcantar (1995) and Moutoux *et al.* (1996). Calculated and model-calibrated first-order decay rates are presented in Table 5.5. The flow path used to calculate the first-order decay rates extended across the entire plume from the source area to the leading edge of contamination. Data available at the time of the modeling effort suggested that the CAH plume was expanding, and the first-order decay rates calculated using the method of Buscheck and Alcantar (1995) were considered to be an upper bound on the biodegradation rate. The first-order reductive dehalogenation rates calculated using the method of Moutoux *et al.* (1996) were considered to be lower bound decay rates. The results of the Moutoux *et al.* (1996) method for FTA-2 are in agreement with the conclusion that reductive dechlorination is confined to the immediate source area, and is negligible along the downgradient plume axis (Parsons ES, 1999g).

The calibrated model for TCE at FTA-2 utilized first-order decay rates for TCE that varied across the model domain. Use of different first-order rates for the various model layers was necessary to achieve an adequate calibration to the measured TCE plume. The higher rate shown in Table 5.5 was used in the immediate source area where conditions conducive to anaerobic reductive dehalogenation were observed. Outside of the source area, aerobic conditions dominate and lower decay rates were utilized. The reductive

dechlorination rate for total chlorinated ethenes computed using the Moutoux *et al.* (1996) approach was approximately three orders-of-magnitude lower than the corresponding rate calculated using the method of Buscheck and Alcantar (1995). This is likely a result of calculating a total reductive dechlorination rate over a long flowpath that traversed areas where reductive dehalogenation is not likely to occur, and the likely aerobic oxidation of DCE and VC (electron donors) probably predominates.

TABLE 5.5
CALCULATED BIODEGRADATION RATES FOR SITE FTA-2
TINKER AFB, OKLAHOMA

Contaminant	Buscheck and Alcantar (1995)		Moutoux <i>et al.</i> (1996)		Model-Calibrated Rate	
	First-Order (day ⁻¹) ^{a/}	Half-Life (years)	First-Order (day ⁻¹)	Half-Life (years)	First-Order (day ⁻¹)	Half-Life (years)
TCE	3.1E-4	6.20	-- ^{b/}	--	3.4E-4 to 3E-5	5.6 to 63
<i>cis</i> -1,2-DCE	4.1E-4	4.65	--	--	NA ^{c/}	NA
<i>Trans</i> -1,2-DCE	7.6E-4	2.51	--	--	NA	NA
Total Chlorinated Ethenes	3.0E-4	6.42	1.9E-7	10,210	NA	NA

^{a/} day⁻¹ = per day.

^{b/} "--" = rate not calculated.

^{c/} NA = not applicable (i.e., only TCE was simulated).

5.3.1.3 Source Term Modeling and Assumptions

The source term in the calibrated contaminant transport model was simulated using the "Black Box" approach (Section 3.3.1). TCE was assumed to enter groundwater through contact between groundwater and residual NAPL at or below the water table. Partitioning was simulated by specifying source concentrations in source-area cells. For predictive simulations, the source term (concentration) in the model was conservatively assumed to decrease geometrically by 2 %/yr due to the effects of dissolution, volatilization, and biodegradation.

5.3.1.4 Predicted Plume Behavior

Predictive modeling was completed for 35 years of simulation time. The simulation for Alternative 1 predicted that the TCE plume would expand by approximately 1,000 feet over 35 years, and that maximum TCE concentration to approximately 10,000 µg/L would persist in the source area. While some biodegradation was expected to occur, the simulated attenuation of the plume was not sufficient to stabilize the plume.

5.3.2 Comparison of Observed and Predicted Plume Behavior

Groundwater monitoring data for Site FTA-2 were collected from 1997 to Fall 1999. Table 5.6 summarizes predicted versus observed conditions for selected wells along the plume axis. Due to preferential flow paths, aquifer heterogeneity, and/or shifting groundwater flow directions, plume migration toward both the northwest and the west appears to have occurred. The monitoring data indicate that TCE concentrations in the downgradient portion of the plume are increasing, similar to model predictions. In addition, source area concentrations also appear to be increasing. However, there also is evidence that the plume may be shifting direction, with some upgradient portions of the plume evidencing a decreasing concentration trend. Overall, the model-predicted plume expansion appears to correlate with observed plume dynamics, although the data are not sufficient to indicate if the predicted rate of expansion is accurate.

5.4 SITE 11 - CAPE CANAVERAL AIR STATION SITE FT-17

Cape Canaveral Air Station (CCAS) is located on a barrier island on the east coast of Florida. Site FT-17 consists of a former fire training area and drum disposal trench located approximately 1,000 feet from the Banana River, on the western side of CCAS. Site contaminants are primarily chlorinated ethenes, including TCE, DCE, and VC. Site characterization and groundwater sampling to support a RNA TS was conducted in two stages (March 1994 and January 1996). The TS report was subsequently completed in May 1997 (Parsons ES, 1997b). Chlorinated ethenes in groundwater for January 1996 are shown in Appendix A. Since the RNA TS, surface soils in the source area have been remediated on-site by excavation and soil washing, and a horizontal air sparging system (HASS) has been installed.

5.4.1 Model Setup and Predictions

5.4.1.1 Model Codes and Predictive Scenarios

MODFLOW and MT3D96 were used during the TS (Parsons ES, 1997b) to evaluate the impact of two remedial scenarios on molar concentrations of total chlorinated ethenes at the FT-17 site. Simulation SR10 assumed that only natural source weathering would occur at the site with no engineered remediation. Simulation SR90 simulated the effects of source remediation via excavation and soil washing. Since the TS was completed, the simulated soil remediation has been completed.

The HASS was not simulated in the models. However, the location of the HASS is far enough downgradient of the source area to allow for comparison of observed and predicted chlorinated ethene concentration trends within the core of the plume. In addition, the predictive modeling results were described in the TS using concentration-versus-time graphs for locations representing the HASS to estimate future contaminant influent concentrations to the HASS.

TABLE 5.6
SUMMARY OF MODEL-PREDICTED VERSUS OBSERVED CONDITIONS FOR SITE FTA-2
TINKER AFB, OKLAHOMA

	Condition at Model Calibration Date (1997)	Predicted Condition - Alternative 1	Observed Condition (To October 1999)
Plume Dynamics	Expanding	Expanding	Expanding
Maximum TCE Concentration at Source Area	1997: 5,900 µg/L ^{a/}	2032: 10,500 µg/L	November 1998: 6,000 µg/L October 1999: 6,900 µg/L
Maximum TCE Concentration along Upgradient Plume Axis	1997: 344 µg/L	2032: >100 and < 500 µg/L	September 1998: 230 µg/L September 1999: 140 µg/L
Maximum TCE Concentration along Downgradient Plume Axis	1997: 28.1 µg/L	2032: >100 and < 500 µg/L	November 1998: 360 µg/L October 1999: 630 µg/L
Maximum TCE Concentration at Plume Toe	1997: < 1 µg/L	2032: ~ 100 µg/L	November 1998: 2.4 µg/L October 1999: 1.9 µg/L

^{a/} µg/L = micrograms per liter.

5.4.1.2 Calculated and Model-Calibrated Biodegradation Rates

The methods of Buscheck and Alcantar (1995) and Moutoux *et al.* (1996) were used to estimate first-order biodegradation rate constants for CAHs at Site FT-17. The flow path used to calculate the first-order decay rates extends from the source area to the leading edge of the CAH plume and is representative of the entire plume axis. The results of the biodegradation rate calculations are summarized in Table 5.7.

5.4.1.3 Source Term Modeling and Assumptions

The source of total chlorinated ethenes was simulated in the model using the “black box” approach (Section 3.3.1), with source loading simulated by recharge of total chlorinated ethenes at specified molar concentrations. A geometric source weathering rate ranging from 6 %/yr to 10 %/yr was utilized for the model calibration period after fire training operations ceased, to account for the effects of natural weathering processes (i.e., volatilization, dissolution, and biodegradation). The variation in the source reduction rate was derived using a trial-and-error approach that provided a “best fit” for model calibration.

TABLE 5.7
CALCULATED BIODEGRADATION RATES FOR SITE FT-17
CCAS, FLORIDA

Contaminant	Buscheck and Alcantar (1995)		Moutoux <i>et al.</i> (1996)		Model-Calibrated Rate	
	First-Order (day ⁻¹) ^{a/}	Half-Life (years)	First-Order (day ⁻¹)	Half-Life (years)	First-Order (day ⁻¹)	Half-Life (years)
TCE	5.0E-4	3.8	-- ^{b/}	--	NA ^{c/}	NA
DCE	5.0E-4	3.8	--	--	NA	NA
Total Chlorinated Ethenes	3.0E-4	6.3	7.0E-5	27	9.0E-4	2.1

^{a/} day⁻¹ = per day.

^{b/} “--” = rate not calculated.

^{c/} NA = not applicable (i.e., only total chlorinated ethenes was simulated).

For model SR10, a geometric weathering rate of 10 %/yr was used throughout the predictive modeling period. To simulate the effects of soil remediation in model SR90, the source was reduced by 90 percent in 1998, followed by a geometric weathering rate of 10 %/yr for the remaining source mass. Simulation SR90 provides the best scenario for comparison to monitoring data.

5.4.1.4 Predicted Plume Behavior

Model predictions were described using concentration-versus-time graphs of maximum predicted molar concentrations of total chlorinated ethenes at the simulated location of the HASS. Simulation SR10 (natural attenuation alone) predicted that total chlorinated ethene concentrations along the plume axis at the location of the HASS

would gradually decrease to approximately 0.8 micromoles per liter ($\mu\text{mol/L}$), equivalent to approximately 105 $\mu\text{g/L}$ of TCE or 50 $\mu\text{g/L}$ of VC, within 46 years (2043).

Simulation SR90 predicted that total chlorinated ethenes along the plume axis at the location of the HASS would decrease from approximately 130 $\mu\text{mol/L}$ to approximately 50 $\mu\text{mol/L}$ in 9 years (2005), to 0.8 $\mu\text{mol/L}$ in 26 years (2023), and to 0.4 $\mu\text{mol/L}$ in 32 years (2029). Simulation SR90 also predicted that maximum total chlorinated ethene concentrations in the source area would decrease from over 500 $\mu\text{mol/L}$ to approximately 50 $\mu\text{mol/L}$ in 20 years (2016), and to 0.4 $\mu\text{mol/L}$ in approximately 60 years (2057).

5.4.2 Comparison of Observed and Predicted Plume Behavior

Groundwater samples were collected by the Base just upgradient of the HASS using direct-push technology in April 1999. A summary of model-predicted and observe plume conditions is contained in Table 5.8. The maximum detected concentration of total chlorinated ethenes was 10,800 $\mu\text{g/L}$, equivalent to a total molar concentration of 159 $\mu\text{mol/L}$. The total chlorinated ethenes concentration at a well just upgradient of the HASS decreased from 6.0 $\mu\text{mol/L}$ in 1996 to 1.25 $\mu\text{mol/L}$ in April 2000, likely due to the influence of the HASS.

Total chlorinated ethene concentrations at a well located further upgradient, outside the influence of the HASS, decreased from over 1,000 $\mu\text{mol/L}$ in July 1993 and March 1994 to 489 $\mu\text{mol/L}$ in August 1999, and to less than 1 $\mu\text{mol/L}$ in February 2000. While the effects of a state-wide drought over the past several years have not been accounted for, it appears that there is evidence of substantial reductions in total chlorinated ethene concentrations at this well location. However, the total chlorinated ethene concentration of 159 $\mu\text{mol/L}$ obtained just upgradient of the HASS during direct push sampling in April 1999 is greater than concentrations detected at nearby locations during the RNA TS, and concentrations used for model calibration. Therefore, the elevated concentration detected in 1999 may not be suitable for direct comparison of simulated to observed contaminant plumes.

At the source area, the maximum total chlorinated ethene concentration measured during direct-push testing in April 2000 was 429 $\mu\text{mol/L}$. Total chlorinated ethene concentrations at a well pair located near the source area decreased over time. At the shallow well of the pair, total chlorinated ethene concentrations decreased from over 500 $\mu\text{mol/L}$ (detected from March 1994 to January 1996), to less than 1.1 $\mu\text{mol/L}$ (detected from November 1998 to February 2000). For the intermediate-depth well, concentrations decreased from 8.2 $\mu\text{mol/L}$ in August 1999 to 6.0 $\mu\text{mol/L}$ in February 2000. These data suggest that chlorinated ethene concentrations in source area groundwater are decreasing at a significant rate due to the soil remediation.

In summary, available data suggest that total chlorinated ethene concentrations are decreasing and that the plume is attenuating, in general agreement with the simulation results for Model SR90. The decrease in source-area concentrations as a result of the soil remediation is readily apparent. Therefore, the model-simulated decrease in the contaminant source term appears to be appropriate. Although the chlorinated ethene concentrations at selected wells along the plume axis also appear to be rapidly declining, the detection of elevated concentrations at direct-push sampling locations indicates that elevated concentrations persist, at least in localized areas.

TABLE 5.8
SUMMARY OF MODEL-PREDICTED VERSUS OBSERVED CONDITIONS FOR SITE FT-17
CCAFS, FLORIDA

	Condition at Model Calibration Date (January 1996)	Predicted Condition - Model SR10	Predicted Condition - Model SR90	Observed Condition (February/April 2000)
Plume Dynamics	Slowly Expanding	Stable, Slowly Attenuating	Stable, Attenuating	Stable, Attenuating
Maximum Total Molar Chlorinated Ethene Concentration at Source Area Wells	1,637 µmol/L ^{a/}	2066: ~ 0.8 µmol/L	2016: ~ 50 µmol/L	February/April 2000: 0.15 µmol/L (well sample) 429 µmol/L (direct-push grab sample)
Maximum Total Molar Chlorinated Ethene Concentration at Downgradient Wells (upgradient of HASS)	4.3 µmol/L to 88 µmol/L	2043: < 1 µmol/L	2005: ~ 50 µmol/L 2023: < 1 µmol/L	February/April 2000: 0.02 µmol/L (well sample) 159 µmol/L (direct-push grab sample)

^{a/} µmol/L = micromoles per liter.

The model-calibrated total chlorinated ethene biodegradation rate ($9\text{E-}4 \text{ day}^{-1}$, half-life of 2.1 years) is within the range of reported field-scale half-lives for TCE listed in Wiedemeier, *et al.* (1999) (0.32 years to 3.8 years). The presence of substantial concentrations of the TCE biodegradation daughter products *cis*-1,2-DCE and VC, and the presence of a reducing groundwater environment at the site, support the significant occurrence of reductive dechlorination in site groundwater. However, the biodegradation rate may diminish over time as concentrations of electron donors (primarily BTEX) necessary to sustain reductive dechlorination are depleted by the soil remediation and natural biodegradation.

5.5 SITE 12 - COLUMBUS AFB SITE LF-06

Columbus AFB is located in northeastern Mississippi, approximately 10 miles north of the city of Columbus. A TS in support of RNA at Site LF-06 was completed in 1996 (Parsons ES, 1997c) using data from a groundwater sampling event conducted in November 1996. Groundwater monitoring data provided by the Base for July 2000 is used as the basis for comparison of model-predicted and observed plume conditions.

5.5.1 Model Setup and Predictions

5.5.1.1 Model Codes and Predictive Scenarios

The fate and transport of four compounds were modeled using the analytical solution of van Genuchten and Alves (1982) to help estimate degradation rates and predict the future migration of these compounds. The compounds modeled included benzene, chlorobenzene, TCE and VC. Based on monitoring data for the past five years, only concentrations of TCE and VC remain above regulatory guidelines. VC and DCE isopleth maps for November 1996 are included in Appendix A.

5.5.1.2 Calculated and Model-Calibrated Biodegradation Rates

The method of Buscheck and Alcantar (1995) was used to calculate first-order decay rates for the modeled compounds (Table 5.9). The calculated decay rate for total chlorinated ethenes was used as an estimate for both TCE and VC decay rates. The calculated half-life (0.54 year) is within the range of reported field-scale half-lives (0.32 year to 3.8 years) for TCE listed by Wiedemeier, *et al.* (1999). Model calibration and sensitivity analyses indicated the calculated decay rates were adequate for use in predictive simulations.

TABLE 5.9
CALCULATED BIODEGRADATION RATES FOR SITE LF-06
COLUMBUS AFB, MISSISSIPPI

Contaminant	Buscheck and Alcantar (1995)		Model-Calibrated Rate	
	First-Order (day^{-1}) ^{a/}	Half-Life (years)	First-Order (day^{-1})	Half-Life (years)
Total Chlorinated Ethenes	3.5E-3	0.54	NA ^{b/}	NA
TCE	-- ^{c/}	--	3.5E-3	0.54
VC	--	--	3.5E-3	0.54

^{a/} day^{-1} = per day.

^{b/} NA = not applicable (i.e., only TCE and VC were simulated).

^{c/} "--" = rate not calculated.

5.5.1.3 Source Term Modeling and Assumptions

Because of the lack of temporal and spatial site monitoring data, the source area concentrations were conservatively assumed to remain constant over time. The highest dissolved concentrations from the November 1996 sampling event were used as the source input term in the models to project future downgradient concentrations. For TCE and VC, the source area concentrations were 7.6 µg/L and 10 µg/L, respectively.

5.5.1.4 Predicted Plume Behavior

Because source decay was not included in any of the model simulations, the objective of each simulation was to determine the maximum downgradient extent of contaminant migration given a constant source. Model-TCE predicted the downgradient extent of the steady-state TCE plume, TCE concentrations in excess of State of Mississippi groundwater standard of 5 µg/L were predicted to extend for approximately 165 feet downgradient from the point source. Similarly, Model-VC predicted that VC concentrations exceeding the State groundwater standard of 2 µg/L would extend approximately 1,000 feet downgradient of the point source under steady-state conditions.

5.5.2 Comparison of Observed and Predicted Plume Behavior

Groundwater monitoring data for Site LF-06 were collected from 1997 to July 2000. Table 5.10 summarizes predicted versus observed concentrations for selected wells simulated as point sources or located along the plume axis. Available data indicate that TCE and VC concentrations are stable or decreasing at most locations, with the exception of a slight increase in the VC concentration at one well location. The apparent stability of contaminant concentrations indicates that the calculated first-order decay rates are conservative, but reasonably accurate. The model appears to have adequately simulated maximum plume expansion, and the relatively low contaminant concentrations combined with the calculated decay rate suggests that the plume will either be stable or receding in the future.

TABLE 5.10
SUMMARY OF MODEL-PREDICTED VERSUS OBSERVED CONDITIONS
FOR SITE LF-06
COLUMBUS AFB, MISSISSIPPI

	Present Condition at Model Calibration Date (1996)	Predicted Condition - Steady-State Model Simulation	Observed Condition
Plume Dynamics	Steady-State	Steady-State	Stable to Receding
TCE Concentration in Source Area Well	7.4 µg/L ^{a/}	7.4 µg/L	July 2000: 1.61 µg/L
TCE Plume Extent at 5 µg/L	~ 150 feet	165 feet	July 2000: 0 feet
VC Concentration in Source Area Wells	4.9 µg/L to 10 µg/L	10 µg/L	July 2000: 7.84 µg/L to 8.17 µg/L
VC Plume Extent at 2 µg/L	~ 1,000 feet	1,500 feet	July 2000: ~ 1,000 feet

^{a/} µg/L = micrograms per liter.

SECTION 6

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 FUEL CONTAMINATED SITES

6.1.1 Summary and Conclusions

Most of the models described in Section 4 tended to overestimate plume migration distance, source persistence, and/or the time required for the BTEX or benzene plumes to attenuate to below MCLs. The conservatism of these models may be attributable to underestimation of natural source weathering rates, overestimation of the mass of contaminant present in the source area, and/or use of overly conservative first-order solute decay rates. Although more difficult to evaluate than source weathering rates, first-order biodegradation rates used in the models were sometimes conservative compared to average literature values and observed dissolved BTEX plume attenuation rates. Table 6.1 presents a comparative summary of model input parameters and observed site conditions for fuel contaminated sites.

Several of the models were intentionally constructed to be conservative [e.g., Hill AFB (Hill-A), King Salmon Airport (NaknekA), Elmendorf AFB (ST41A)] in order to provide evidence that, even under a worst-case scenario, the plume would not impact potential receptors. Use of worst-case models may be beneficial for some sites, but sufficient data regarding source weathering rates and the fate and transport of dissolved BTEX plumes are becoming available to enable more realistic simulations in many cases.

Four of the 16 models evaluated appear to have simulated observed conditions reasonably accurately; these models include King Salmon NaknekB, Elmendorf ST41D, Myrtle Beach MB2, and Hill-A (Table 6.1). The NaknekB and ST41D models used source weathering rates of 10 %/yr (linear) and 8 %/yr (geometric), respectively. The Elmendorf ST41D model used a first-order decay rate of $5.0\text{E-}3 \text{ day}^{-1}$ (half-life of 0.40 year) combined with a reaeration coefficient of $2.0\text{E-}3 \text{ day}^{-1}$. Model NaknekB used only a reaeration coefficient of $1.0\text{E-}3 \text{ day}^{-1}$ to model solute decay. Both the NaknekB and ST41D models were intended to simulate natural source weathering without engineered remediation.

Simulation results for Myrtle Beach model MB2 also predicted site conditions with a reasonable degree of accuracy, despite the fact that this model was intended to predict remediation of the site via bioslurping. The MB2 model used geometric source weathering rates of 5 %/yr to 27 %/yr (average 13 %/yr) for the first 5 years of simulation (1995 to 2000), and a first-order decay rate of $2.1\text{E-}3 \text{ day}^{-1}$ (half-life of 0.90 year). The Hill-A model assumed a constant source over time, which was reasonably realistic because additional fuel releases occurred at Site 870 subsequent to the modeling event.

TABLE 6.1
SUMMARY OF FUEL HYDROCARBON MODELING RESULTS

Site Identification	Site History	Contaminant ^{a/}	Model Code	Model Name	Modeling Scenario/ Assumptions	Source-Reduction Rate (%/yr) ^{b/}	Simulated Anaerobic Decay Rate (day ⁻¹) ^{c/}	Anaerobic Decay Rate Half-Life (years)	Simulated Reaeration Rate (day ⁻¹)	Model Characterization Based on Comparsion to Actual Site Data
Travis AFB, CA North and South Gas Stations	No Engineered Remediation	BTEX	BIOPLUME II	TRV1	Natural Source Weathering	2.3 to 4.9 (g)	4.9E-4	3.9	0	Overly Conservative
				TRV2	Bioslurping	100% in 3 years	4.9E-4	3.9	0	Overly Conservative
Myrtle Beach AFB, SC POL Yard	No Engineered Remediation	BTEX	BIOPLUME II	MB1	Natural Source Weathering	1.0 (g)	2.1E-3	0.90	0	Overly Conservative
				MB2	Engineered Remediation	12 to 37 (l)	2.1E-3	0.90	0	Good
Hill AFB, UT Site 870	Bioventing/ Passive LNAPL Recovery/ Additional Fuel Releases	BTEX	BIOPLUME II	Hill-A	No Source Weathering	0	Instantaneous Reaction for Oxygen and Nitrogen	NA	3.0E-3	Good
				Hill-B	Engineered Source Reduction	5 (g)	Instantaneous Reaction for Oxygen and Nitrogen	NA	3.0E-3	Overly Optimistic
				Hill-C	Engineered Source Reduction	15 (g)	Instantaneous Reaction for Oxygen and Nitrogen	NA	3.0E-3	Overly Optimistic
Elmendorf AFB, AK Site ST-41	Groundwater Extraction System (shut down)/ Natural Attenuation	BTEX	BIOPLUME II	ST41A	No Source Weathering or Engineered Remediation	0	5E-3	0.40	2.0E-3	Overly Conservative
				ST41D	Natural Source Weathering	8 (g)	5E-3	0.40	2.0E-3	Good, although source area concentrations are under-estimated

TABLE 6.1 (Continued)
SUMMARY OF FUEL HYDROCARBON MODELING RESULTS

Site Identification	Site History	Contaminant ^{a/}	Model Code	Model Name	Modeling Scenario/ Assumptions	Source-Reduction Rate (%/yr) ^{b/}	Simulated Anaerobic Decay Rate (day ⁻¹) ^{c/}	Anaerobic Decay Rate Half-Life (years)	Simulated Reaeration Rate (day ⁻¹)	Model Characterization Based on Comparsion to Actual Site Data
King Salmon Airport, AK Upper Naknek Site	No Engineered Remediation	BTEX	BIOPLUME II	Naknek A	No Source Weathering	0	None	None	1.0E-3	Overly Conservative
				Naknek B	Mobile LNAPL Recovery, Natural Weathering, and Bioventing	10 (l)	None	None	1.0E-3	Good
Langely AFB, VA Site SS-04	No Engineered Remediation	Benzene	BIOSCREEN	Natural Attenuation	Natural Attenuation	3.5 (g)	Instantaneous Reaction	NA	NA	Overly Conservative
				Biosparging	Biosparging	50 % for 2 years, then 3.5 %/yr (g)	Instantaneous Reaction	NA	NA	Overly Conservative
Dover AFB, DE Site SS27/XYZ	Bioslurping Pilot Test/ Product Skimming/ LNAPL Persists at Site	BTEX	BIOPLUME II	CAL	No Source Reduction	0	Instantaneous Reaction for Oxygen and Nitrogen	NA	3.0E-3	Overly Conservative
				SR8	Natural Weathering, Bioslurping and Bioventing	12.5 (l)	Instantaneous Reaction for Oxygen and Nitrogen	NA	3.0E-3	Overly Conservative
				SR6	Natural Weathering, Soil Vapor Extraction, LNAPL Recovery, Biosparging	17 (l)	Instantaneous Reaction for Oxygen and Nitrogen	NA	3.0E-3	Overly Conservative

^{a/} BTEX = benzene, toluene, ethylbenzene, and xylenes.
^{b/} %/yr = percent per year; (g) indicates a geometric reduction rate, (l) indicates a linear reduction rate.
^{c/} day⁻¹ = per day.

The fact that the simulated BTEX plume magnitude and extent predicted by this model are similar to observed conditions suggests that the first-order reaeration rate used by the model ($3.0\text{E-}3 \text{ day}^{-1}$) is reasonably accurate.

In cases where sufficient data were available, an attempt was made to estimate actual source weathering rates by assuming that these rates are directly proportional to reductions in dissolved BTEX concentrations in source area wells. The calculated geometric rates for four sites ranged from 9 %/yr to 60 %/yr and averaged 24 %/yr. If the 60 %/yr rate (Travis AFB) is ignored, the average geometric source weathering rate is 17 %/yr.

