In cooperation with the
UNITED STATES AIR FORCE
Dover Air Force Base

Assessment of Natural Attenuation of Ground-Water Contamination at Sites FT03, LF13, and WP14/LF15, Dover Air Force Base, Delaware

Water-Resources Investigations Report 01–4150

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By Jeffrey R. Barbaro

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Acronyms and Abbreviations

BTEX	benzene, toluene, ethylbenzene, total xylenes
COC	chain of custody
DAFB	Dover Air Force Base
cis-1,2-DCE	*cis*-1,2-dichloroethene
cm	centimeter
1,2-DCA	1,2-dichloroethane
DIC	dissolved inorganic carbon
EMU	East Management Unit
f_{oc}	weight fraction of organic carbon
ft	foot
ft/d	foot per day
ft/ft	foot per foot
FT03	Fire Training Area Three
g	gram
g/cm^3	gram per cubic centimeter
g/g	gram per gram
in	inch
in/yr	inch per year
K_d	distribution coefficient
K_{oc}	organic-carbon-based partition coefficient
L^3/M	volume per unit mass
LF13	Rubble Area Landfill
LF15	Receiver Station Landfill
MCL	maximum contaminant level
MDL	method detection limit
mg/L	milligram per liter
mL/g	milliliter per gram
n	porosity
NAPL	non-aqueous phase liquid
OD	outer diameter
1,1,2,2-TeCA	1,1,2,2-tetrachloroethane
PCE	tetrachloroethene
POC	point of compliance
PVC	polyvinylchloride
QC	quality control
R	retardation factor
RI	remedial investigation
TEAP	terminal electron-accepting process
TCE	trichloroethene
trans-1,2-DCE	*trans*-1,2-dichloroethene
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VOC	volatile organic compound
WP14	Liquid Waste Disposal Landfill
ρ_b	dry bulk density
µg/L	microgram per liter
VC	vinyl chloride
yr	year

Conversion Factors and Vertical Datum

Multiply	By	To obtain
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
foot per day (ft/d)	30.48	centimeter per day
inch per year (in/yr)	2.54	centimeter per year
acre	0.4047	hectare

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) by using the following equation:

$$°C = 5/9 \times (°F - 32)$$

Vertical datum: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Assessment of Natural Attenuation of Ground-Water Contamination at Sites FT03, LF13, and WP14/LF15, Dover Air Force Base, Delaware

By Jeffrey R. Barbaro

Abstract

Water-quality, aquifer-sediment, and hydrologic data were used to assess the effectiveness of natural attenuation of ground-water contamination at Fire Training Area Three, the Rubble Area Landfill, the Liquid Waste Disposal Landfill, and the Receiver Station Landfill in the East Management Unit of Dover Air Force Base, Delaware. These sites, which are contaminated with chlorinated solvents and fuel hydrocarbons, are undergoing long-term monitoring to determine if natural attenuation continues to sufficiently reduce contaminant concentrations to meet regulatory requirements. This report is the first assessment of the effectiveness of natural attenuation at these sites since long-term monitoring began in 1999, and follows a preliminary investigation done in 1995–96. This assessment was done by the U.S. Geological Survey in cooperation with the U.S. Air Force.

Since 1995–96, additional information has been collected and used in the current assessment. The conclusions in this report are based primarily on ground-water samples collected from January through March 2000. Previous analytical results from selected wells, available geologic and geophysical well logs, and newly acquired information such as sediment organic-carbon measurements, hydraulic-conductivity measurements determined from slug tests on wells in the natural attenuation study area, and water-level measurements from surficial-aquifer wells also were used in this assessment. This information was used to: (1) calculate retardation factors and estimate contaminant migration velocities, (2) improve estimates of ground-water flow directions and inferred contaminant migration pathways, (3) better define the areal extent of contamination and the proximity of contaminants