In summary, models that predicted future plume conditions with a reasonable degree of accuracy employed geometric source weathering rates and first-order decay rates ranging from 5 to 27 %/yr and $1.0\text{E-}3$ to $7.0\text{E-}3 \text{ day}^{-1}$ (half-lives of 1.9 to 0.27 years), respectively. The highest decay rate was a lumped parameter that included an anaerobic decay rate of $5.0\text{E-}3 \text{ day}^{-1}$ (half-life of 0.40 year) and a reaeration rate of $2\text{E-}3 \text{ day}^{-1}$. The range of source weathering rates used in the more “successful” models encompasses both average first-order weathering rates for BTEX in JP-4 derived during a LNAPL weathering study (Parsons ES, 1999a) (11 %/yr to 23 %/yr) and the average rate estimated using site-specific dissolved BTEX data (24 %/yr). The decay rates used in the more “successful” models are the same order-of-magnitude as geometric mean first-order decay rates for BTEX constituents derived from field studies of combined aerobic/anaerobic sites and presented by Suarez and Rifai (1999) ($1.0\text{E-}3$ to $2.0\text{E-}3 \text{ day}^{-1}$).

Examples of models that proved to be overly conservative included those constructed for Dover AFB (SR8 and SR6) and Travis AFB (TRV2). In these cases, natural attenuation processes resulted in greater reductions in plume size and concentrations than were predicted by simulations of engineered remediation.

In summary, models that under-predicted the effects of natural attenuation employed widely-variable source weathering rates that ranged from 0 %/yr (constant source) at Elmendorf AFB to complete source removal over a 3-year period at Travis AFB. Five of the nine overly-conservative models used source reduction rates that were less than or equal to 4.9 %/yr. One of the remaining four conservative models used a geometric 50 %/yr reduction over a 2-year period, followed by an annual geometric rate of 3.5 %/yr. Natural source-reduction rates derived using the OILLENS module of the HSSM (USEPA, 1994) did not exceed 4.9 %/yr, suggesting that rates obtained from this model may be conservative and should be used with caution.

First-order decay rates used in the four of the nine overly-conservative models ranged from $4.9\text{E-}4$ to $5\text{E-}3 \text{ day}^{-1}$ (half-lives of 3.9 to 0.40 years). The remaining five models used an instantaneous reaction approach to simulate contaminant decay; three of these five models coupled instantaneous decay with a reaeration rate of $3.0\text{E-}3 \text{ day}^{-1}$.

6.1.2 Recommendations

The accuracy of contaminant fate and transport model input parameters should be discussed so that the limitations of the model are understood. For example, uncertainty regarding source weathering rates often was concluded to be a potentially significant

source of error in the model; however, source weathering was often only represented by one rate per scenario for each site. A more realistic and defensible approach in cases where site-specific weathering rate data are not available would be to present predictive results from the use of a range of potentially realistic source reduction rates, such as those presented in Parsons ES (1999a).

The results of the modeling effort for Elmendorf ST41 demonstrate the importance of documenting inconsistencies between calibrated and observed plume conditions. If the calibrated plume does not match observed site conditions, predictions derived from use of that model will likely be erroneous.

The results of this comparative study indicate that first-order decay rates for dissolved BTEX that are less than $1\text{E-}3 \text{ day}^{-1}$ should be used with caution for predictive modeling purposes. In many, if not most, cases available data suggest that use of dissolved BTEX decay rates equal to or greater than $1\text{E-}1 \text{ day}^{-1}$ will result in more accurate fate and transport predictions. The occurrence of decay rates less than this value is certainly feasible; however, in the absence of site-specific data that justify use of lower rates, use of higher rates may be more accurate.

Similarly, unless construction of a conservative model is intended, use of geometric source weathering rates that are less than 5 %/yr should be justified based on site-specific data. Data presented in this report suggest that rates of 8 %/yr to 27 %/yr are realistic for most sites.

6.2 CHLORINATED SOLVENT SITES

6.2.1 Biodegradation Decay Rates

First-order decay rates for the five chlorinated solvent sites discussed in this report are summarized in Table 6.2. TCE decay rates derived using the method of Buscheck and Alcantar (1995) ranged from $5.1\text{E-}5 \text{ day}^{-1}$ (half-life of 37 years) to $5.0\text{E-}4 \text{ day}^{-1}$ (half-life of 3.8 years). Total chlorinated ethene decay rates ranged from $1.9\text{E-}7 \text{ day}^{-1}$ (half-life of 10,210 years) calculated using the method of Moutoux *et al.* (1996) to $3.5\text{E-}3 \text{ day}^{-1}$ (half-life of 0.54 year) calculated using the method of Buscheck and Alcantar (1995). In many instances, use of the method of Moutoux *et al.* (1996) yielded a negative decay rate that was invalid. Half-lives calculated using the method of Buscheck and Alcantar (1995) are typically higher than the range of reported field-scale half-lives for TCE (0.32 years to 3.8 years) listed by Wiedemeier, *et al.* (1999).

Model-calibrated rates at four of the five sites (F.E. Warren AFB Site LF-03, Tinker AFB Site FTA-2, CCAFS Site FT-17, and Columbus AFB Site LF06) were equal to or slightly less than rates calculated using the method of Buscheck and Alcantar (1995). Chlorinated solvent plumes at three of these four sites appear to be either at or near steady-state, satisfying the Buscheck and Alcantar (1995) assumption of a steady-state plume.

The model constructed for Hill AFB OU5 used a decay rate for TCE ($6\text{E-}6 \text{ day}^{-1}$) that was intermediate between those calculated using the methods of Buscheck and Alcantar (1995) and Moutoux *et al.* (1996). This model appears to be overly conservative, and

TABLE 6.2
SUMMARY OF CHLORINATED SOLVENT MODELING RESULTS

Site Identification	Contaminant ^{a/}	Buscheck & Alcantar (1995) Decay Rate (day ⁻¹) ^{b/}	Buscheck & Alcantar (1995) Half-Life (years)	Moutoux, et al. (1996) Decay Rate (day ⁻¹)	Moutoux, et al. (1996) Half-Life (years)	Model Calibration Decay Rate (day ⁻¹)	Model Calibration Half-Life (years)	Modeled Source Term Reduction Rate (%/yr) ^{c/}	Modeled-Predicted Plume Dynamics	Observed Plume Dynamics	Model Simulation Accuracy	Comments
F.E. Warren AFB, WY Site LF-03	TCE cis-1,2-DCE Total Chlorinated Ethenes	5.1E-5 1.0E-4 7.0E-5	37 19 27	NA ^{d/} NA NA	NA NA NA	7.6E-5 NA NA	25 NA NA	7.3 (g)	Expanding for 10 years, then Stable	Stable	Overly Conservative	Decay rate likely conservative
Hill AFB, UT OU5	TCE	7.4E-5 to 3.8E-4	26 to 5.0	1.3E-6	1,500	6E-6	317	3 (l)	Expanding	Stable Extent, Variable Source Area Concentrations	Overly Conservative	Recalibrated rate of 5.3E-4 day ⁻¹
Tinker AFB, OK Site FPTA-2	TCE cis-1,2-DCE Total Chlorinated Ethenes	3.1E-4 4.1E-4 3.0E-4	6.2 4.7 6.4	NA NA 1.9E-7	NA NA 10,210	3.0E-5 to 3.4E-4 NA NA	5.6 to 63 NA NA	2 (g)	Expanding	Expanding	Good	Source reduction rate likely conservative
CCAS, FL Site FT-17	Total Chlorinated Ethenes TCE DCE	3E-4 5E-4 5E-4	6.3 3.8 3.8	7E-5 NA NA	27 NA NA	9E-4 NA NA	2.1 NA NA	6 to 10 (g)	Stable to Receding Due to Source Removal	Stable to Receding	Good	
Columbus AFB, MO Site LF-06	TCE VC Total Chlorinated Ethenes	NA NA 3.5E-3	NA NA 0.54	NA NA NA	NA NA NA	3.5E-3 3.5E-3 NA	0.54 0.54 NA	Constant Source	Stable	Stable to Receding	Overly Conservative	Model used to determine maximum plume extent

^{a/} TCE = trichloroethene, DCE = dichloroethene, VC = vinyl chloride.
^{b/} day⁻¹ = per day.
^{c/} %/yr = percent per year; (g) indicates a geometric reduction rate, (l) indicates a linear reduction rate.
^{d/} NA = not applicable.

more recent modeling efforts have used a revised TCE decay rate of $5.3\text{E-}4$ (half-life of 3.6 years).

It is apparent that the decay rates calculated using the method of Moutoux, *et al.* (1996) are too low in many cases. It is therefore recommended that rates calculated using the method of Buscheck and Alcantar (1995) be used as a first approximation for modeling purposes, even if the stability of the plume can not be verified. Use of rates derived using the method of Moutoux, *et al.* (1996) should be limited to CAH plumes or flow paths where strict anaerobic conditions exist and there are significant concentrations of VC and ethene to indicate that CAH mass is being conserved. Loss of DCE and VC due to oxidation reactions is likely a primary source of error in applying this method.

6.2.2 Source-Term Reduction

Estimated source-reduction rates for the five chlorinated solvent sites varied from 2 %/yr to 10 %/yr (both geometric rates). No documented studies or actual measurements of natural CAH source weathering rates were available for use as the basis for these estimates. Although models are available to account for equilibrium partitioning or dissolution of contaminants from pure-phase NAPL or adsorbed to soil particles, the influence of other factors such as volatilization and biodegradation is more difficult to quantify.

Due to the absence of source weathering rate information, rates that were believed to be conservative were often selected for use in the models. The apparent conservatism of several of the models described in Section 5 suggest that these rates were overly conservative.

Geometric source reduction rates of 6 %/yr to 10 %/yr yielded acceptable model calibrations and predictions for F.E. Warren AFB Site LF03 and CCAS Site FT-17, suggesting that this range of natural weathering rates is an appropriate first approximation for chlorinated ethenes.

6.2.3 Use of Natural Attenuation Model Predictions for CAHs

The accuracy of numerical or analytical model predictions of natural attenuation of CAHs in groundwater is often limited by:

- Inadequate site characterization in terms of hydrogeology (e.g., hydraulic conductivity or preferential flowpaths) and contaminant transport (e.g., total organic carbon/retardation factors or dispersivity).
- Decay rates that may be substantially variable across the contaminant plume.
- Lack of adequate source characterization, both in terms of source history and location, contaminant mass, and natural or engineered reduction rates.

Models are often intentionally designed to be conservative in order to support decisions regarding whether to implement MNA or proceed with engineered remediation. Models for three sites (F.E. Warren AFB Site LF-03, Hill AFB Site OU5, and Tinker AFB Site FTA-2) predicted plume expansion for at least a 10-year period. With the

exception of Tinker AFB Site FTA-2, monitoring data for these sites indicate stable plumes (i.e., the model simulations were overly conservative). Plumes at four of the five sites are currently thought to be stable or receding, including two sites where source removal actions were performed. The ability of natural attenuation processes to stabilize chlorinated solvent plumes is not as generally accepted as for fuel hydrocarbon plumes.

As more information regarding the evolution and attenuation of chlorinated solvent plumes is obtained over time, the level of confidence associated with key fate and transport model input parameters such as decay rates and source weathering rates will increase. The necessity for using significantly conservative modeling assumptions due to a lack of information regarding realistic values for these parameters will diminish. Continued monitoring of chlorinated solvent sites may provide an empirical basis for application of MNA as opposed to engineered remediation.

SECTION 7

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APPENDIX A

HISTORICAL CONTAMINANT PLUME MAPS AND MODEL PREDICTIONS

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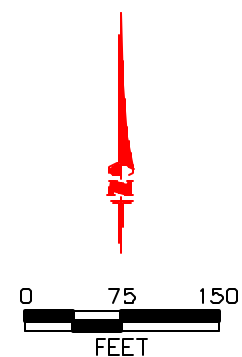
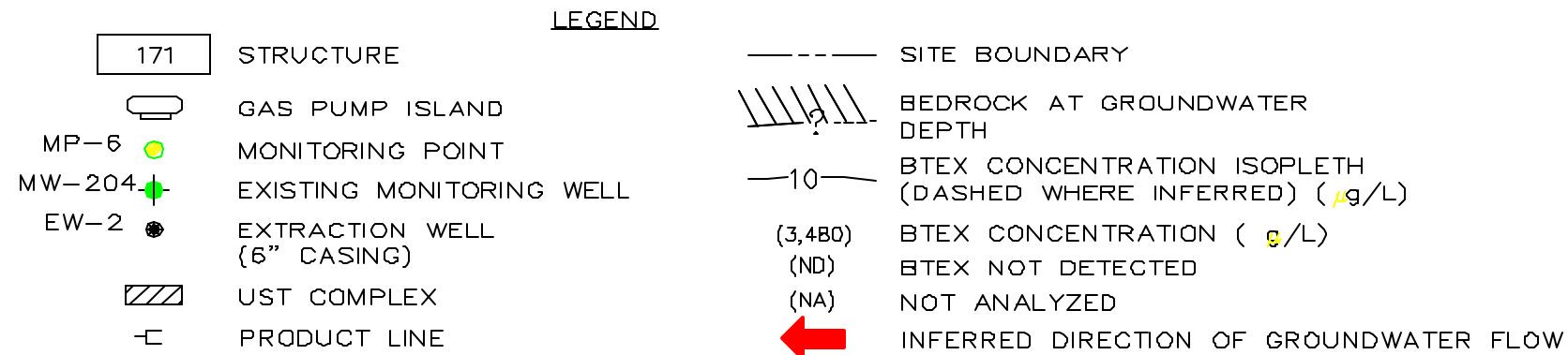
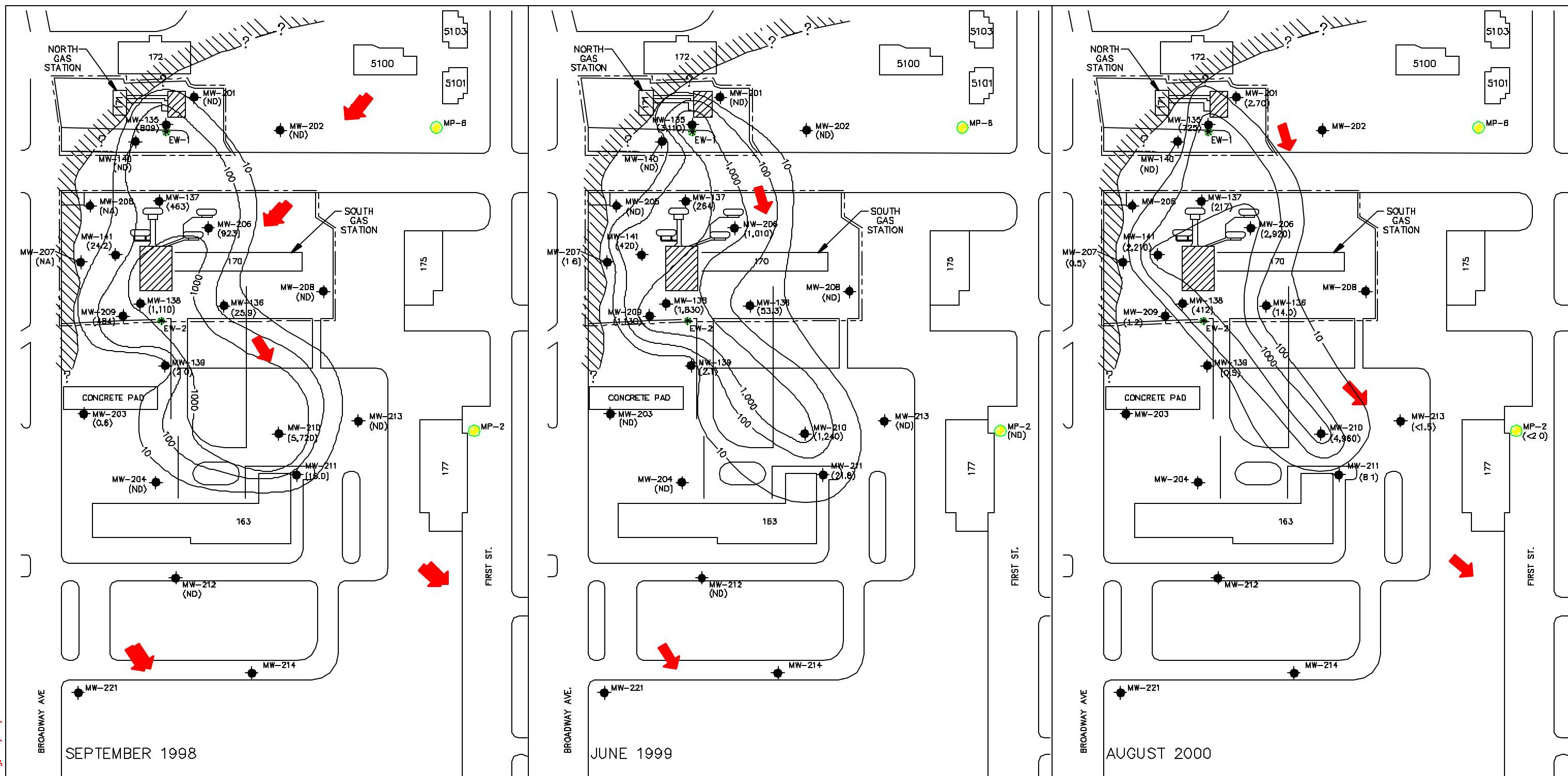
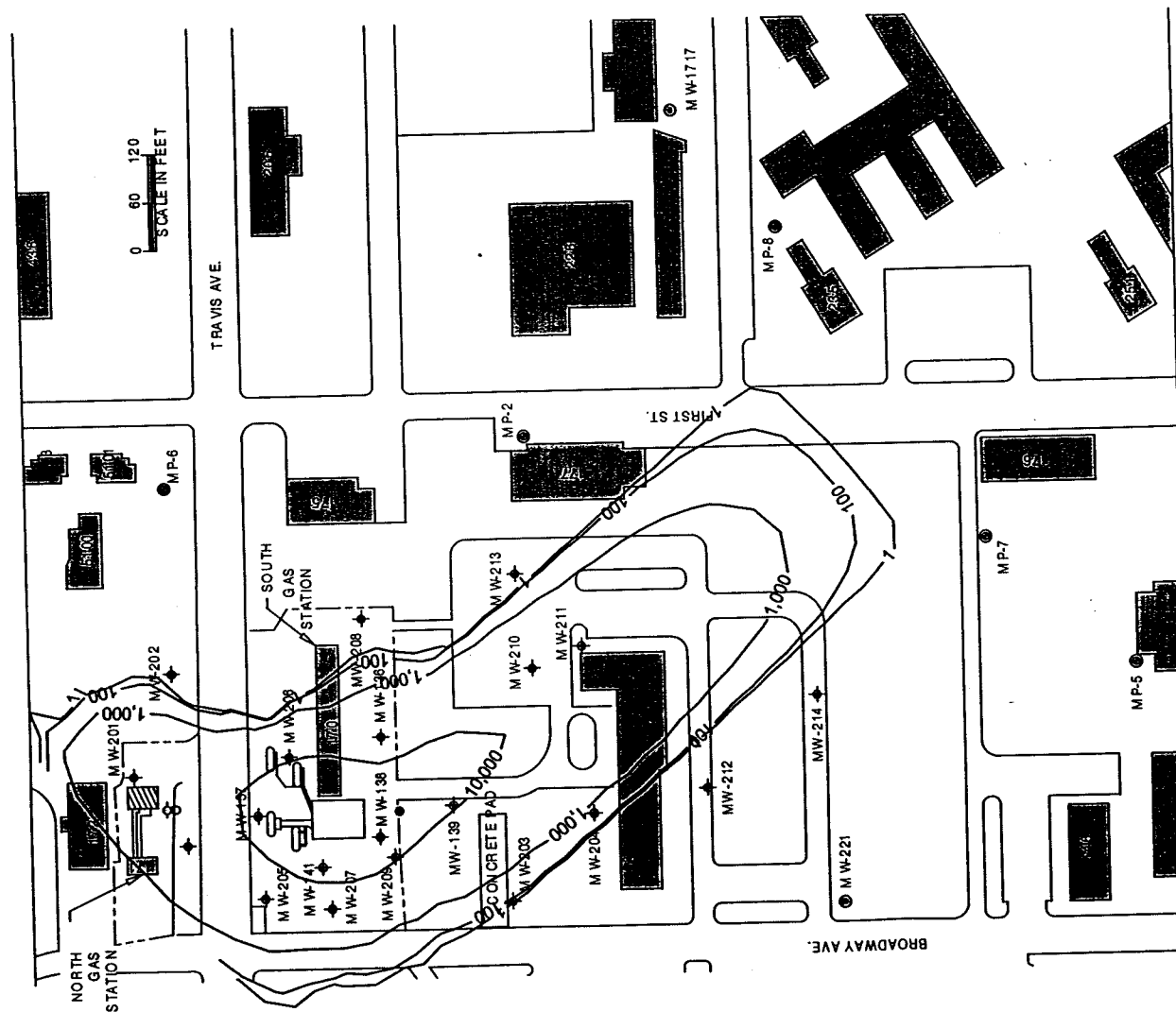


FIGURE 4

TOTAL BTEX ISOPLETHS FOR GROUNDWATER

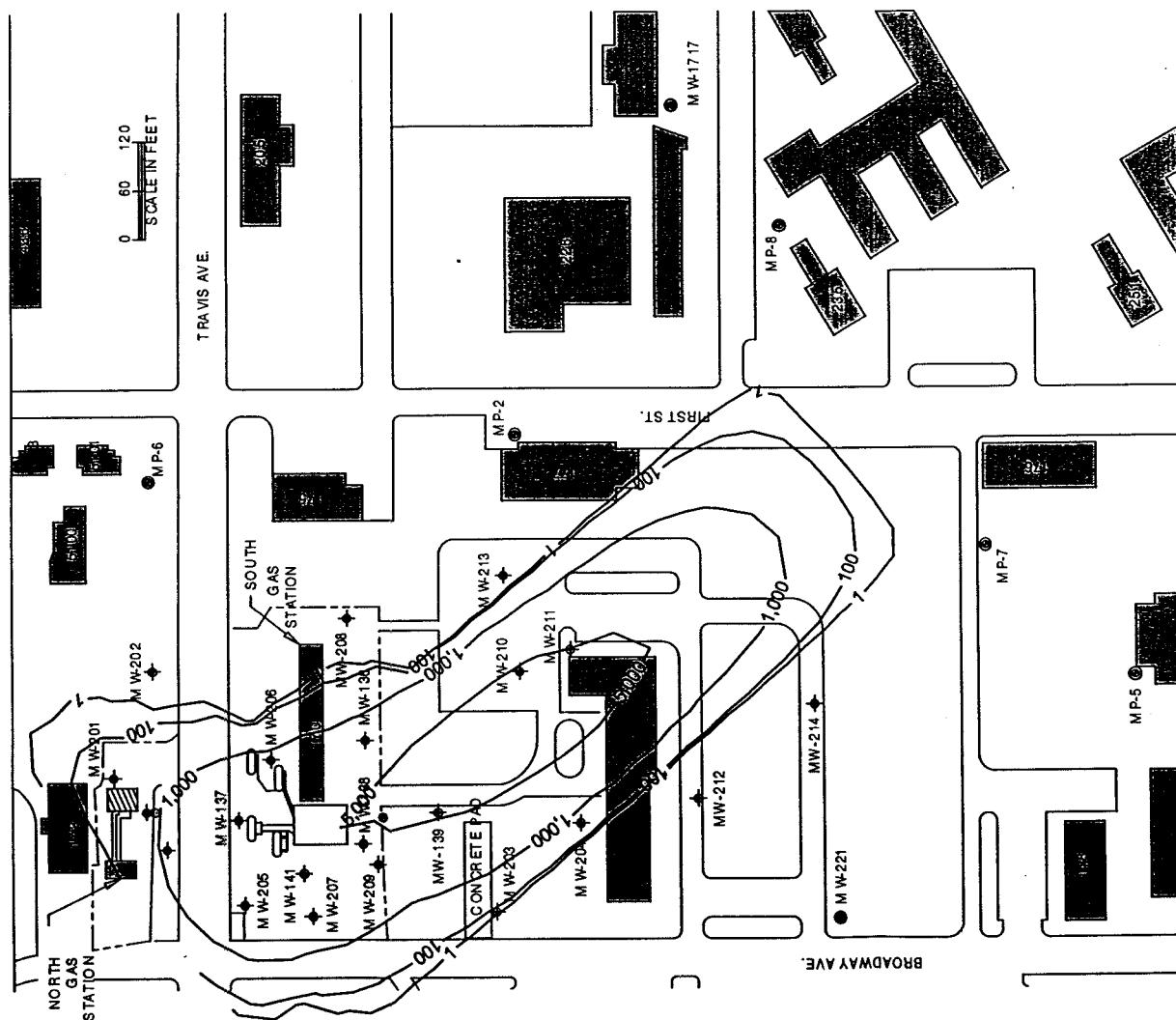
North and South Gas Stations
Intrinsic Remediation TS Addendum II
Travis AFB, California

PARSONS
PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado



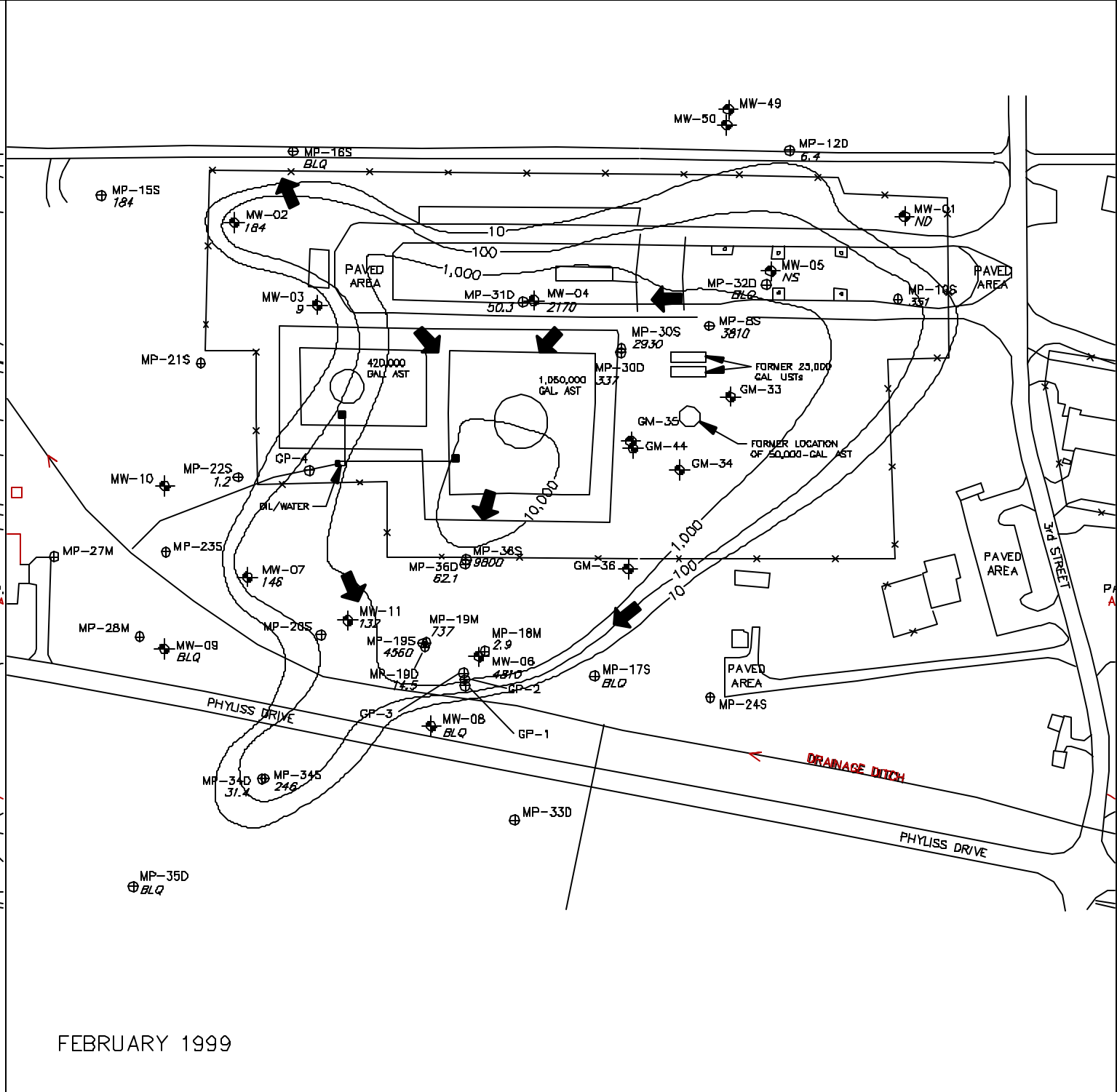
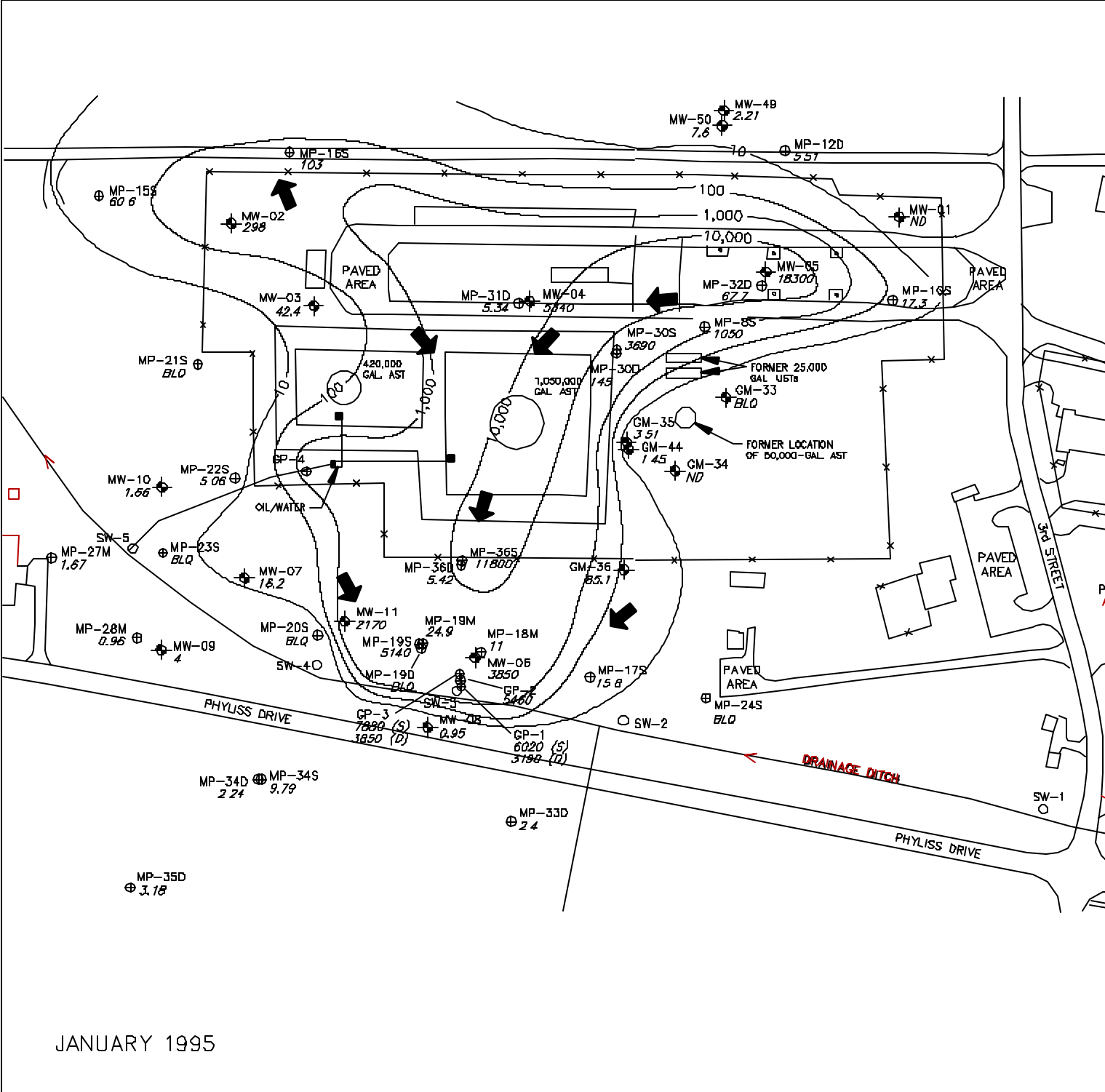
**PREDICTED PLUME MIGRATION
YEAR 2006, MODEL TRV1
NORTH AND SOUTH GAS STATIONS**

TRAVIS AIR FORCE BASE, CALIFORNIA



**PREDICTED PLUME MIGRATION
YEAR 2006, MODEL TRV2
NORTH AND SOUTH GAS STATIONS**

TRAVIS AIR FORCE BASE, CALIFORNIA



LEGEND

MW-02 298	MONITORING WELL WITH TOTAL BTEX CONCENTRATION (µg/L)	→	APPROXIMATE DIRECTION OF GROUNDWATER FLOW
MP-15S 60.6	MONITORING POINT WITH TOTAL BTEX CONCENTRATION (µg/L)	—10—	LINE OF EQUAL TOTAL BTEX CONCENTRATION (µg/L) (DASHED WHERE INFERRED) CONTOUR INTERVAL = VARIABLE
SW-1	SURFACE WATER SAMPLING LOCATION (1995)	NS	NOT SAMPLED
ND	NOT DETECTED		
BLQ	BELOW LEVEL OF QUANTIFICATION		

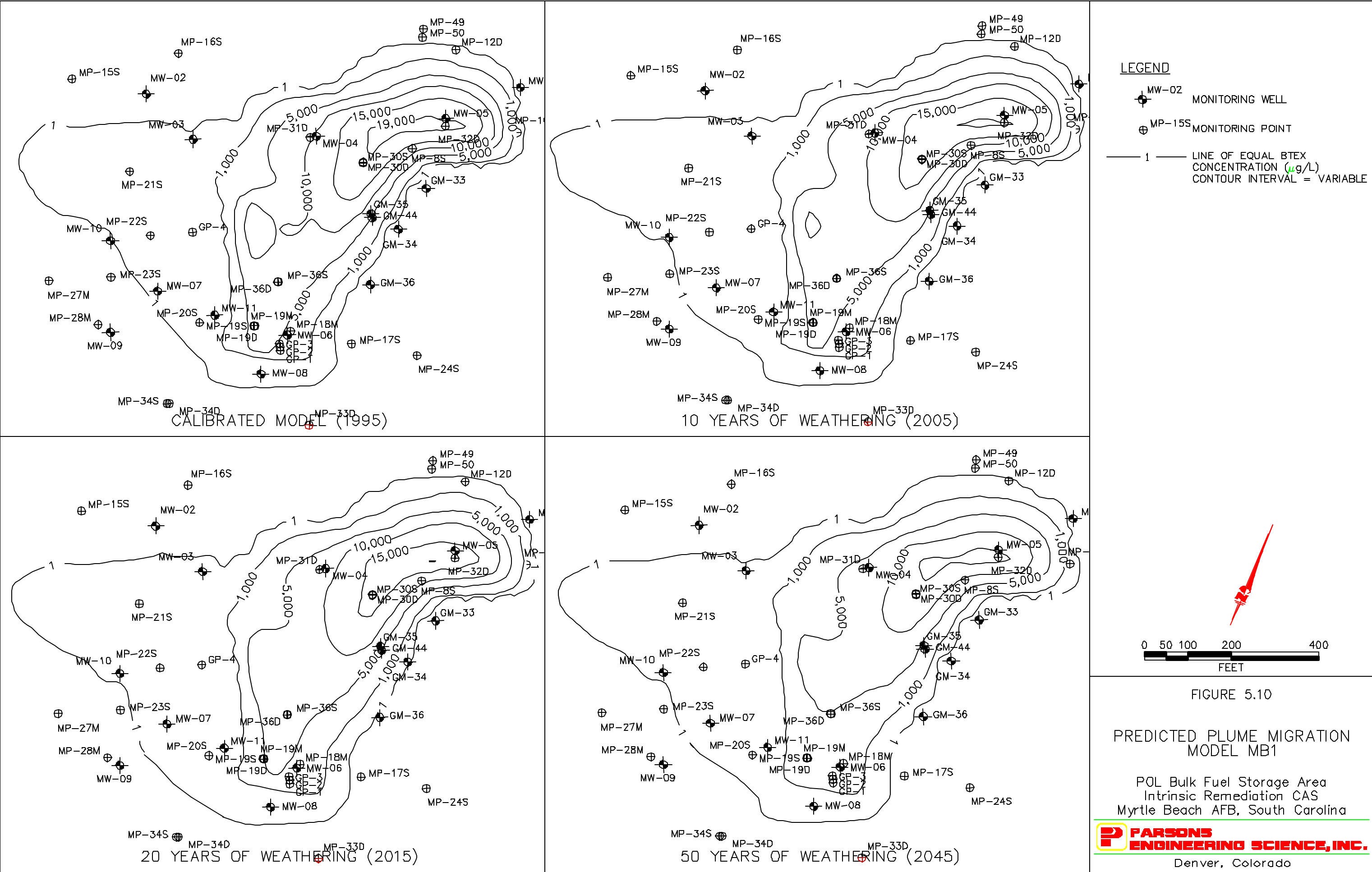
FIGURE 3

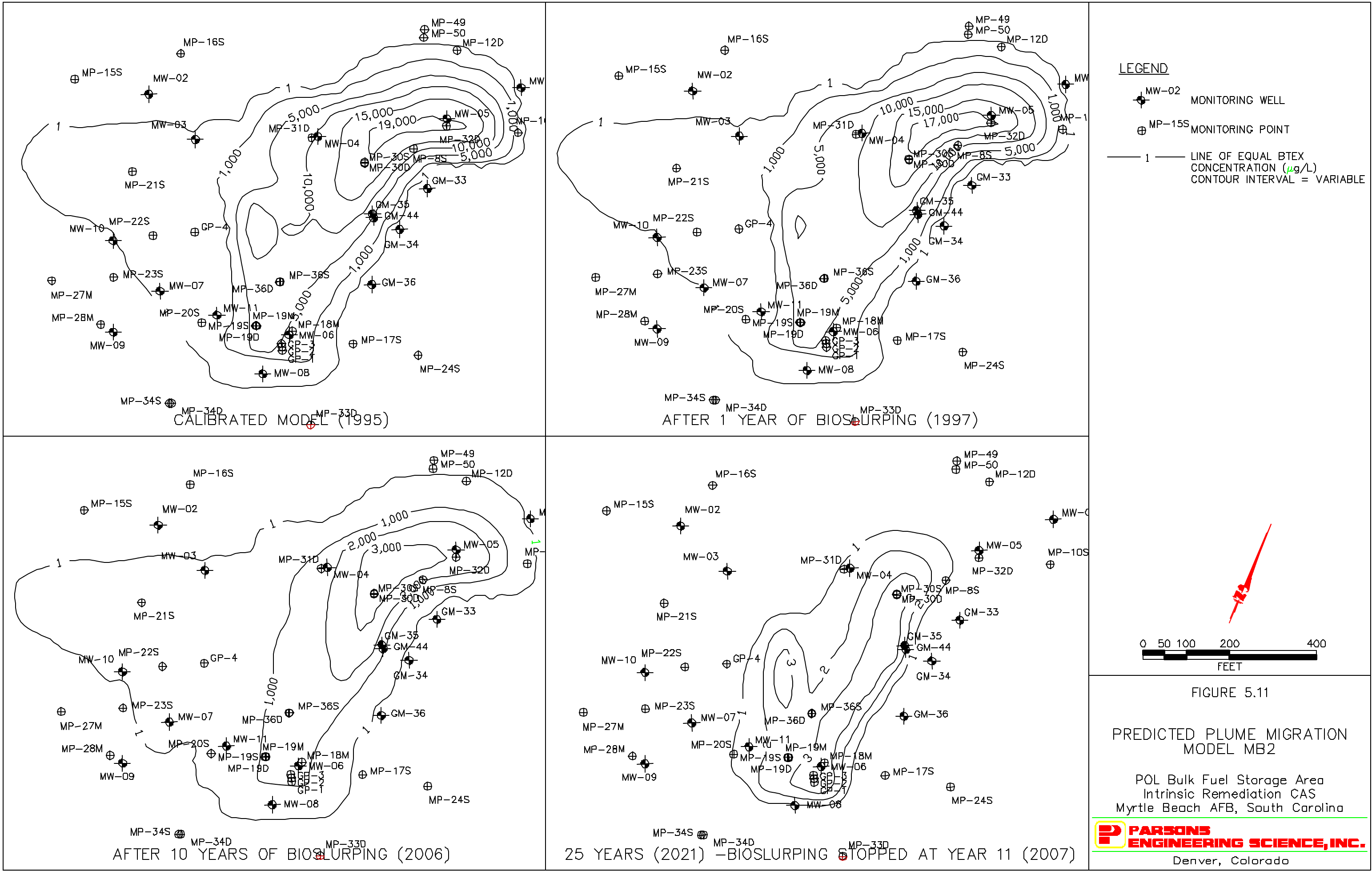
TOTAL BTEX ISOPLETH MAP
FOR SHALLOW GROUNDWATER

POL Bulk Fuel Storage Area
Intrinsic Remediation CAS Addendum
Myrtle Beach AFB, South Carolina

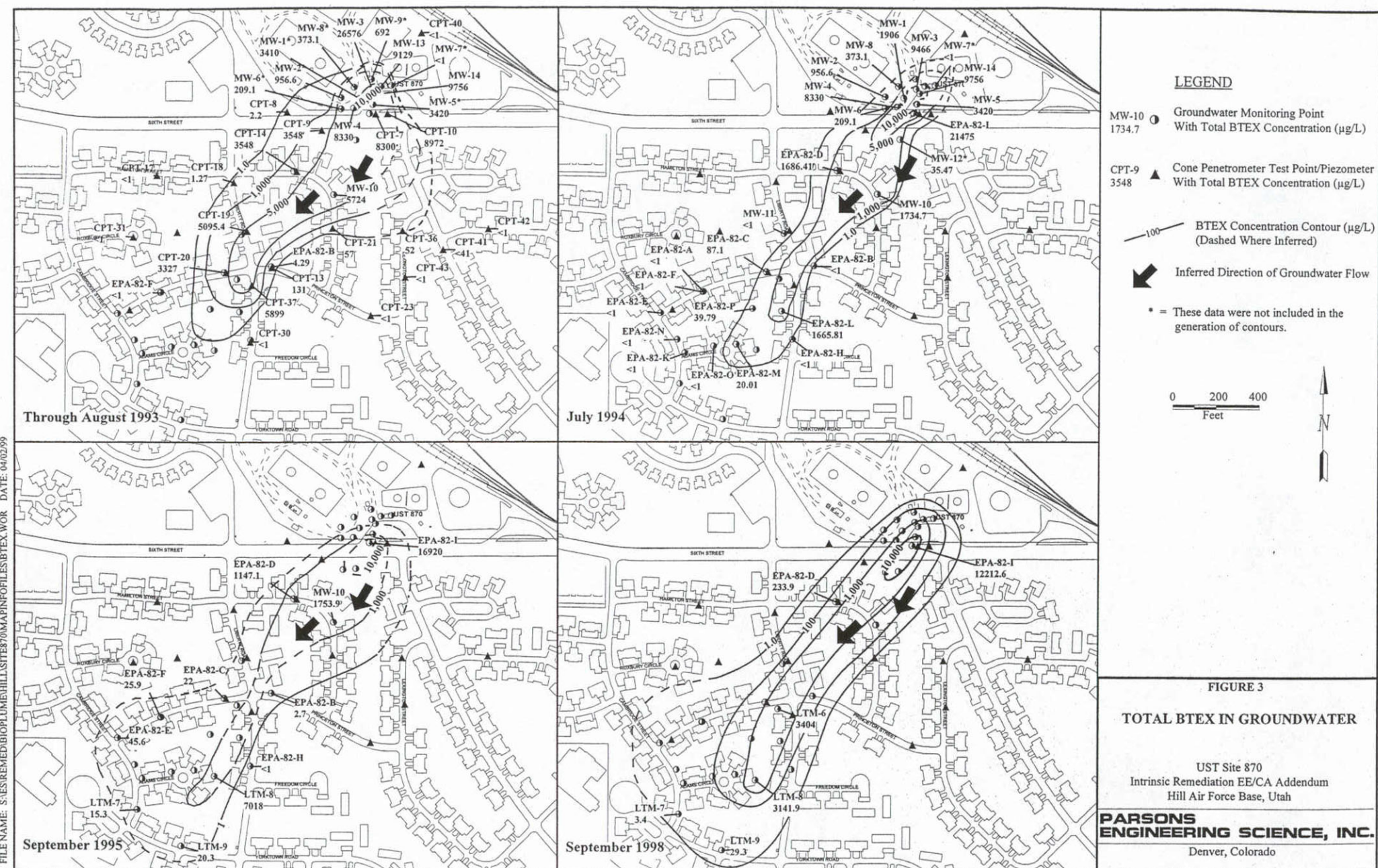
PARSONS
PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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FILE NAME: S:\ES\REMEDI\BIOP\HILL\SITE870\MAPINFOFILES\BTEX.WOR DATE: 04/02/99

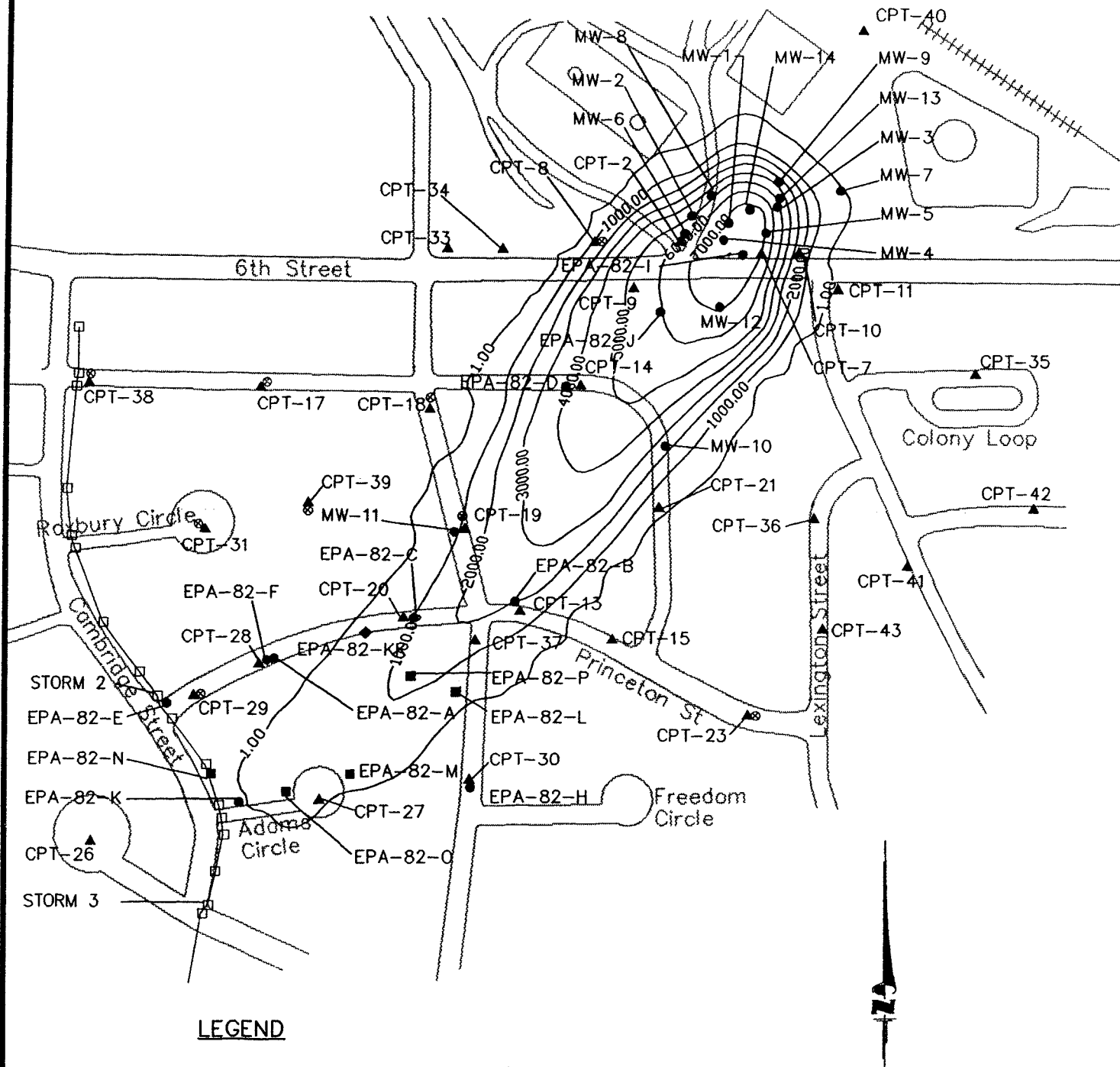


Through August 1993

July 1994

September 1995

September 1998



LEGEND

- CPT-26 ▲ CONE PENETROMETER TEST POINT/
PIEZOMETER
- MW-11 ● MONITORING WELL LOCATION
- ⊗ AUGUST 1993 GEOPROBE SAMPLING
LOCATION
- STORM DRAIN SURVEY LOCATION
- EPA-82-M ■ JULY 1994 GEOPROBE SAMPLING
LOCATION
- EPA-82-KK ◆ JULY 1994 SOIL BORING LOCATION
- 1 — LINE OF EQUAL TOTAL
BTEX CONCENTRATION (UG/L)

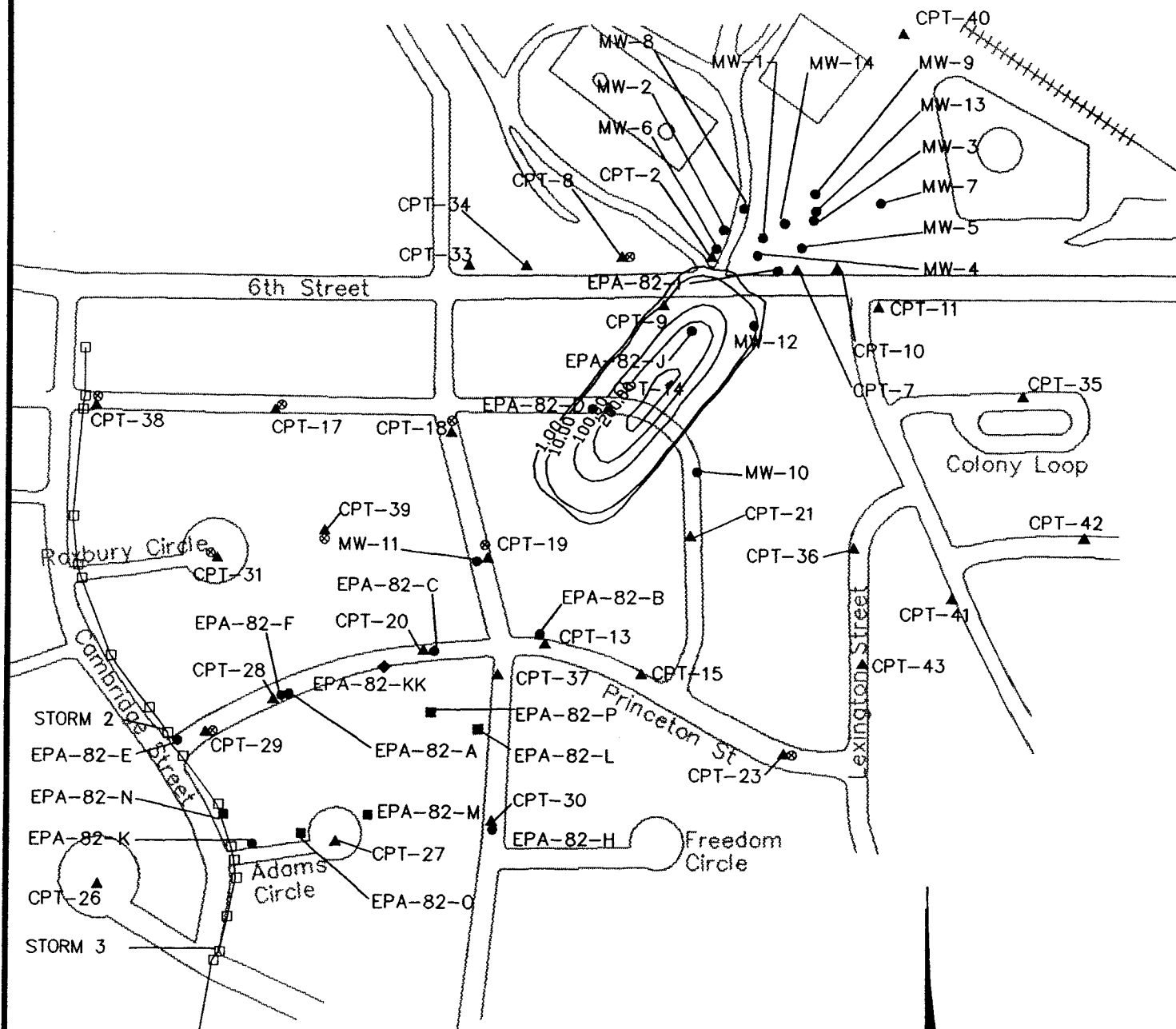
0 0 150 300 600
FEET

FIGURE 5.9 MODEL RESULTS TOTAL DISSOLVED BTEX NO LNAPL REMOVAL T=10 YEARS

UST Site 870
Intrinsic Remediation EE/CA
Hill Air Force Base, Utah

**PARSONS
ENGINEERING SCIENCE, INC.**

Denver, Colorado



LEGEND

- CPT-26 ▲ CONE PENETROMETER TEST POINT/
PIEZOMETER
- MW-11 ● MONITORING WELL LOCATION
- ⊙ AUGUST 1993 GEOPROBE SAMPLING
LOCATION
- STORM DRAIN SURVEY LOCATION
- EPA-82-M ■ JULY 1994 GEOPROBE SAMPLING
LOCATION
- EPA-82-KK ◆ JULY 1994 SOIL BORING LOCATION
- 1 — LINE OF EQUAL TOTAL BTEX
CONCENTRATION ($\mu\text{g/L}$)

CONTOUR INTERVAL = 100 $\mu\text{g/L}$

FIGURE 5.12 MODEL RESULTS TOTAL DISSOLVED BTEX 5% ANNUAL LNAPL REMOVAL T=7 YEARS

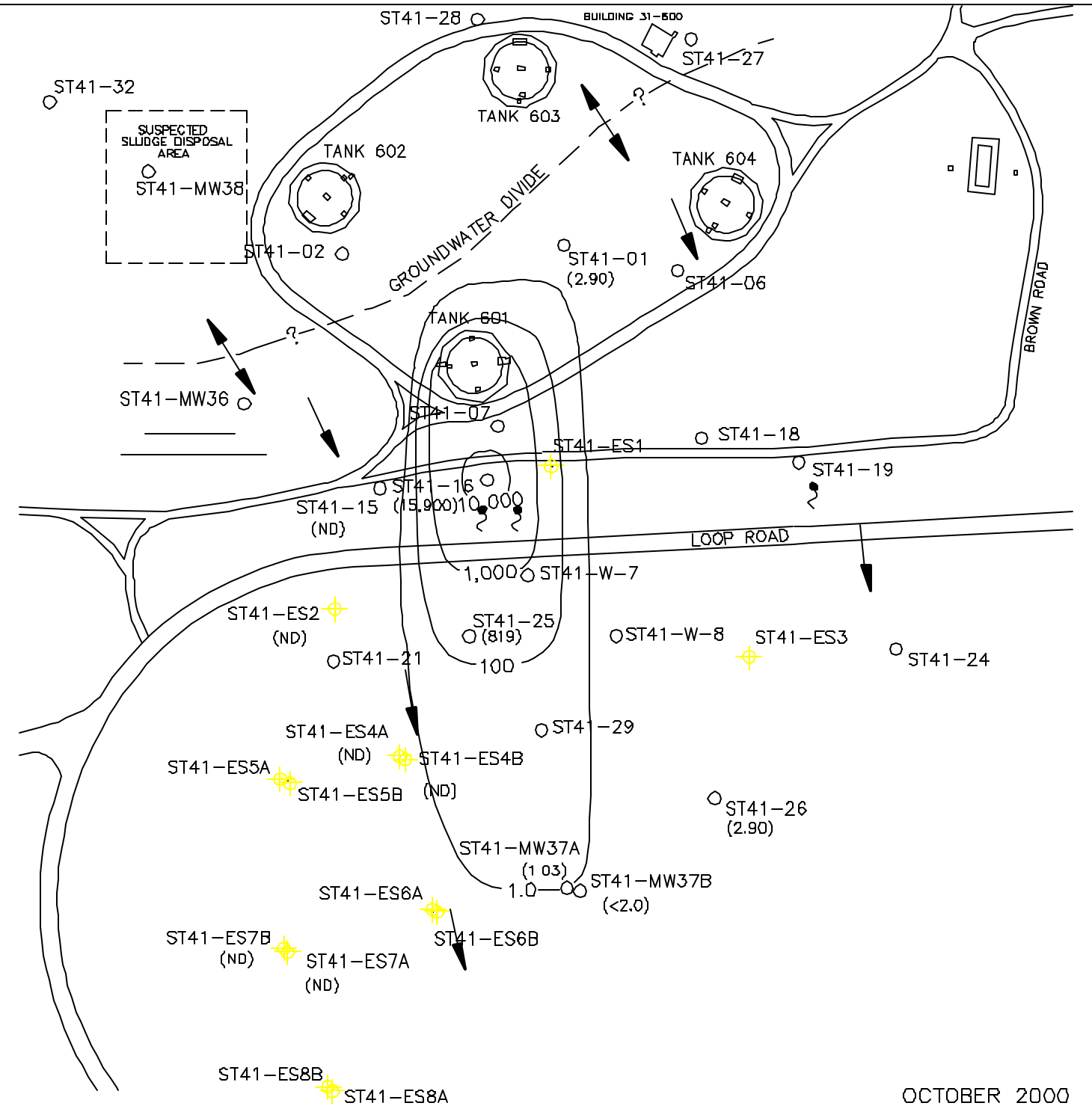
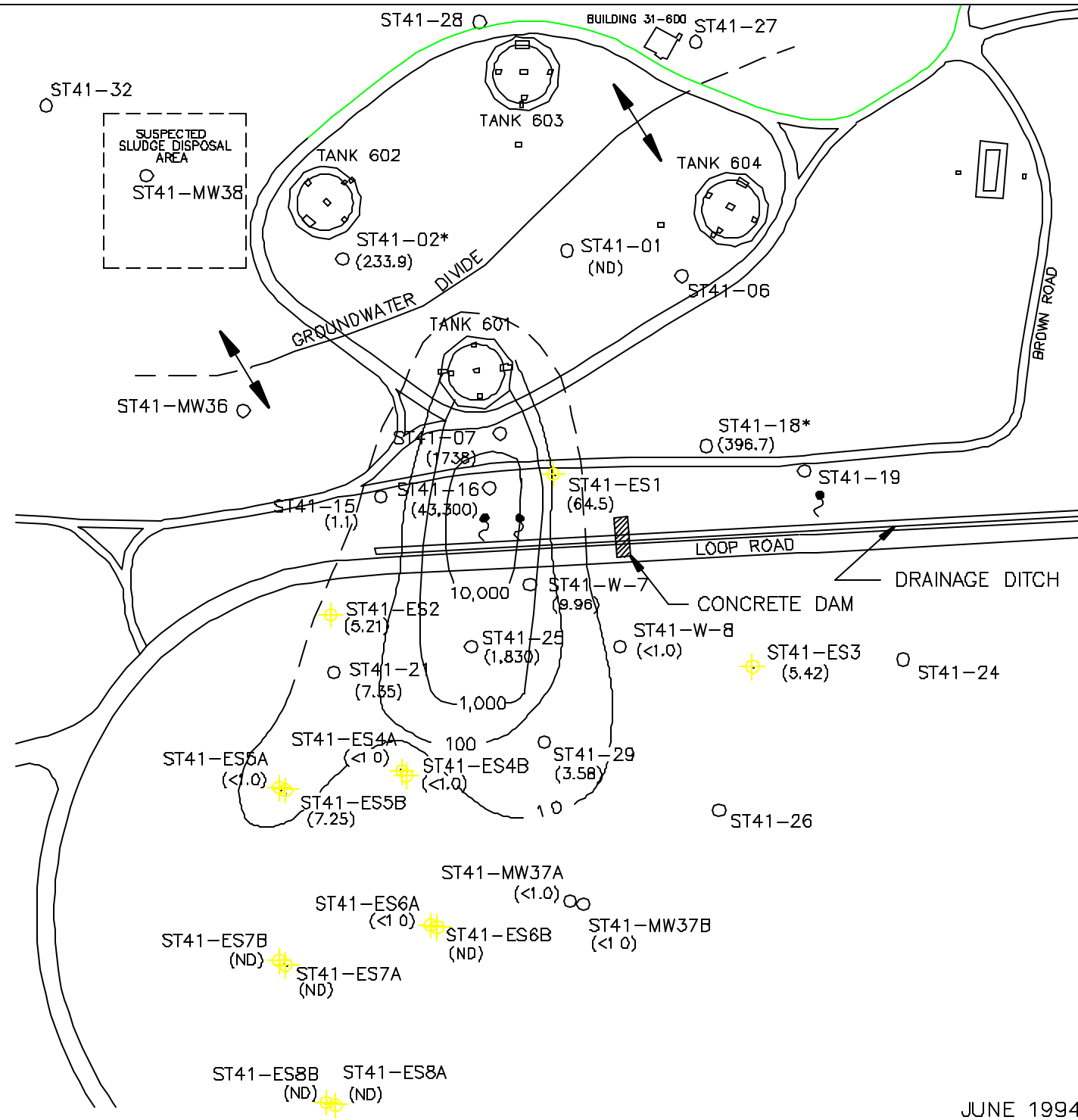
UST Site 870
Intrinsic Remediation EE/CA
Hill Air Force Base, Utah



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Denver, Colorado

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JUNE 1994

OCTOBER 2000

LEGEND

	ROAD		
	GROUNDWATER SEEP		
	ST41-29 MONITORING WELL (1988-1992)	*	INDICATES WELLS UPGRADIENT FROM TANK 601 THAT ARE NOT CONSIDERED THE RESULT OF CONTAMINATION ORIGINATING FROM TANK 601.
	ST41-ES4B MONITORING WELL (1994)	(203.65)	BTEX CONCENTRATION (μ /L)
	100 LINE OF EQUAL BTEX CONCENTRATION (μ /L) (DASHED WHERE INFERRED)	(ND)	BTEX NOT DETECTED
			INFERRED DIRECTION OF GROUNDWATER FLOW

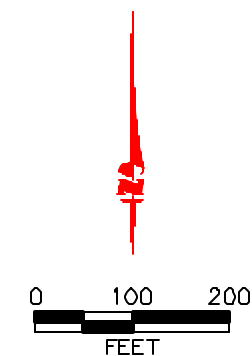


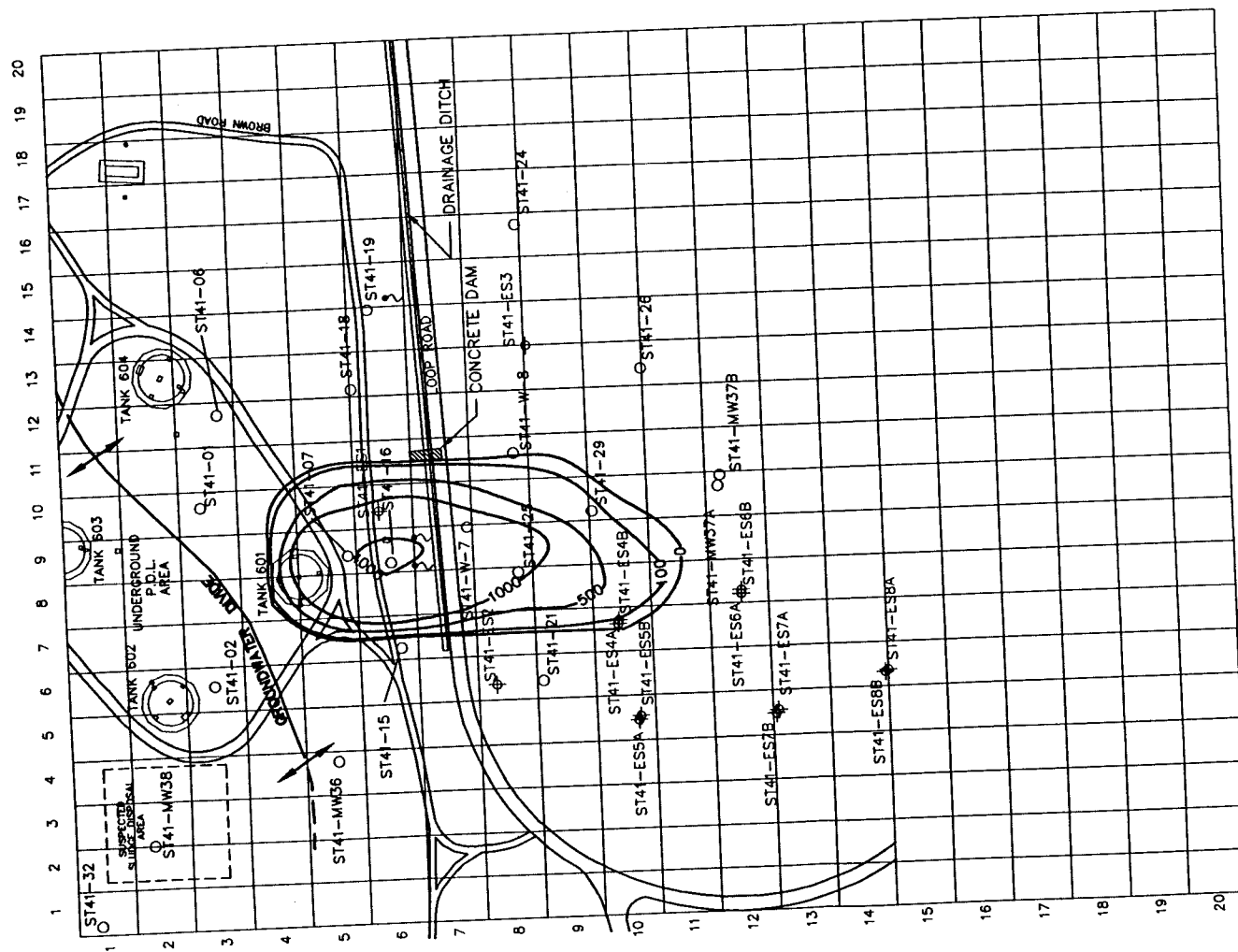
FIGURE 6

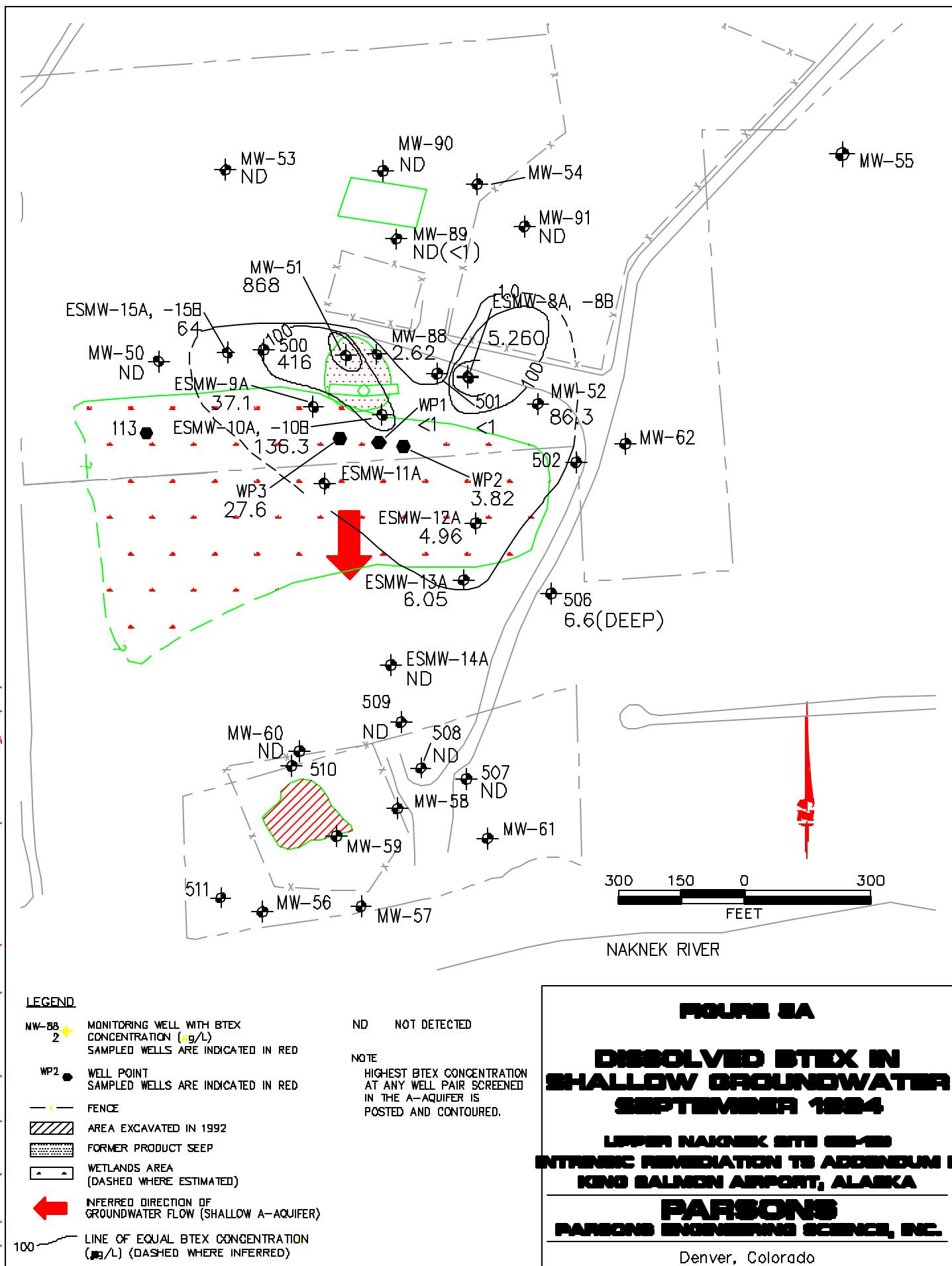
TOTAL BTEX ISOPLETHS
FOR GROUNDWATER

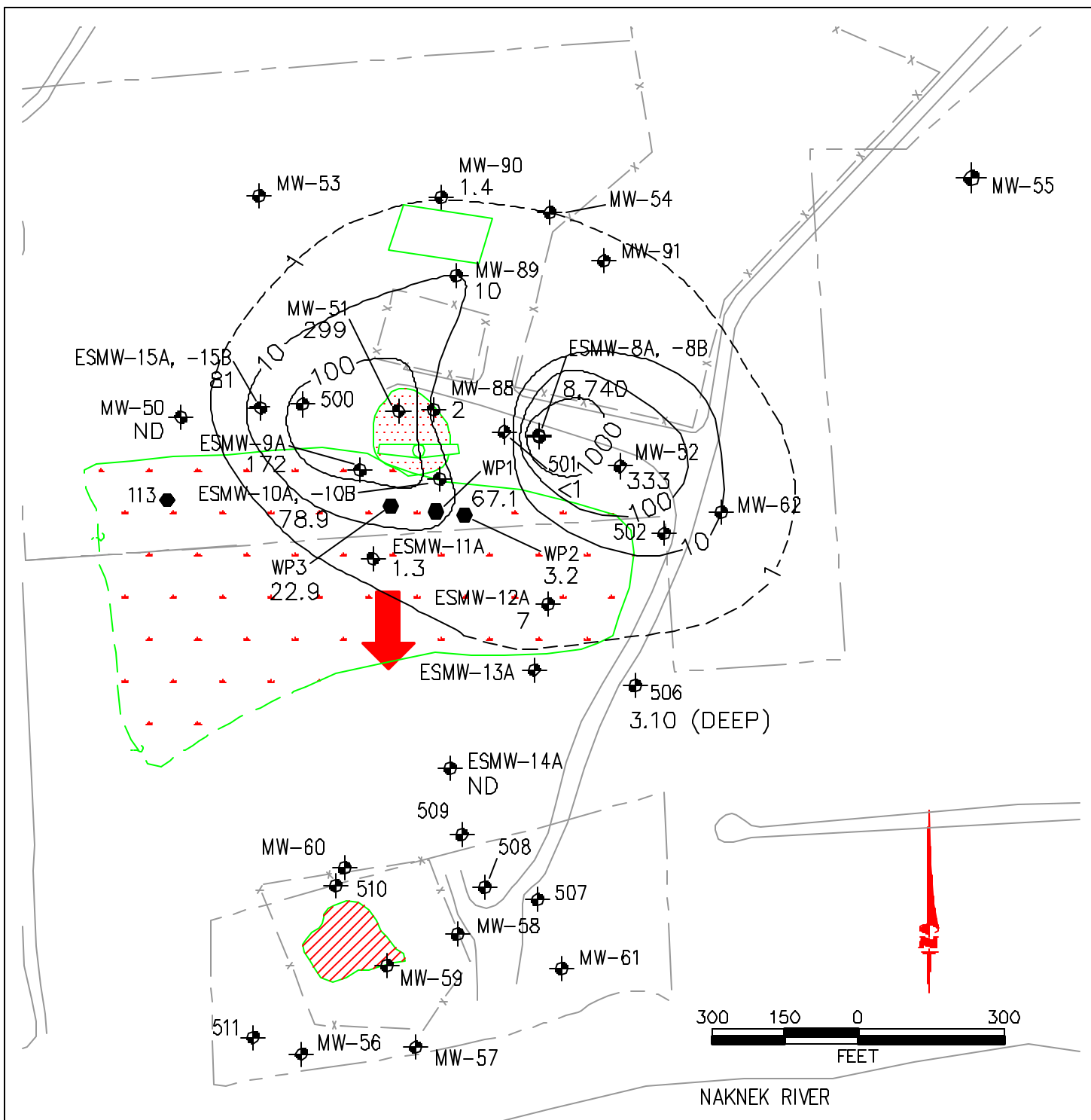
Site ST41
Intrinsic Remediation TS Addendum
Elmendorf AFB, Alaska

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Denver, Colorado







LEGEND

- MW-88 2
MONITORING WELL WITH BTEX CONCENTRATION (g/L)
SAMPLED WELLS ARE INDICATED IN RED
- WP2
WELL POINT
SAMPLED WELLS ARE INDICATED IN RED
- x —
FENCE
- ▨
AREA EXCAVATED IN 1992
- ▤
FORMER PRODUCT SEEP
- · —
WETLANDS AREA
(DASHED WHERE ESTIMATED)
- ←
INFERRED DIRECTION OF GROUNDWATER FLOW (SHALLOW A-AQUIFER)
- 100 —
LINE OF EQUAL BTEX CONCENTRATION (g/L) (DASHED WHERE INFERRED)

ND NOT DETECTED

NOTE:
HIGHEST BTEX CONCENTRATION AT ANY WELL PAIR SCREENED IN THE A-AQUIFER IS POSTED AND CONTOURED.

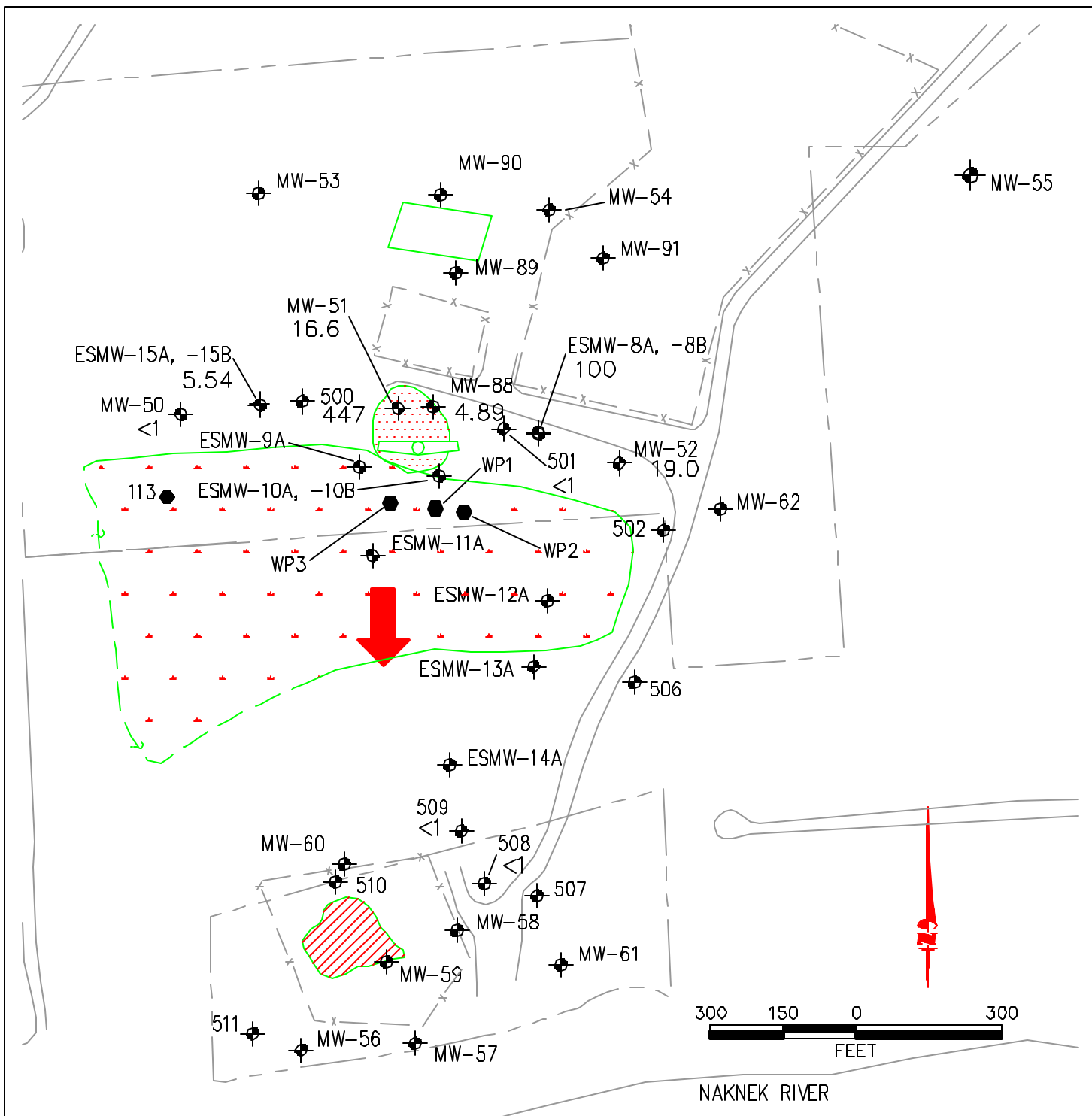
FIGURE 5B

DISSOLVED BTEX IN SHALLOW GROUNDWATER JULY 1998

UPPER NAKNEK SITE (SS-10)
INTRINSIC REMEDIATION T5 ADDENDUM I
KING SALMON AIRPORT, ALASKA

PARSONS
PARSONS ENGINEERING SCIENCE, INC.

Denver, Colorado



LEGEND

- MW-88 2 MONITORING WELL WITH BTEX CONCENTRATION (g/L)
SAMPLED WELLS ARE INDICATED IN RED
- WP2 WELL POINT
SAMPLED WELLS ARE INDICATED IN RED
- FENCE
- AREA EXCAVATED IN 1992
- FORMER PRODUCT SEEP
- WETLANDS AREA
(DASHED WHERE ESTIMATED)
- INFERRED DIRECTION OF GROUNDWATER FLOW (SHALLOW A-AQUIFER)

ND NOT DETECTED

NOTE:
HIGHEST BTEX CONCENTRATION AT ANY WELL PAIR SCREENED IN THE A-AQUIFER IS POSTED AND CONTOURED.

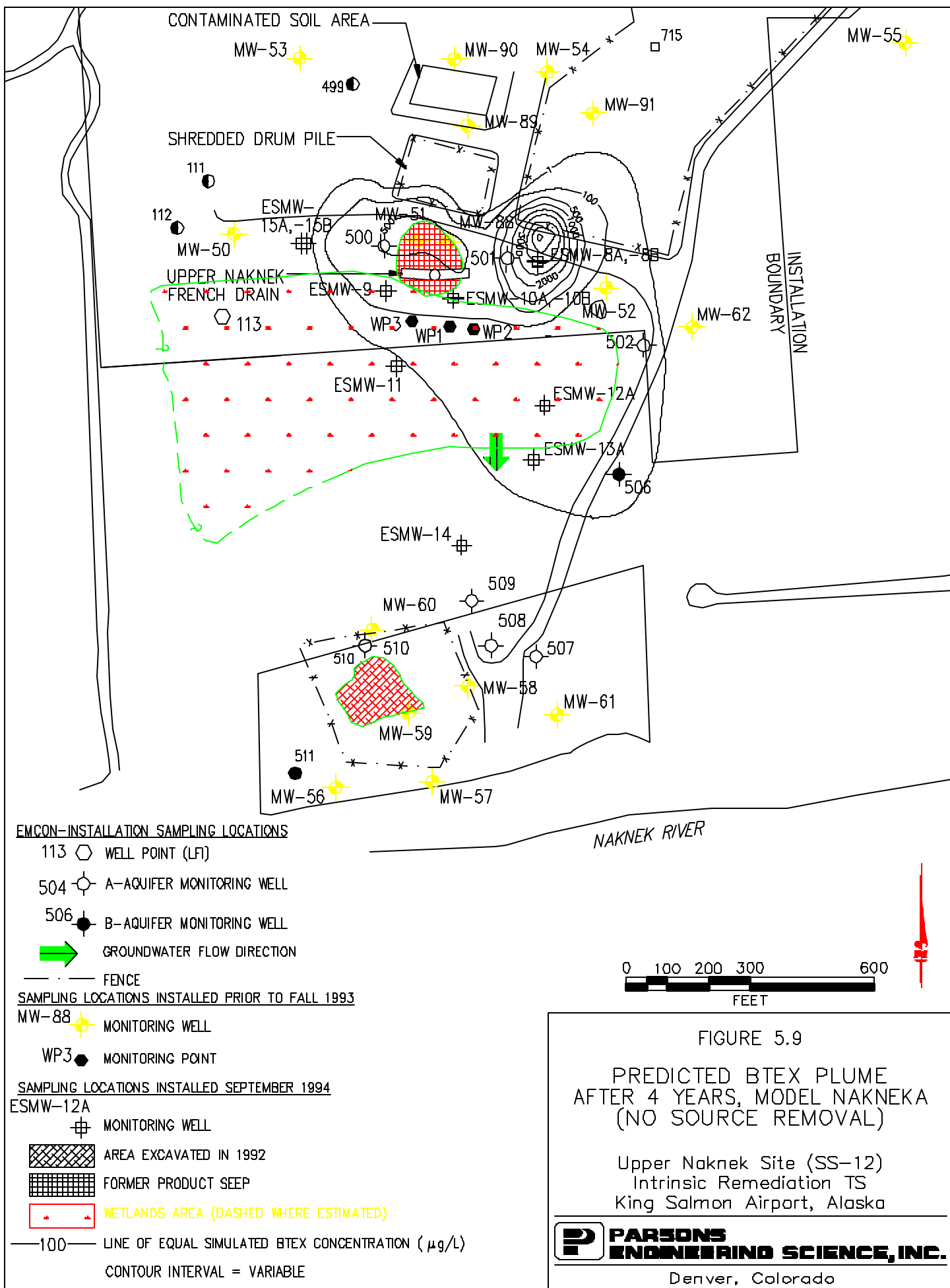
FIGURE 8C

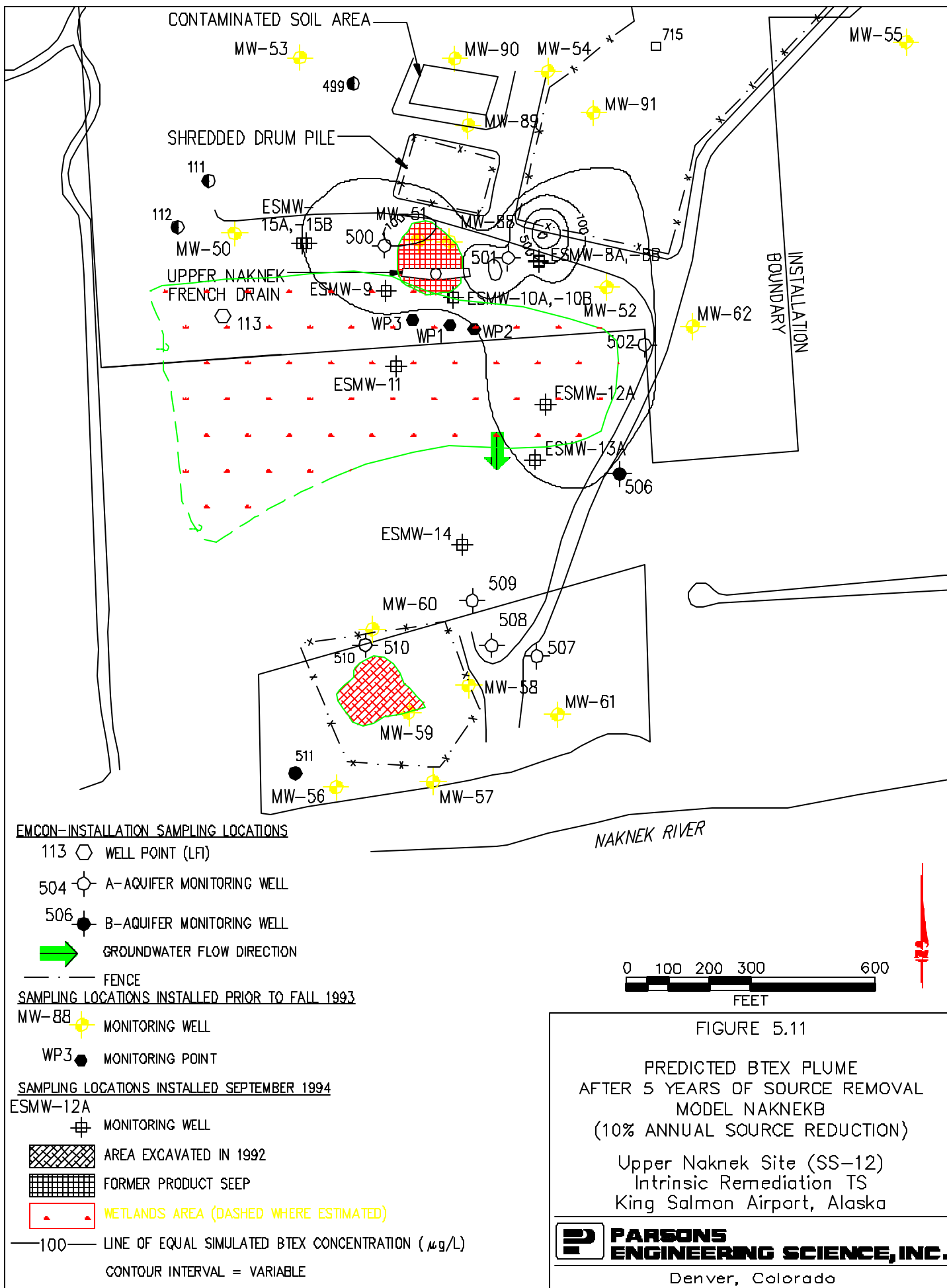
DISSOLVED BTEX IN SHALLOW GROUNDWATER JUNE 2000

UPPER NAKNEK SITE GS-180
INTRINSIC REMEDIATION TO ADDRESS
KING SALMON AIRPORT, ALASKA

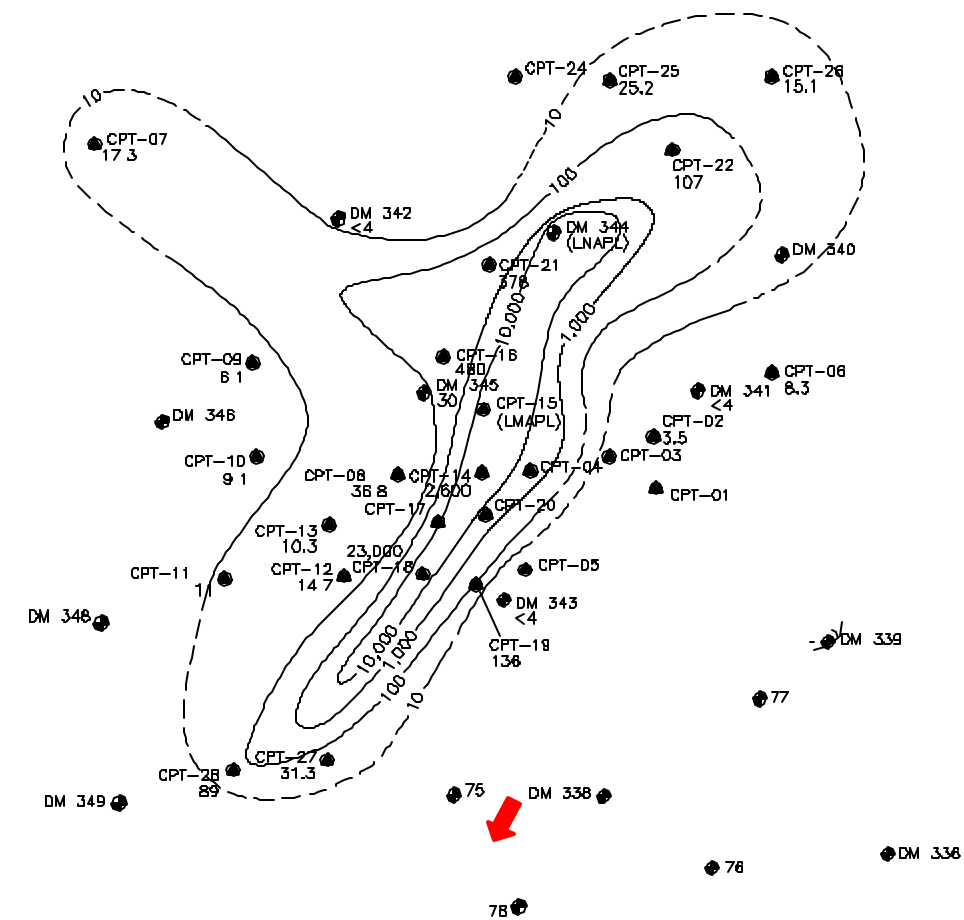
PARSONS
PARSONS ENGINEERING SCIENCE, INC.

Denver, Colorado

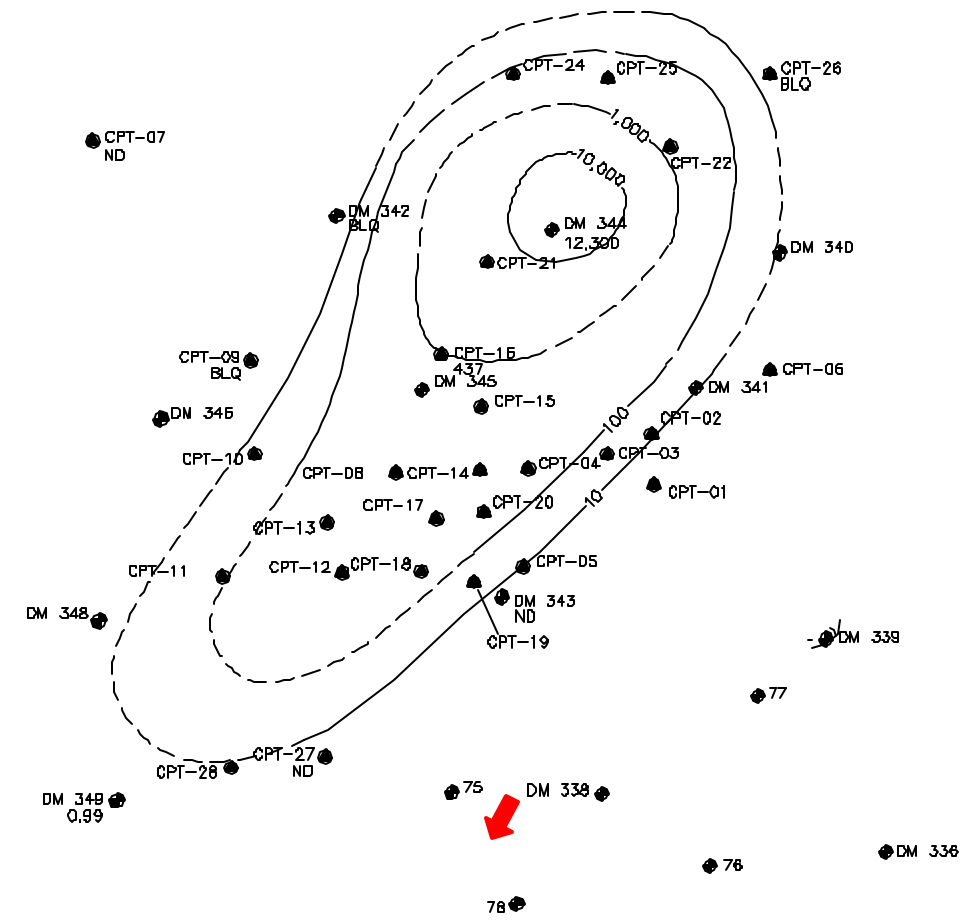




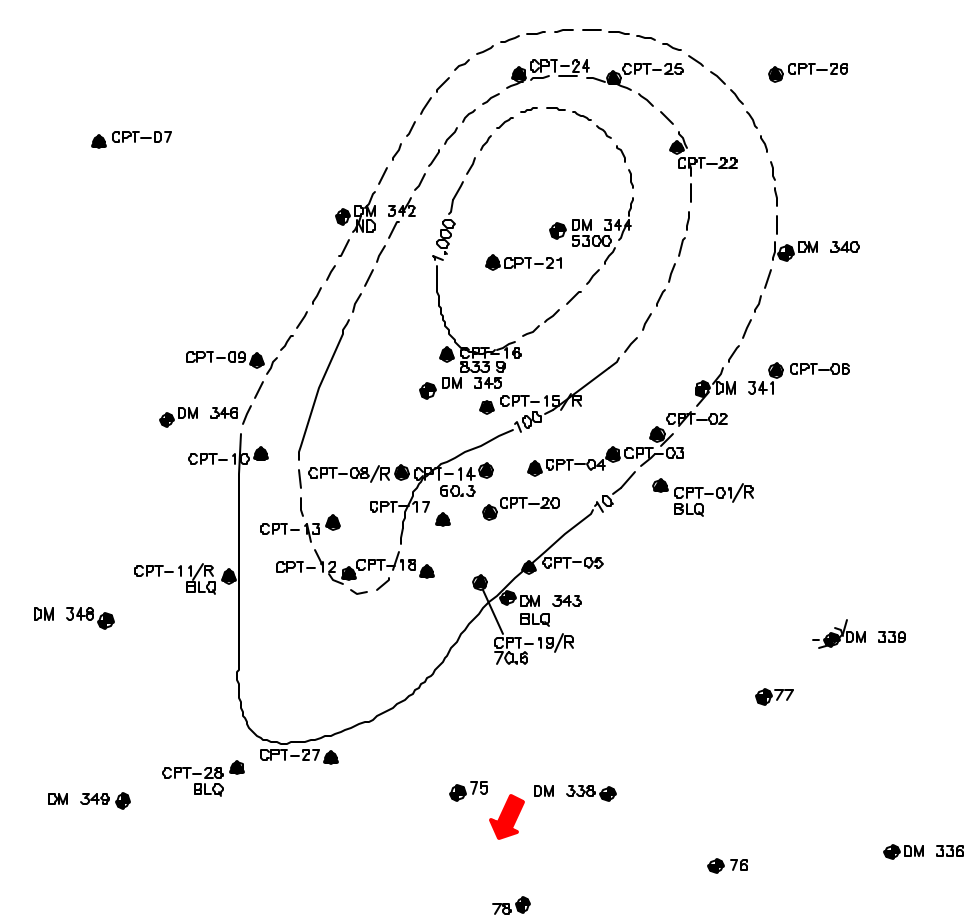
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APRIL 1994



SEPTEMBER 1997



FEBRUARY 1999

LEGEND

- | | | | |
|--------|--|---------|---|
| DM 341 | MONITORING WELL | —10— | TOTAL BTEX CONCENTRATION IN MICROGRAMS PER LITER (µg/L) |
| CPT-01 | MONITORING POINT AND CPT TEST LOCATION INSTALLED BY CPT RIG. | 89 | TOTAL BENZENE, TOLUENE, ETHYLBENZENE AND XYLENES (BTEX) CONCENTRATIONS (µg/L) |
| /R | INDICATES REPLACEMENT WELL INSTALLED IN 1999 | ND | NOT DETECTED |
| ☐ | FORMER C-10 FUELING PAD | BLQ | BELOW LIMIT OF QUANTITATION |
| ➔ | APPROXIMATE GROUNDWATER FLOW DIRECTION | (LNAPL) | LNAPL EMULSIFIED IN SAMPLE |

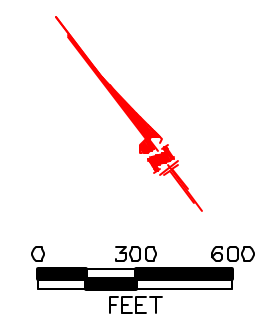


FIGURE 4

TOTAL BTEX ISOPLETH MAPS

Site SS27/XYZ
Intrinsic Remediation EE/CA Addendum
Dover AFB, Delaware

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

Model Boundary

Dover AFB Property Boundary

Model Axis

Y

X

Assumed Discharge Boundary For Model (5' Contour)

TO LOWER 14 1/2 MILES

US ROUTE 113

Approximate Groundwater Flow Direction

St. Jones River

LEGEND

- DM 341 Monitoring well.
- CPT-01 Monitoring point and CPT test location installed by CPT rig.
- 10 Total benzene, toluene, ethylbenzene and xylenes (BTEX) concentration ($\mu\text{g/L}$) contour.
- Former C-10 fueling pad

400' 200' 0 400'

Approximate Scale in Feet

Source: USGS Little Creek, Delaware Quad, 1993

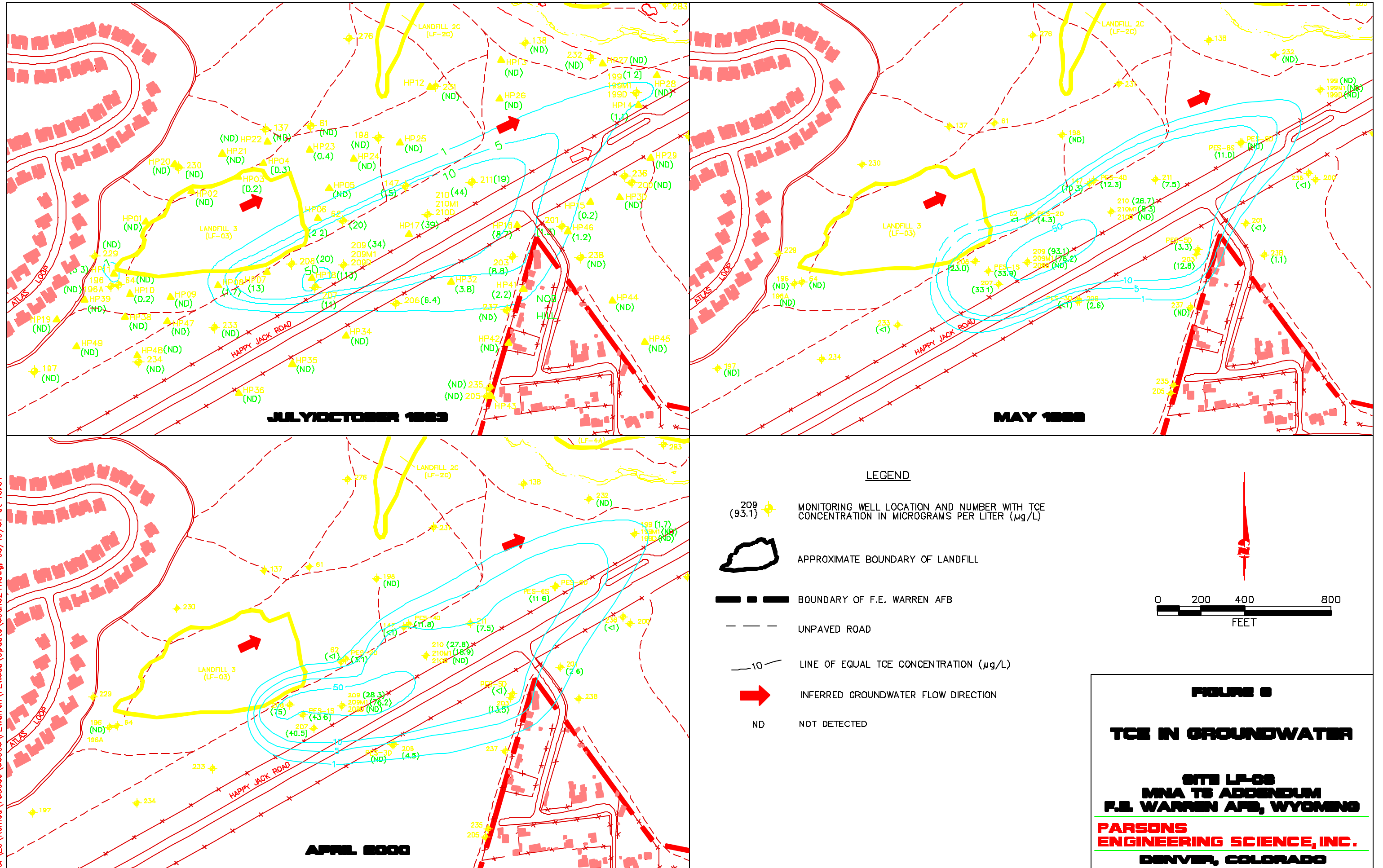
Predicted BTEX Distribution at 5 Years (Year 2000) Model SR6 Results

Site SS27/XYZ

Intrinsic Remediation EE/CA

Dover AFB, Delaware

S:\ES\Remed\733939\50000\FEWarren\Update\00dm0241.dwg, 03/19/01 at 13:51



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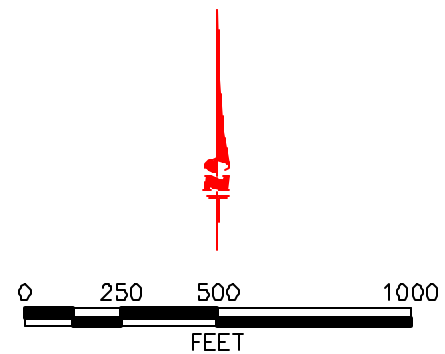
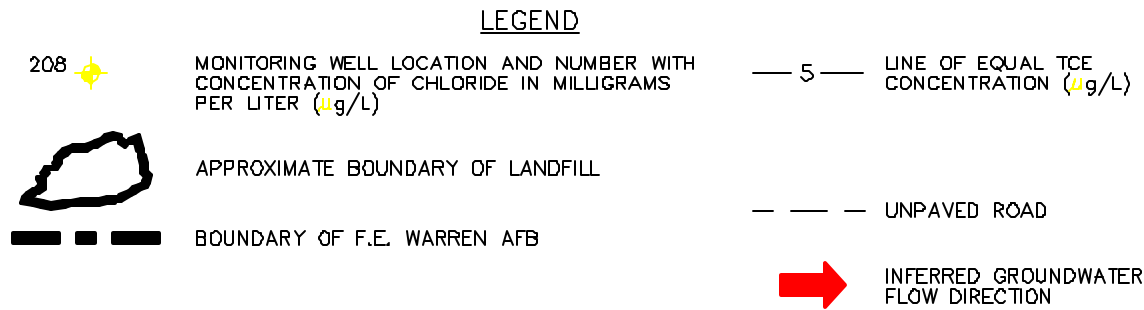
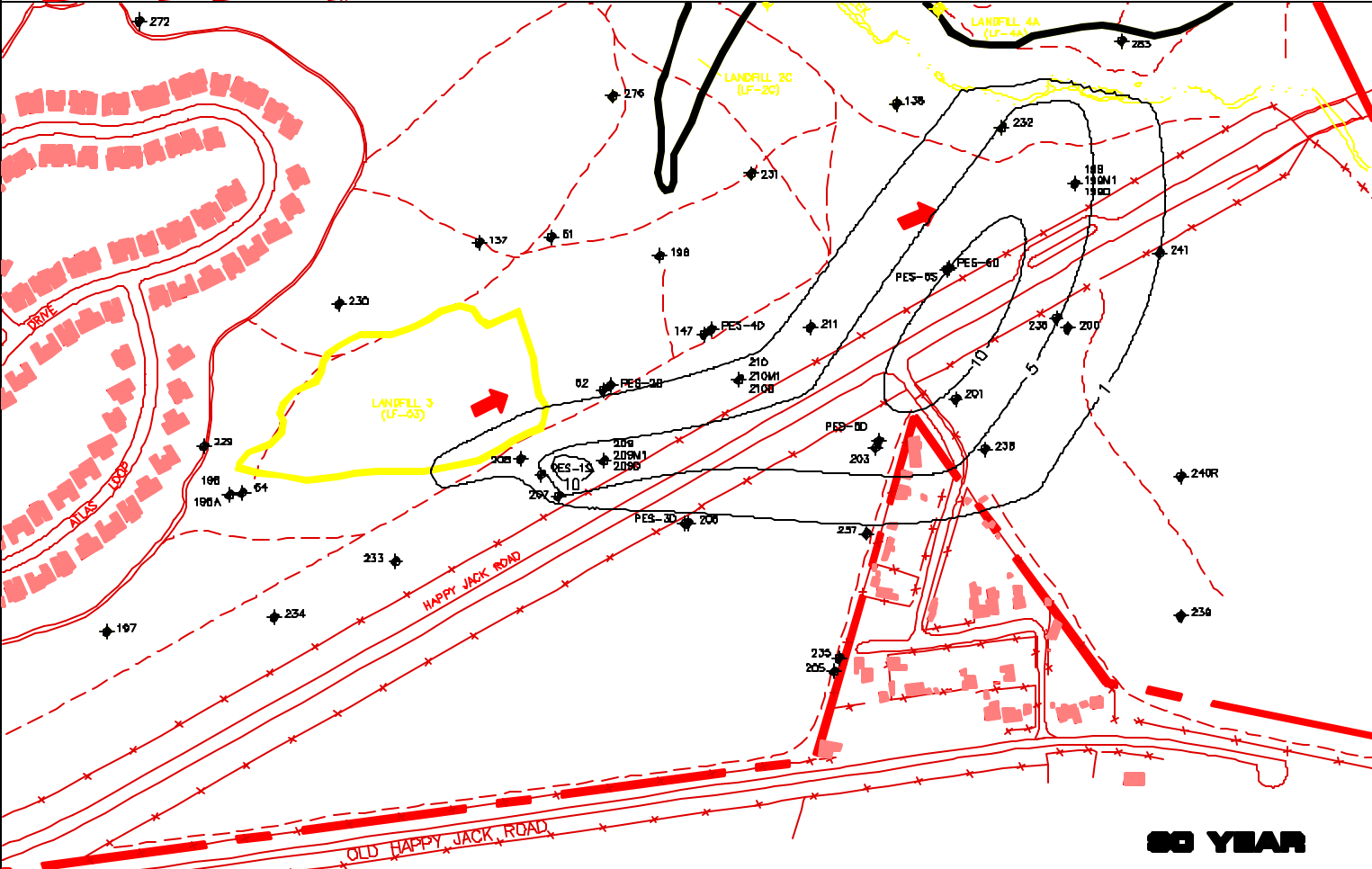
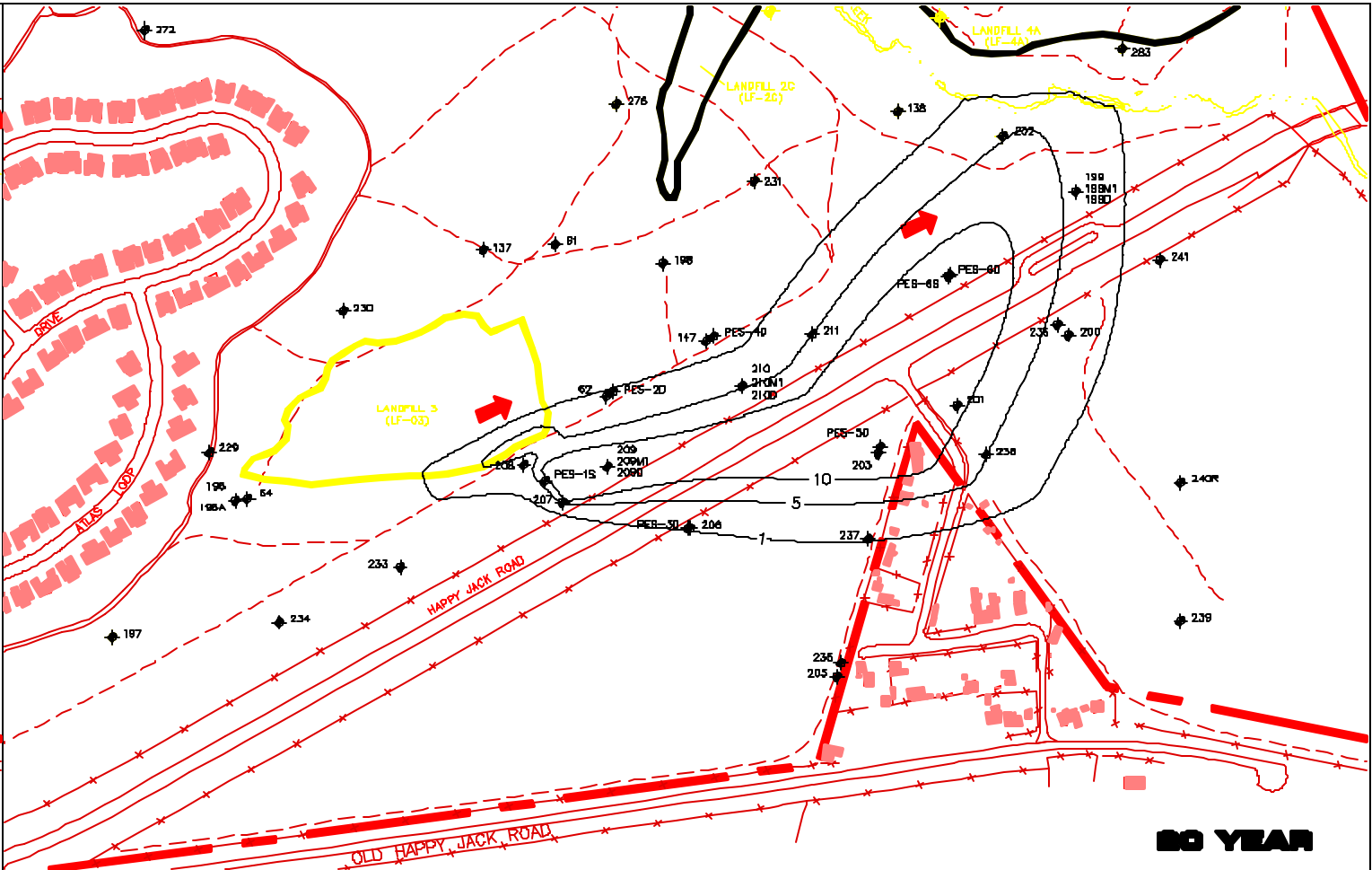
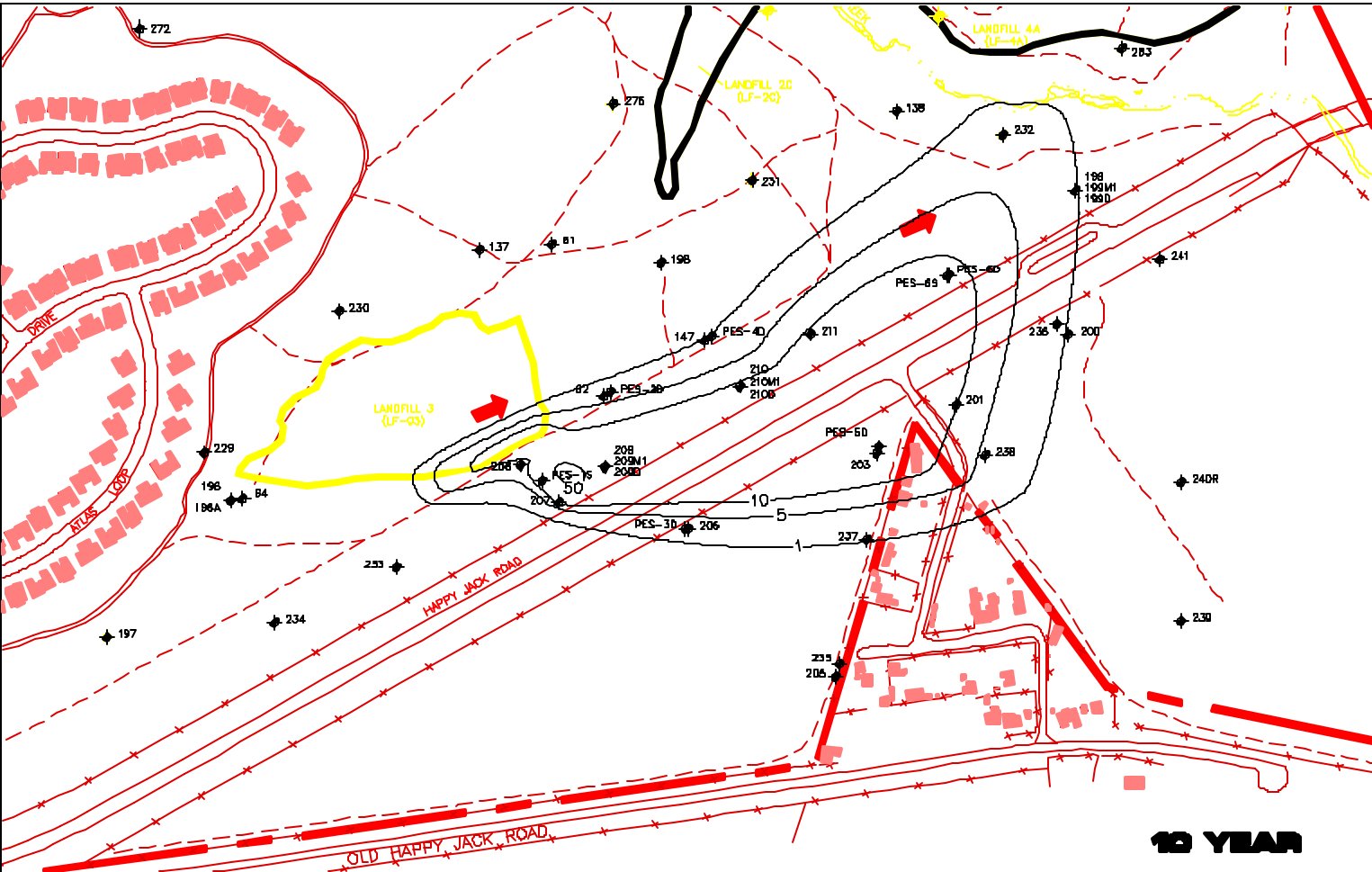
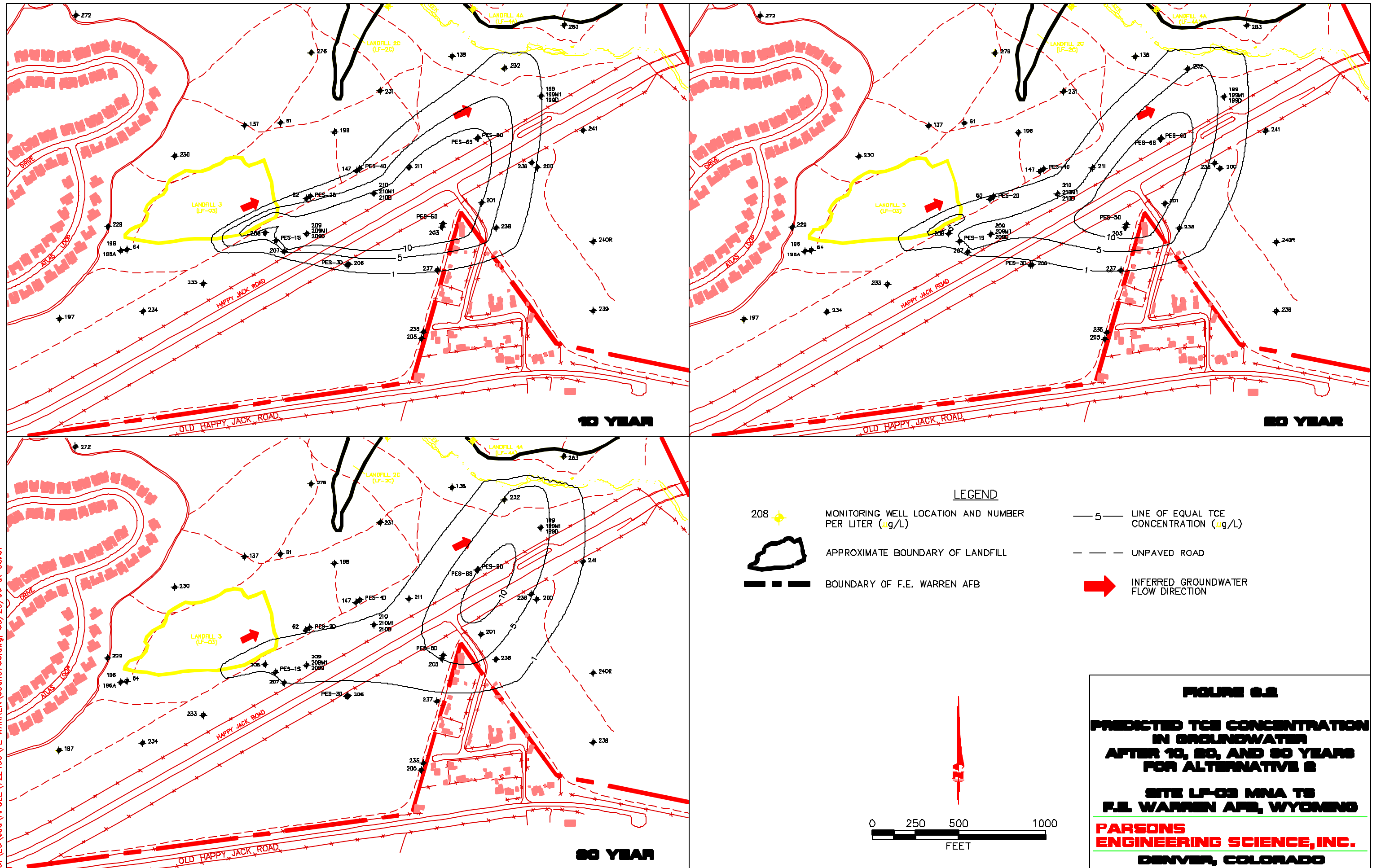
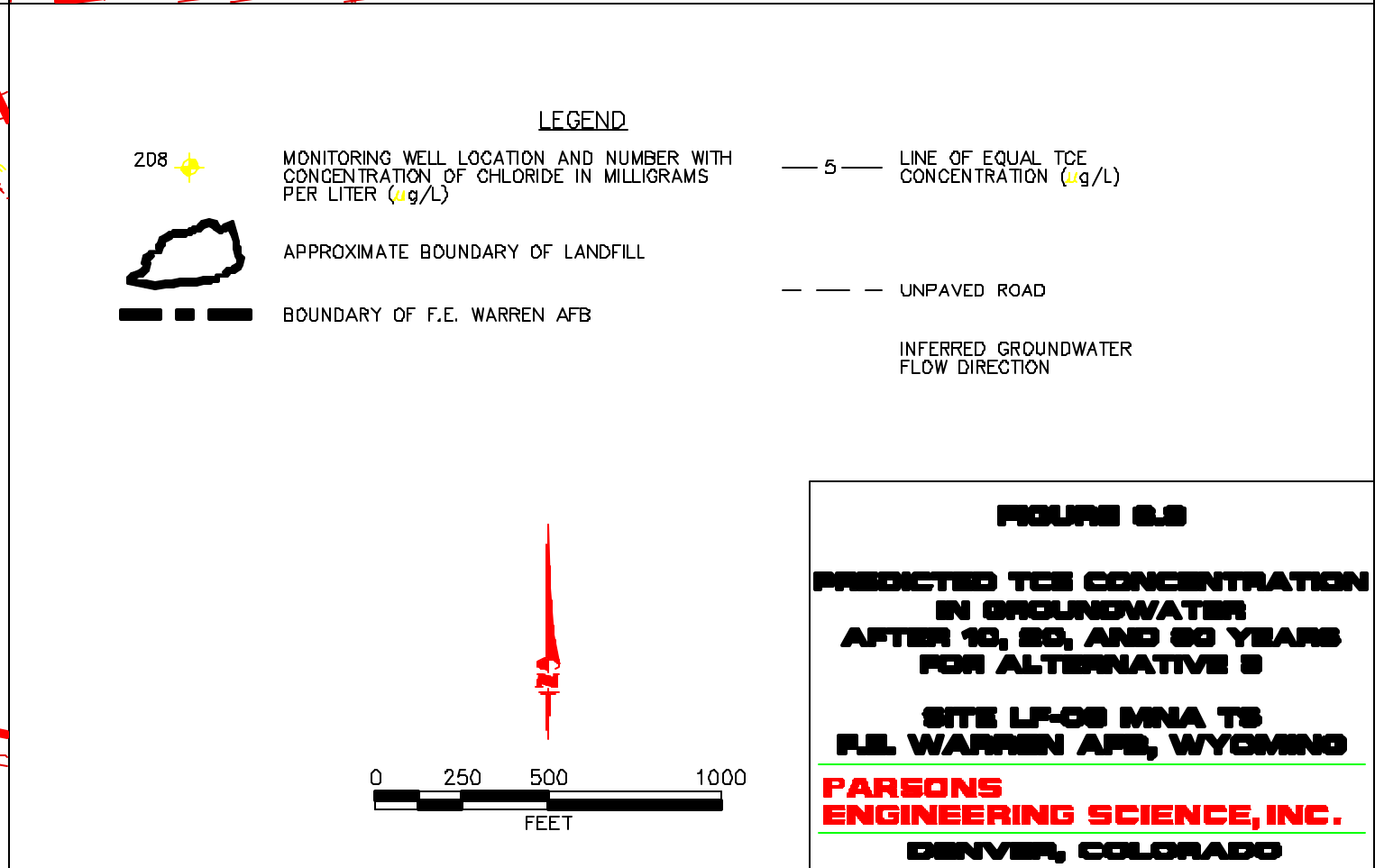
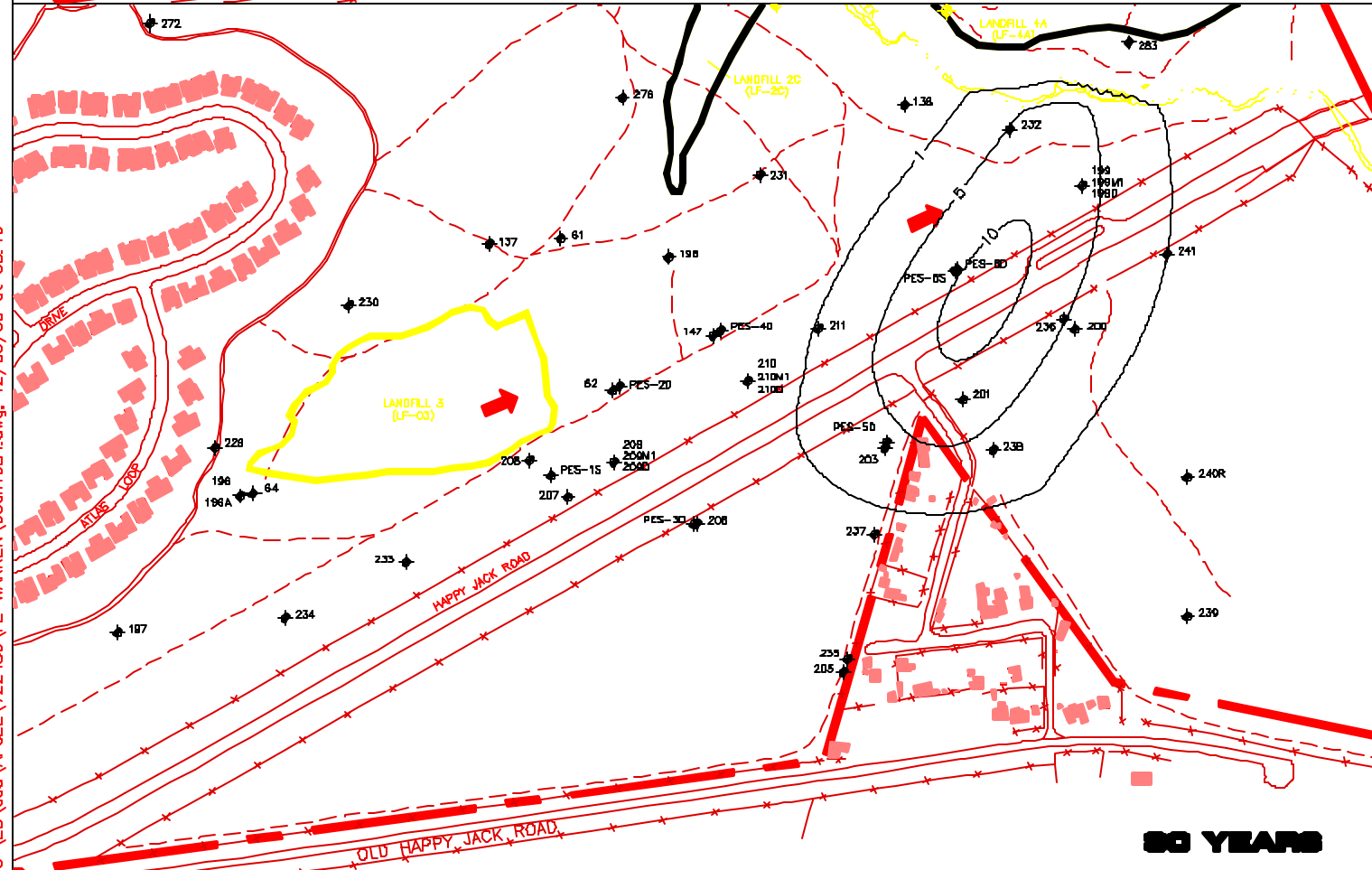
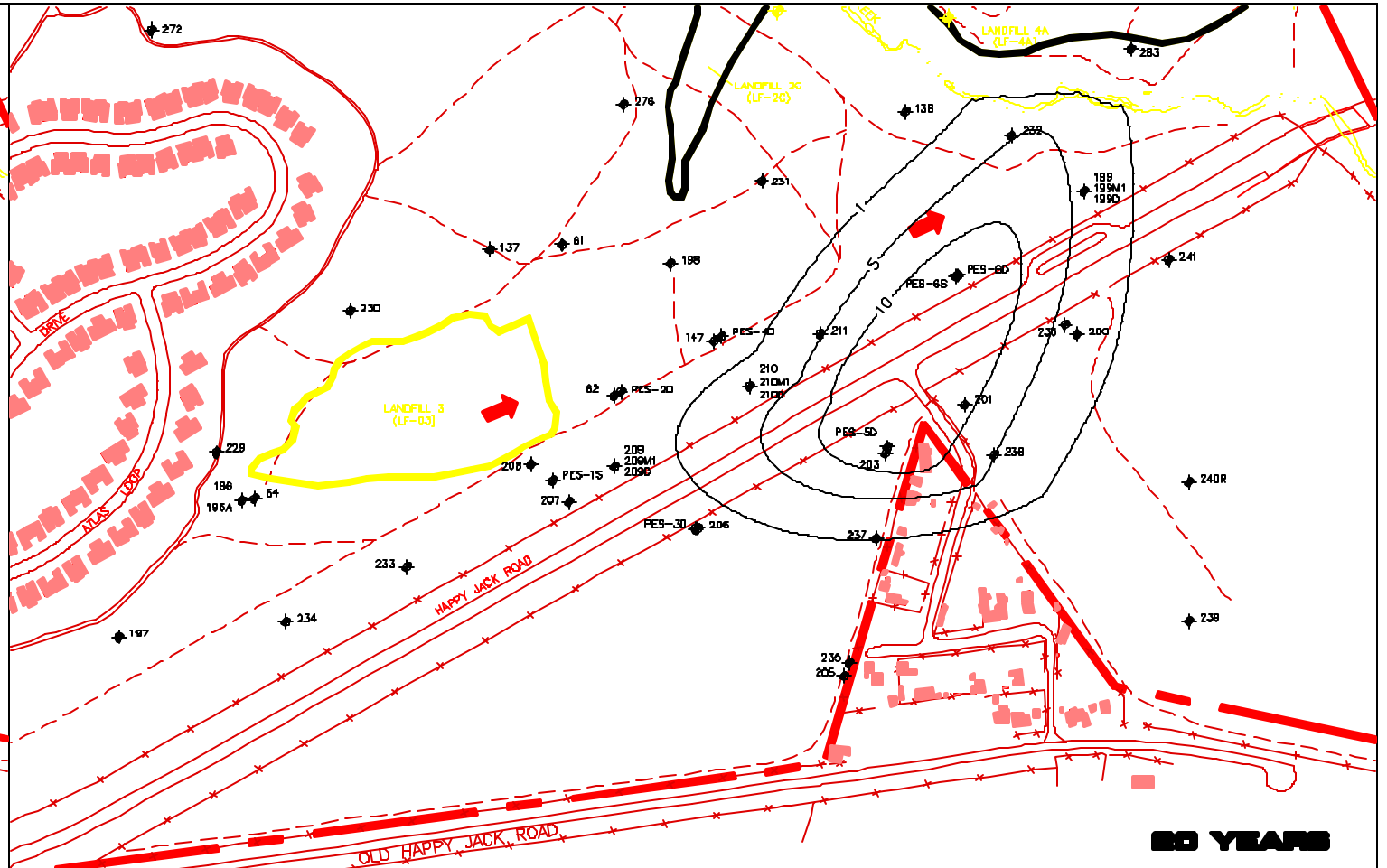
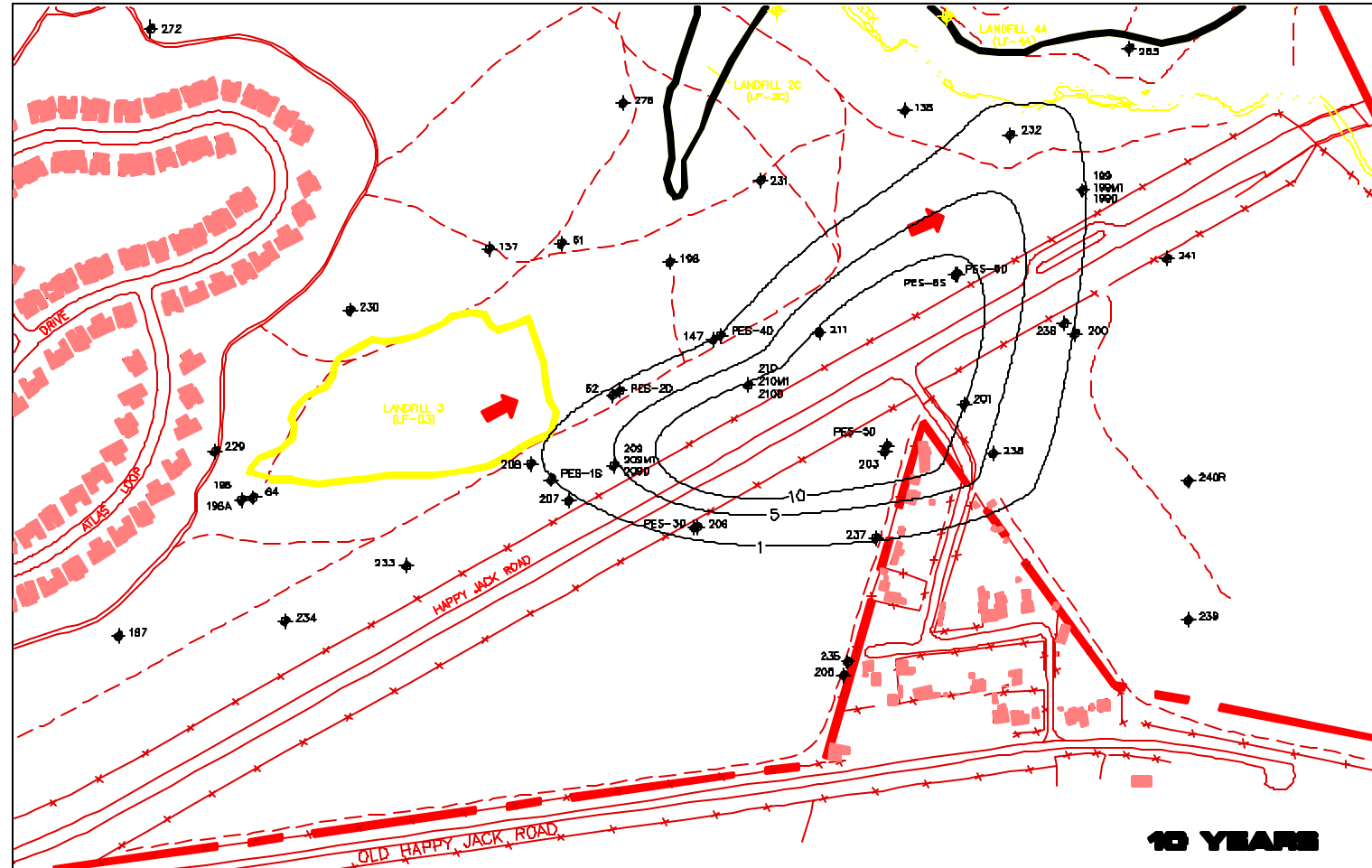


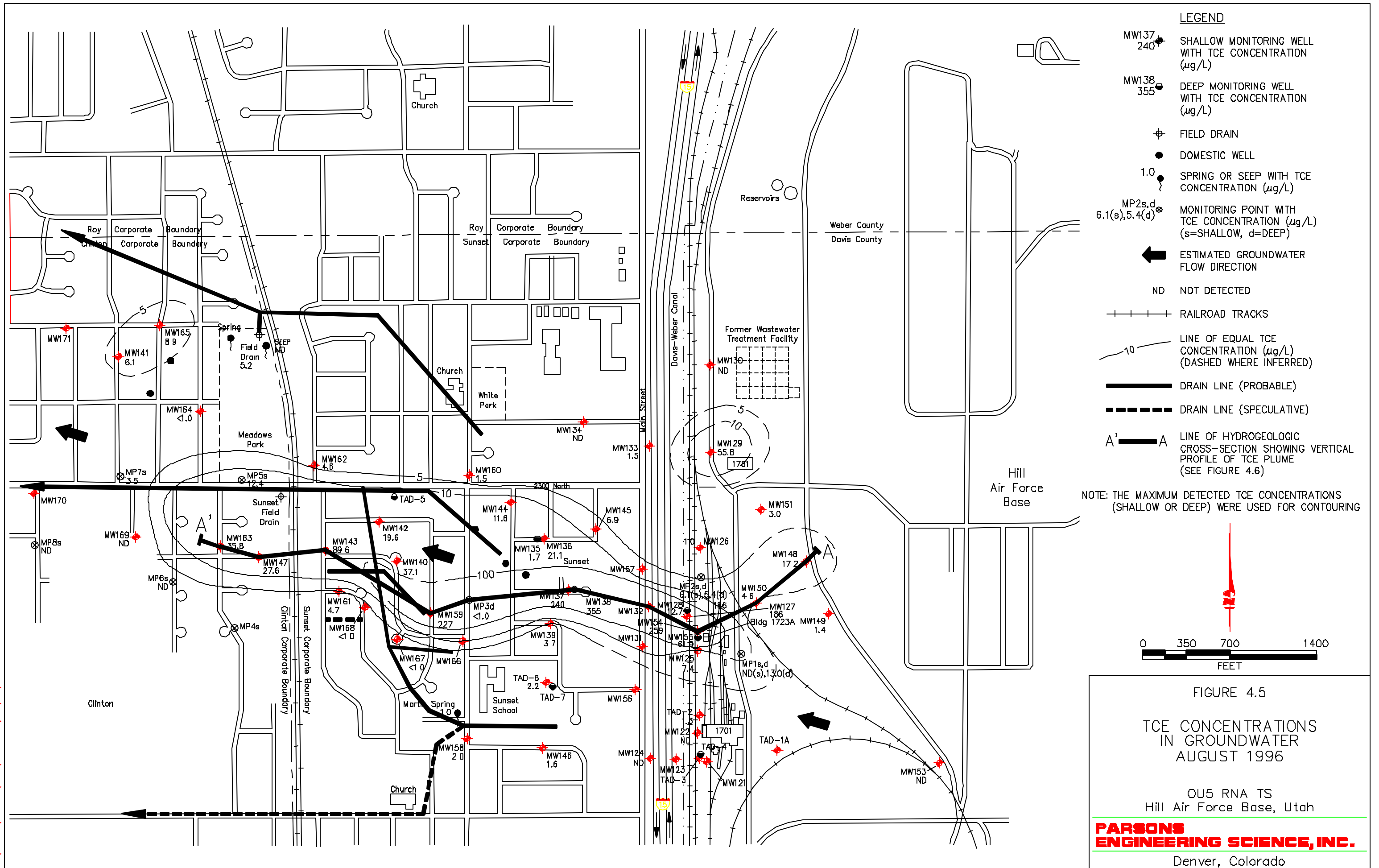
FIGURE 8.1
PREDICTED TCE CONCENTRATION
IN GROUNDWATER
AFTER 10, 20, AND 30 YEARS
FOR ALTERNATIVE 1
SITE LF-03 MNA TO
F.E. WARREN AFB, WYOMING
PARSONS
ENGINEERING SCIENCE, INC.
DENVER, COLORADO

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YEAR 2002



YEAR 2012



YEAR 2047



YEAR 2097

LEGEND

- ◆ SHALLOW MONITORING WELL
- DEEP MONITORING WELL
- ⊗ MONITORING POINT
- MWA ▲ SIMULATED OBSERVATION WELL
- 50 — LINE OF EQUAL SIMULATED TCE CONCENTRATION ($\mu\text{g/L}$)
CONTOUR INTERVAL = VARIABLE
- ➔ DIRECTION OF GROUNDWATER FLOW

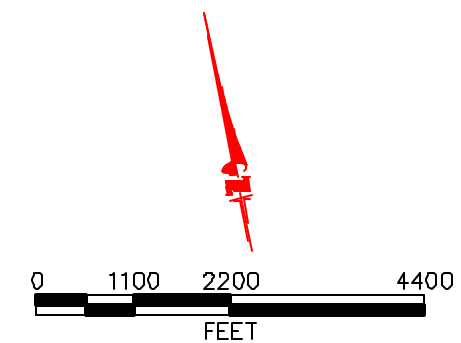


FIGURE 6.1

SIMULATED PLUME
MIGRATION
MODEL OU5-A

OU5 RNA TS
Hill Air Force Base, Utah

**PARSONS
ENGINEERING SCIENCE, INC.**

Denver, Colorado



YEAR 2002



YEAR 2012



YEAR 2047



YEAR 2097

LEGEND

- SHALLOW MONITORING WELL
- DEEP MONITORING WELL
- ⊗ MONITORING POINT
- MWA ▲ SIMULATED OBSERVATION WELL
- 50 — LINE OF EQUAL SIMULATED TCE CONCENTRATION ($\mu\text{g/L}$)
CONTOUR INTERVAL = VARIABLE
- ← DIRECTION OF GROUNDWATER FLOW

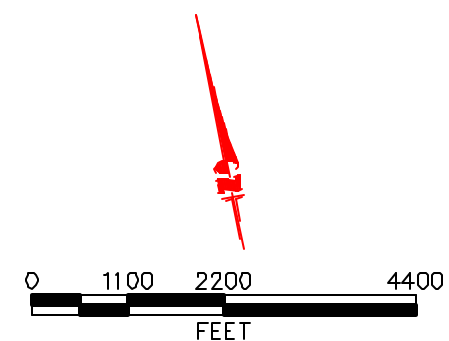


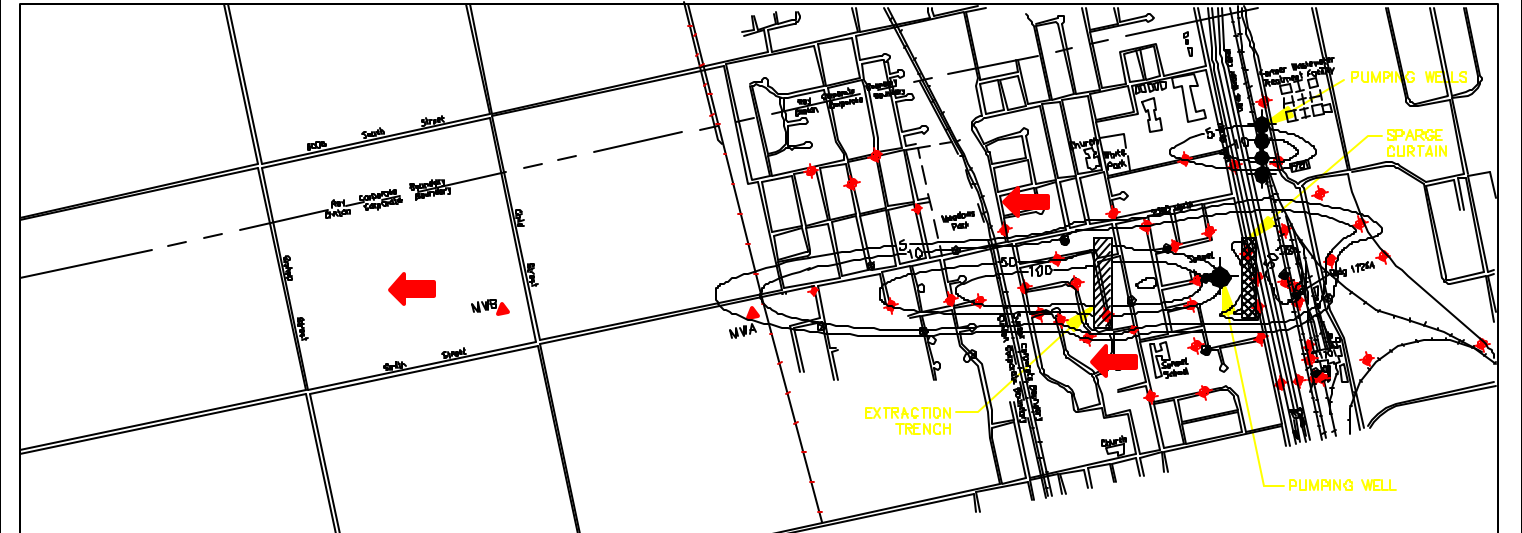
FIGURE 6.2
SIMULATED PLUME
MIGRATION
MODEL OU5-B

OU5 RNA TS
Hill Air Force Base, Utah

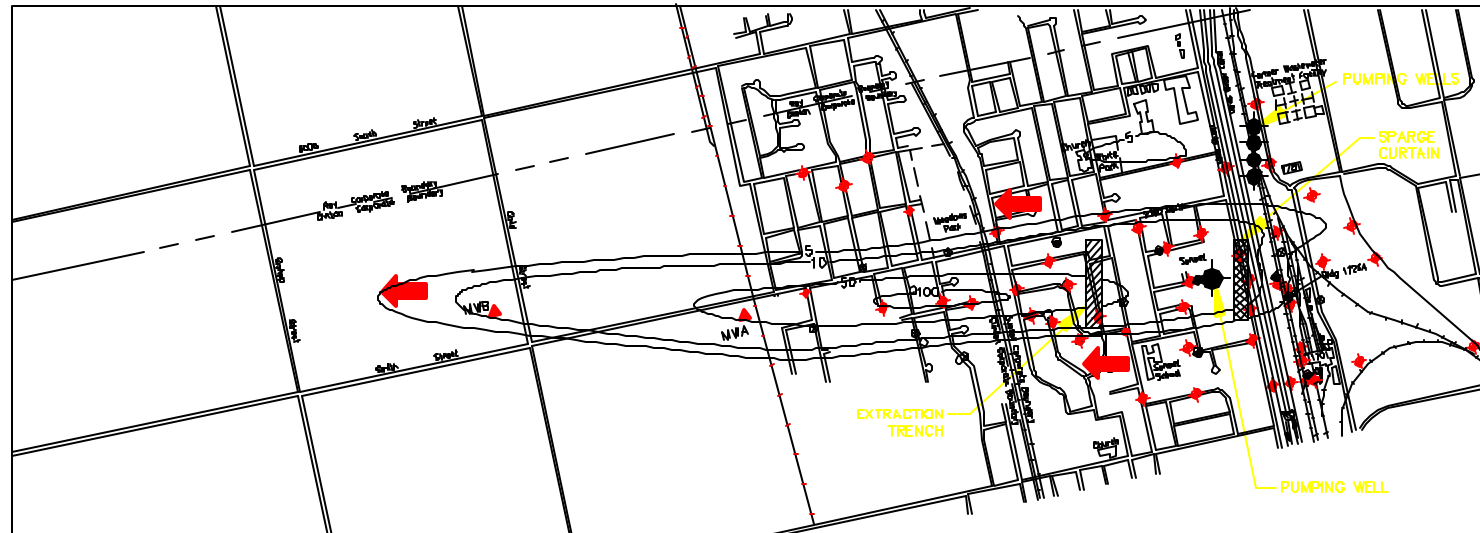
**PARSONS
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Denver, Colorado



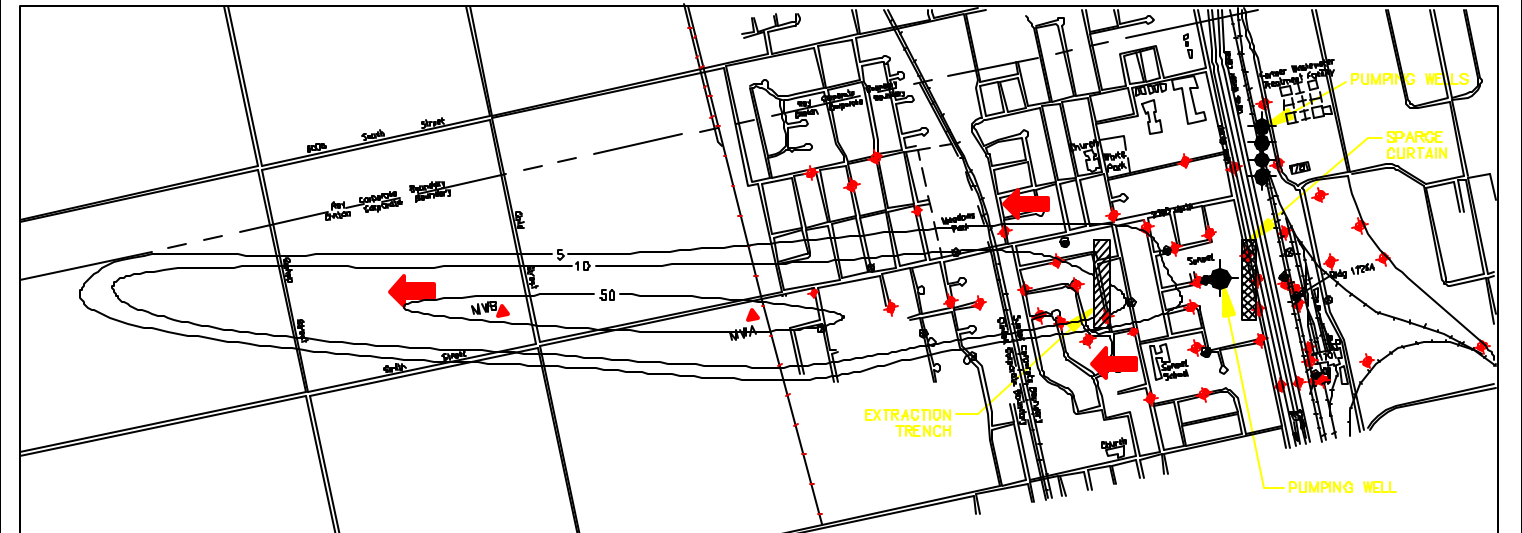
YEAR 2008



YEAR 2018



YEAR 2047



YEAR 2087

LEGEND

- ◆ SHALLOW MONITORING WELL
- DEEP MONITORING WELL
- ⊗ MONITORING POINT
- MWA ▲ SIMULATED OBSERVATION WELL
- 50 — LINE OF EQUAL SIMULATED TCE CONCENTRATION (µg/L)
CONTOUR INTERVAL = VARIABLE
- ← DIRECTION OF GROUNDWATER FLOW

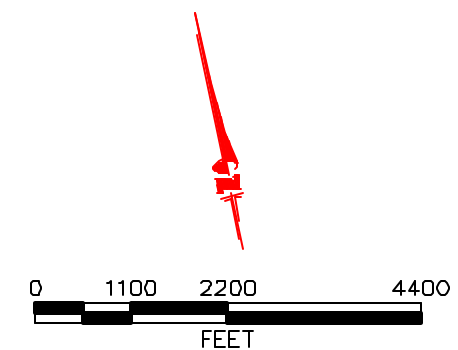
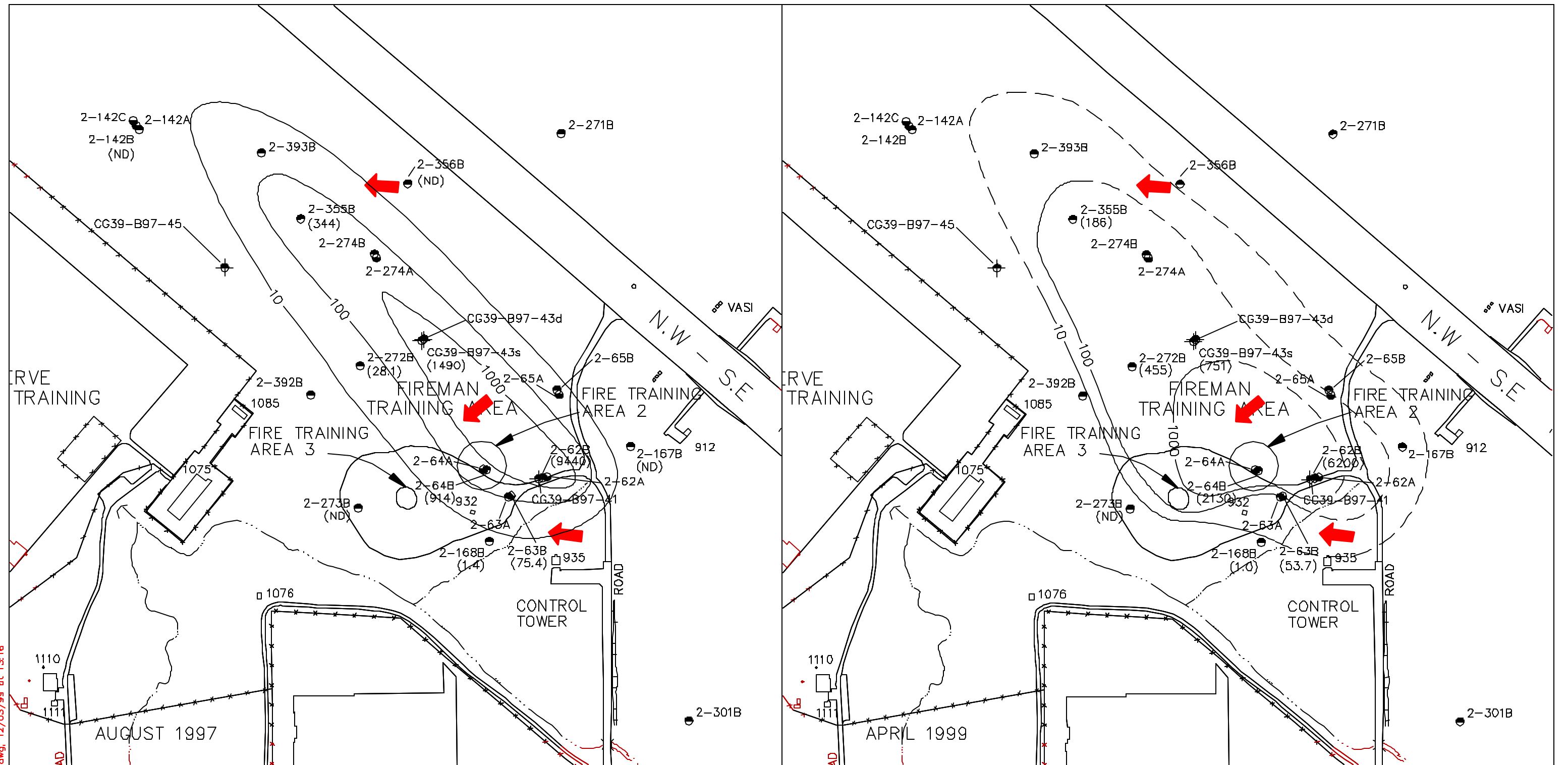


**FIGURE 6.3
SIMULATED PLUME
MIGRATION
MODEL CUS-C**

**CUS FNA TS
HILL AIR FORCE BASE, UTAH**
**PARSONS
ENGINEERING SCIENCE, INC.**
DENVER, COLORADO

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LEGEND

- | | | | |
|-------------|---|-------|--|
| 2-142B | UPPER SATURATED ZONE MONITORING WELL LOCATION AND ID NUMBER | | DIRECTION OF USZ GROUNDWATER FLOW |
| 2-142A | LOWER SATURATED ZONE MONITORING WELL LOCATION AND ID NUMBER | ND | NOT DETECTED |
| CG39-B97-41 | MONITORING POINT LOCATION/UPPER SATURATED ZONE | (1.4) | ALL CONCENTRATIONS IN MICROGRAMS PER LITER ($\mu\text{g/L}$) |
| s,d | SHALLOW AND DEEP USZ MONITORING POINT/ WELL PAIR | —10— | LINE OF EQUAL TCE CONCENTRATION ($\mu\text{g/L}$) |

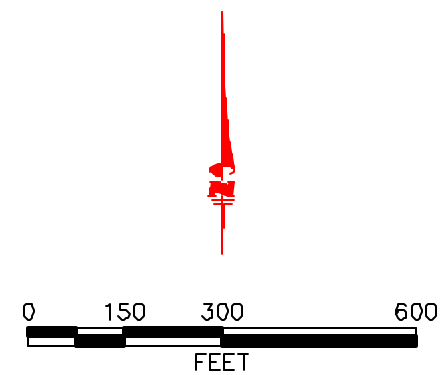


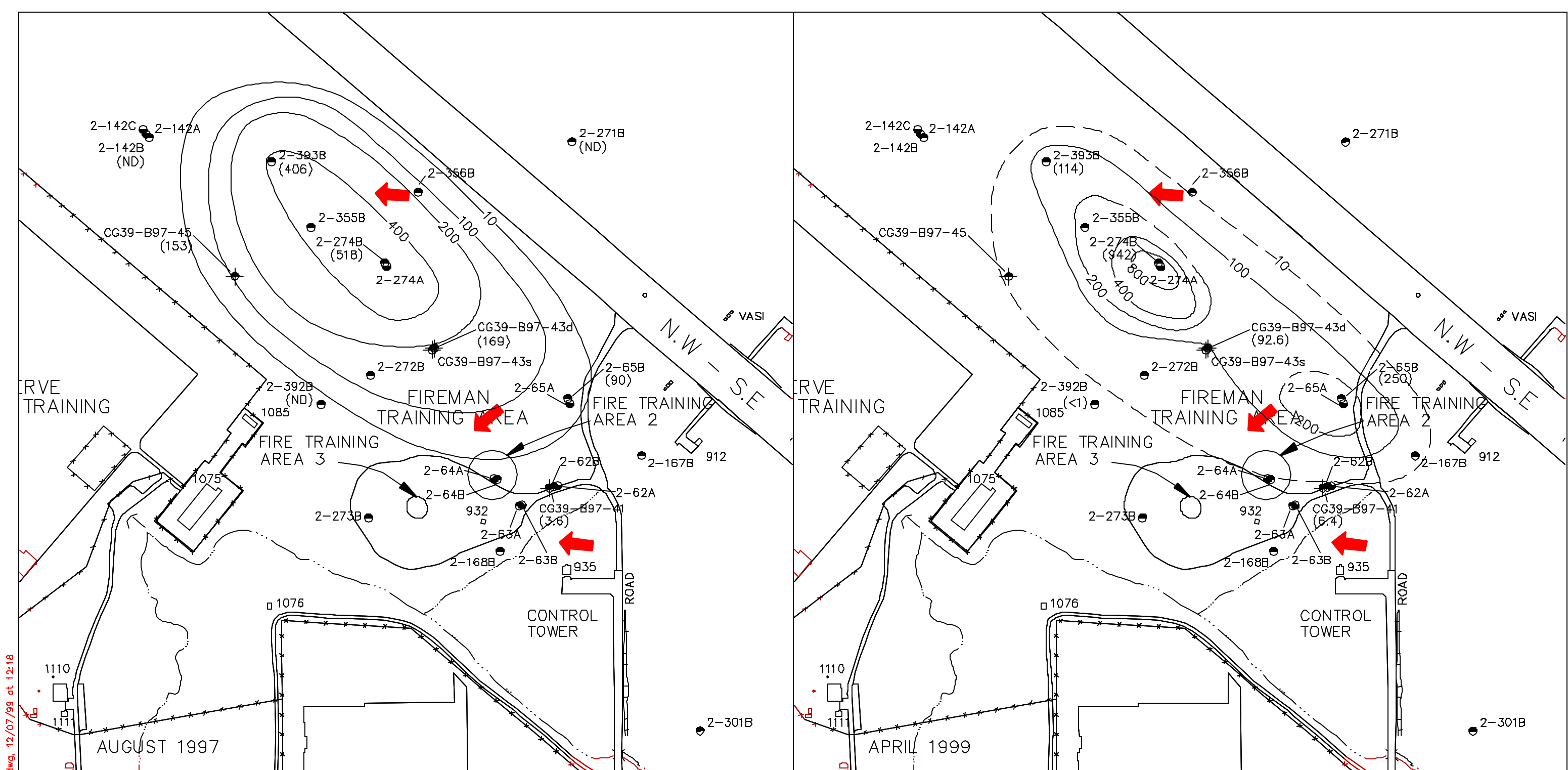
FIGURE 5

CONCENTRATION OF TCE
IN UPPER USZ GROUNDWATER
AUGUST 1997 AND APRIL 1999

Site FTA-2 RNA TS Addendum
Tinker AFB, Oklahoma

**PARSONS
ENGINEERING SCIENCE, INC.**
Denver, Colorado

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LEGEND

- | | | | |
|---------------|---|-------|---|
| 2-142B ● | UPPER SATURATED ZONE MONITORING WELL LOCATION AND ID NUMBER | —10— | LINE OF EQUAL TCE CONCENTRATION (µg/L) |
| 2-142A ● | LOWER SATURATED ZONE MONITORING WELL LOCATION AND ID NUMBER | (3.6) | ALL CONCENTRATIONS IN MICROGRAMS PER LITER (µg/L) |
| CG39-B97-41 ● | MONITORING POINT LOCATION/ UPPER SATURATED ZONE | (ND) | NOT DETECTED |
| s,d | SHALLOW AND DEEP USZ MONITORING POINT/WELL PAIR | ➔ | DIRECTION OF USZ GROUNDWATER FLOW |

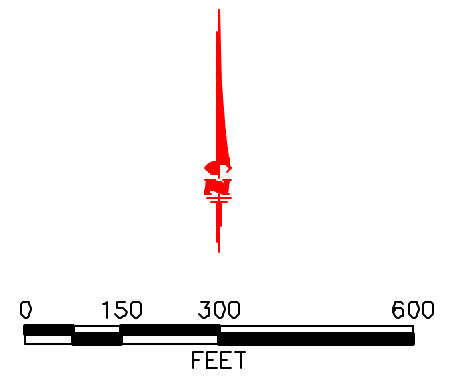


FIGURE 6

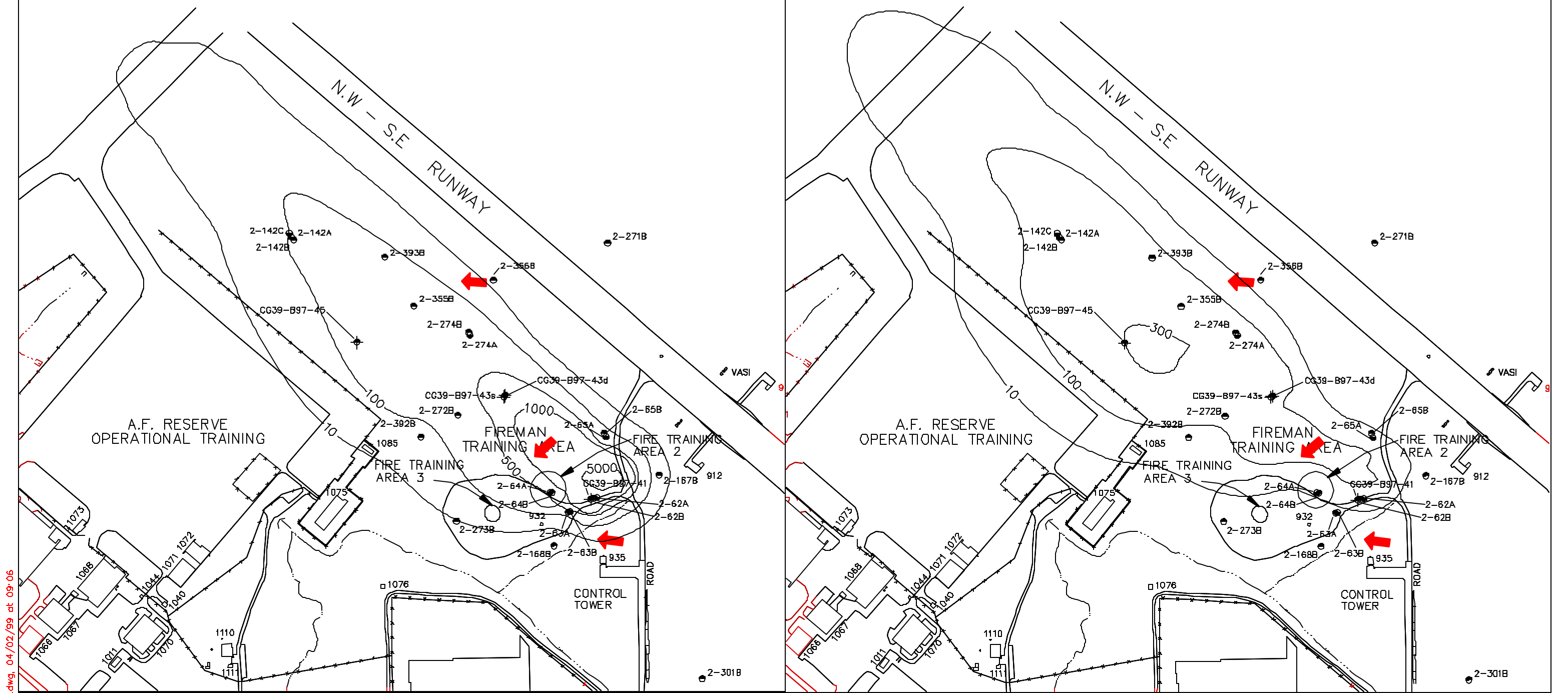
CONCENTRATION OF TCE
IN LOWER USZ GROUNDWATER
AUGUST 1997 AND APRIL 1999

Site FTA-2 RNA TS Addendum
Tinker AFB, Oklahoma

**PARSONS
ENGINEERING SCIENCE, INC.**
Denver, Colorado

PREDICTED TCE CONCENTRATIONS IN UPPER
USZ GROUNDWATER AFTER 35 YEARS

PREDICTED TCE CONCENTRATIONS IN LOWER
USZ GROUNDWATER AFTER 35 YEARS



LEGEND

- 2-142B ● UPPER SATURATED ZONE MONITORING WELL LOCATION AND ID NUMBER
- 2-142A ● LOWER SATURATED ZONE MONITORING WELL LOCATION AND ID NUMBER
- CG39-B97-41 ● MONITORING POINT LOCATION/ UPPER SATURATED ZONE
- s,d ● SHALLOW AND DEEP USZ MONITORING POINT/ WELL PAIR
- ← GROUNDWATER FLOW DIRECTION
- ALL CONCENTRATIONS IN MICROGRAMS PER LITER (µg/L)
- 10— LINE OF EQUAL TCE CONCENTRATION (µg/L)

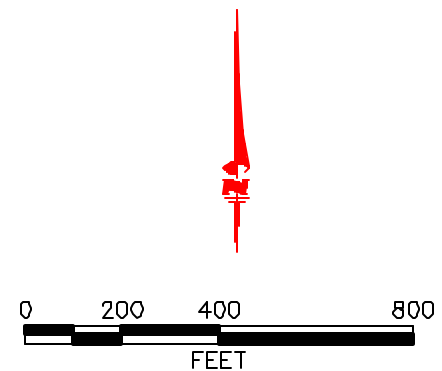
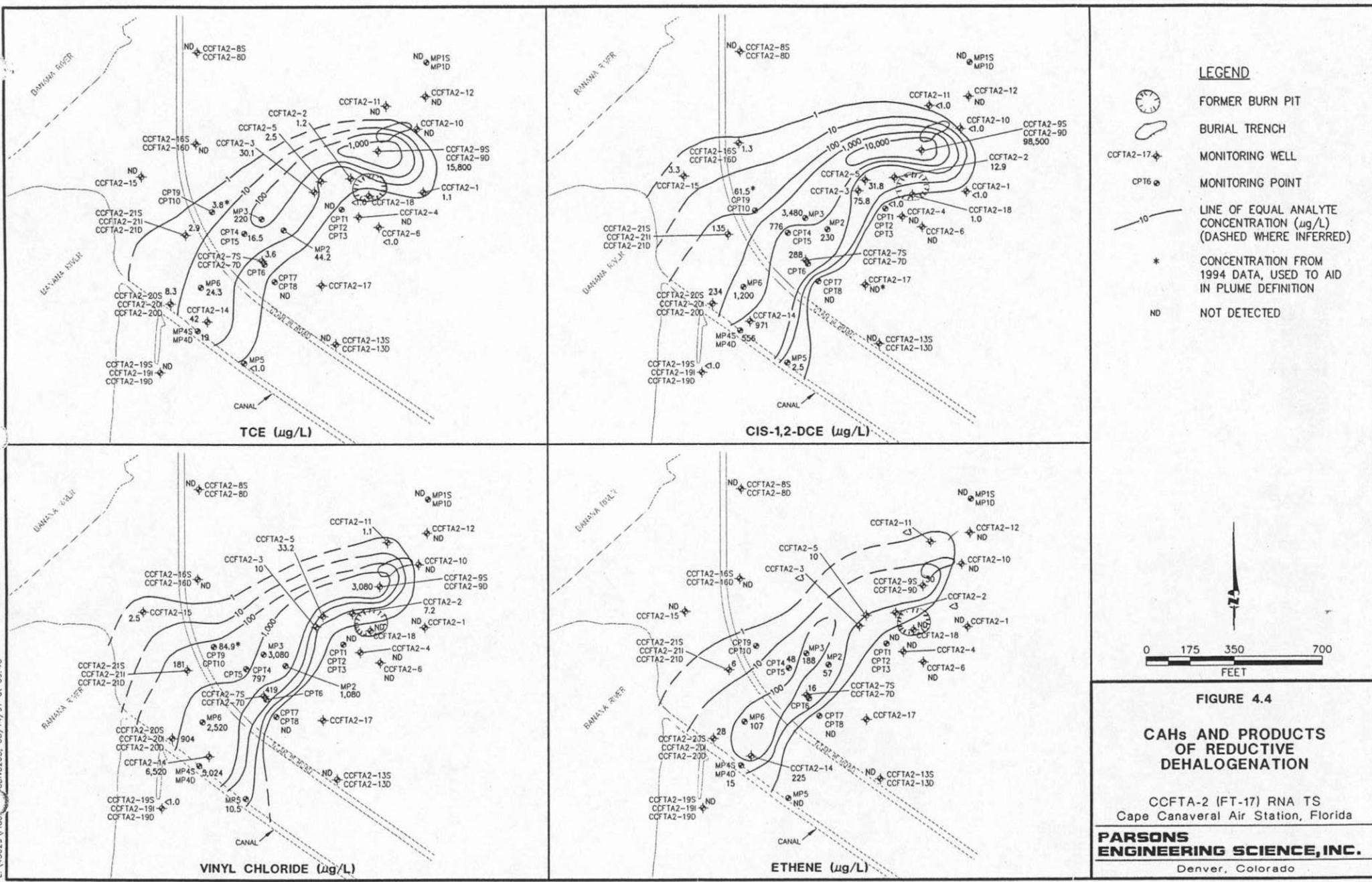


FIGURE 6.1
PREDICTED TCE
CONCENTRATIONS IN USZ
GROUNDWATER AFTER 35
YEARS FOR ALTERNATIVE 1
Site FTA-2
RNA TS
Tinker AFB, Oklahoma
**PARSONS
ENGINEERING SCIENCE, INC.**
Denver, Colorado

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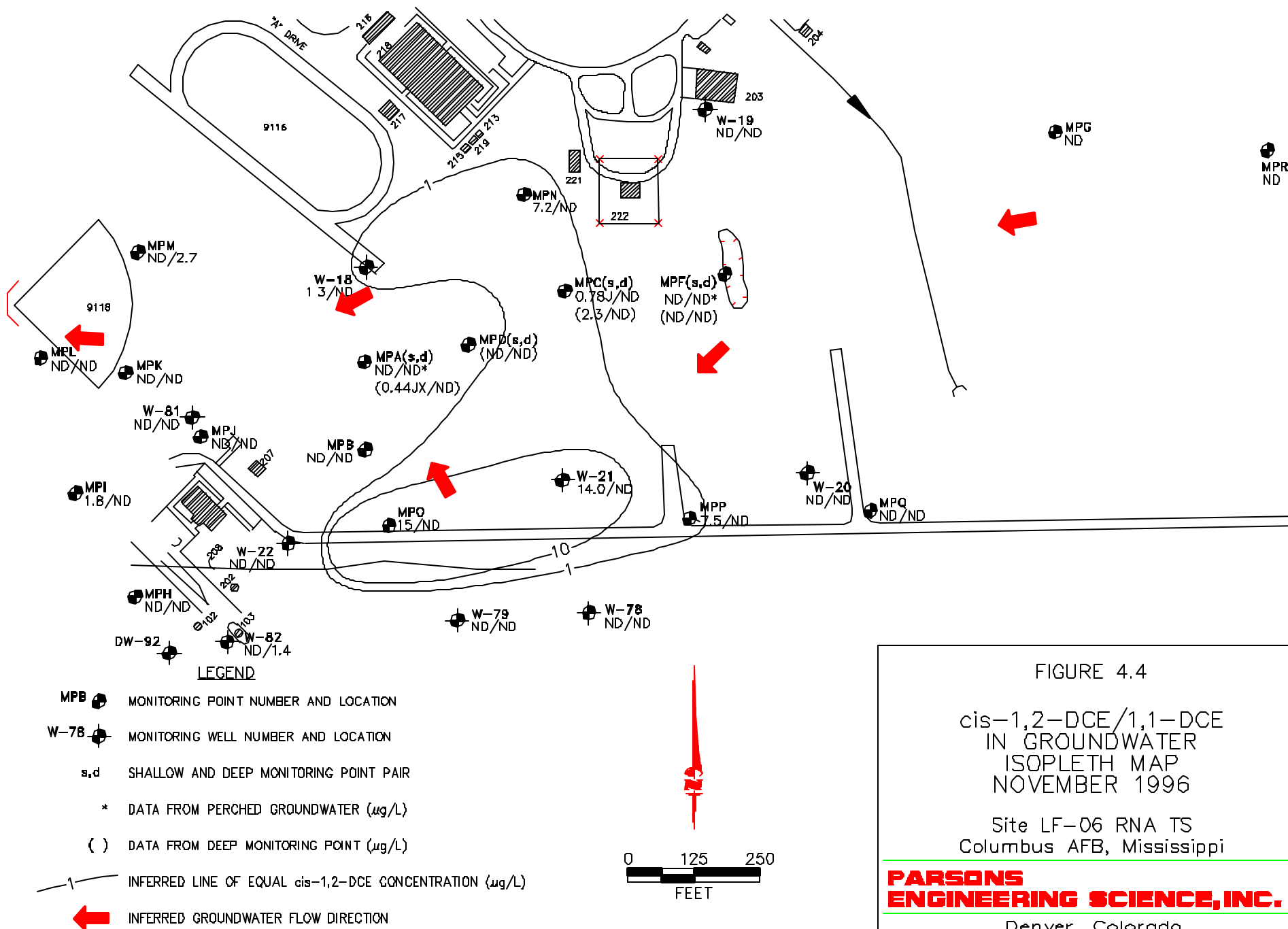


FIGURE 4.4

cis-1,2-DCE/1,1-DCE
IN GROUNDWATER
ISOPLETH MAP
NOVEMBER 1996

Site LF-06 RNA TS
Columbus AFB, Mississippi

**PARSONS
ENGINEERING SCIENCE, INC.**

Denver, Colorado

LEGEND

- | | | |
|------|--|--|
| MPB | | MONITORING POINT NUMBER AND LOCATION |
| W-78 | | MONITORING WELL NUMBER AND LOCATION |
| s,d | | SHALLOW AND DEEP MONITORING POINT PAIR |
| * | | DATA FROM PERCHED GROUNDWATER (g/L) |
| () | | DATA FROM DEEP MONITORING POINT (μg/L) |
| 1 | | LINE OF EQUAL VINYL CHLORIDE CONCENTRATION (μg/L)
{ DASHED WHERE INFERRED } |
| | | INFERRED GROUNDWATER FLOW DIRECTION |

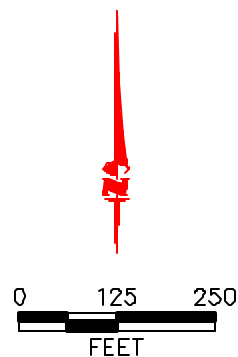


FIGURE 4.5

VINYL CHLORIDE
IN GROUNDWATER
ISOPLETH MAP
NOVEMBER 1996

Site LF-06 RNA TS
Columbus AFB, Mississippi

**PARSONS
ENGINEERING SCIENCE, INC.**

Denver, Colorado

APPENDIX B
RESPONSES TO COMMENTS

11 June 2001

Mr. Jerry Hansen
Technical Program Manager
AFCEE/ERT
3207 North Road, Bldg. 532
Brooks AFB, TX 78235-5363

Subject: Responses to Comments on the Draft Comparison of Predicted and Observed
Plume Trends at Fuel and Solvent Contaminated Sites, Technical Summary
Report (Contract F11623-94-D0024, RL71)

Dear Mr. Hansen:

This letter provides responses to comments received on the Draft Comparison of Predicted and Observed Plume Trends at Fuel and Solvent Contaminated Sites, Technical Summary Report. This draft report was prepared by Parsons Engineering Science, Inc. (Parsons ES) for the Technology Transfer Division, Air Force Center for Environmental Excellence Technology Transfer Division (AFCEE/ERT). The draft report was submitted to AFCEE/ERT on 26 April 2001. Comments on the draft report were received from AFCEE/ERT as reviewed by Jon Atkinson dated 07 June 2001. Responses to these comments were prepared by Parsons ES and are presented herein.

AFCEE/ERT Comments

General Comment

Comment 1) Inclusion in Sections 4 and 5 of plume concentration contour maps for several sites comparing and contrasting historical contaminant trends with computer model predicted concentration distributions would enhance the discussion significantly.

Parsons ES Response: *Parsons ES agrees that plume maps would enhance the discussion. However, these plume maps are available in the referenced documents and inclusion in this report is not within the intended brevity of this technical summary report. Therefore, Parsons ES requests that plume maps not be added to the report, but that references be provided for the readers use.*

Specific Comments

Comment 2) Page ES-2, Para 1:

- a. Here, or in a following paragraph, suggest briefly describing the analytical model BIOSCREEN that was used at two sites.
- b. Sent 2: Here, and throughout the report, “Bioplume II” should be changed to “BIOPLUME II.”

Parsons ES Response: a. A description of the BIOSCREEN model, and all other models referenced in the report, is contained in Section 3. For completeness, the following sentence will be added after Sentence 3, Paragraph 1, Page ES-2:

“In addition, BIOSCREEN is common analytical model used to predict the fate and transport of fuel hydrocarbons, and was used for two sites evaluated for this study .”

b. The text will be changed as recommended.

Comment 3) Page ES-2, Para 2, Sent 1: For sake of completeness, suggest expanding as follows: “Most of the calibrated BIOPLUME II and BIOSCREEN models for fuel . . .”.

Parsons ES Response: The text will be changed as suggested.

Comment 4) Page ES-2 Para 3, Sent 1:

- a. Suggest annotating whether the stated source weathering rates are geometric or linear percentages.
- b. Recommend adding the equivalent half-life values “(half lives of 690 – 99 days)” after the stated decay rates. This comment applies to the remainder of the “Fuel Hydrocarbon Sites” section.

Parsons ES Response: a. The text will be amended to indicate that the stated source weathering rates are geometric.

b. Equivalent half-lives will be added to all reported decay rates throughout the report.

Comment 5) Page ES-3, Para 3: Suggest annotating whether the stated source weathering rates are geometric or linear percentages.

Parsons ES Response: *The text will be amended to indicate that the stated source weathering rates are geometric.*

Comment 6) Page 1-1, Sec 1, Para 3, Line 8: To enhance clarity, suggest inserting “to” in front of “evaluate.”

Parsons ES Response: *The text will be changed as suggested.*

Comment 7) Page 2-2, Sec 2.1, Para 1, Line 3: Suggest deleting the “such” following “items.”

Parsons ES Response: *The text will be changed as suggested.*

Comment 8) Page 2-4, Table 2.2: For Site LF-06, “Columbus AFB, MO” should be changed to “Columbus AFB, MS.”

Parsons ES Response: *The table will be corrected as indicated.*

Comment 9) Page 3-9, Sec 3.3.2, Para 1, Sent 2: Recommend deleting “the” immediately preceding “none.”

Parsons ES Response: *The text will be changed as recommended.*

Comment 10) Page 4-2, Sec 4.1.1.3, Para 1, Sent 2: Suggest annotating whether the stated source weathering rates are geometric or linear percentages.

Parsons ES Response: *The text will be amended to indicate that the stated source weathering rates are geometric.*

Comment 11) Pages 4-2 and 4-3, Sec 4.1.1.3, Para 2, Last Sent: Recommend stating briefly the rationale for reducing the weathering rates starting in 2036. Additionally, suggest annotating whether the stated source weathering rates are geometric or linear percentages.

Parsons ES Response: *Review of the Model TRV1 source weathering rates indicates the geometric source weathering rates were reduced gradually from 1996 to 2036, the end of the model run. Therefore, Page 4-2, Section 4.1.1.3, Paragraph 2 will be corrected to read:*

“Model TRV1 assumed that the geometric source weathering rate would gradually decrease over time due to an anticipated decrease in source size and changes in the source composition. The geometric weathering rates were reduced from 2.3 %/yr and 4.9 %/yr in 1996 to 1.2 %/yr and 1.7 %/yr in 2036 for the NGS and SGS source areas, respectively. By the end of the model predictive period in 2036, the simulated source concentrations were approximately 44 percent and 25 percent of the initial source concentrations at the NGS and SGS, respectively.”

Comment 12) Page 4-5, Sec 4.1.2, Para 2:

- a. Line 5: Recommend deleting “from.”
- b. Sents 1 and 3: Suggest annotating whether the stated source weathering rates are geometric or linear percentages..

Parsons ES Response: *a. The text will be changed as recommended*

b. The text will be amended to indicate that the stated source weathering rates are geometric.

Comment 13) Page 4-8, Sec 4.2.1.3, Last Sent: Recommend briefly describing the difference between linear and geometric weathering rates. If some calculations need to be included in this explanation, suggest placing them in an appendix.

Parsons ES Response: *In order to clarify the difference between liner and geometric rates for source reduction, the following text will be added after Paragraph 1, Section 3.3.2, Page 3-9:*

“Geometric (first-order) source reduction rates result in lower reductions in source concentration or mass per year over time because the current reduction is dependent on the previous time-period concentration or mass. Because processes such as volatilization, dissolution, or biodegradation are thought to be concentration dependent, geometric (first-order) rates are typically used to simulate natural weathering rates. Linear (zero-order) source reduction rates result in a fixed reduction of

the initial source concentration or mass per time-period, and are generally used to simulate engineered source reduction.”

Comment 14) Page 4-8, Sec 4.2.1.4, Para 2, Line 5: Suggest inserting “in” following “localized.”.

Parsons ES Response: *The text will be changed as recommended.*

Comment 15) Page 4-9, Sec 4.2.2, Para 1, Line 3: Recommend inserting “be” immediately following “to.”

Parsons ES Response: *The text will be changed as recommended.*

Comment 16) Page 4-16, Sec 4.4.1.3, Sent 1: Suggest annotating whether the stated source weathering rates are geometric or linear percentages.

Parsons ES Response: *The text will be amended to indicate that the stated source weathering rates are geometric.*

Comment 17) Page 4-17, Table 4.7: To better reflect accuracy/certainty of the analytical results, recommend reporting values to no more than three significant figures

Parsons ES Response: *Analytical results will be reported to no more than three significant figures as recommended.*

Comment 18) Page 4-18, Sec 4.4.2, Para 2, Line 3: To better reflect accuracy/certainty of the analytical result, recommend reporting the value to no more than three significant figures.

Parsons ES Response: *Analytical results will be reported to no more than three significant figures as recommended.*

Comment 19) Page 4-19, Sec 4.4.2, Sent 1: Suggest annotating whether the stated source weathering rates are geometric or linear percentages.

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Parsons ES Response: *The text will be amended to indicate that the stated source weathering rates are geometric.*

Comment 20) Page 4-22, Sec 4.6.1.1, Line 1: To enhance completeness, suggest inserting “analytical” in front of “model.”

Parsons ES Response: *The text will be changed as recommended.*

Comment 21) Page 5-18, Sec 5.4.2, Para 1, Line 4: To better reflect accuracy/certainty of the analytical result, recommend reporting the value to no more than three significant figures.

Parsons ES Response: *Analytical results will be reported to no more than three significant figures as recommended.*

Comment 22) Page 6-4, Sec 6.1.1, Para 1, Sent 2 and Para 3, Sent 1: Suggest annotating whether the stated source weathering rates are geometric or linear percentages.

Parsons ES Response: *The text will be amended to indicate that the stated source weathering rates are geometric.*

If you have any questions, have additional comments, or require additional information, please call me at (303) 831-8100.

Sincerely,

PARSONS ENGINEERING SCIENCE, INC.

Bruce M. Henry, P.G.
Project Manager

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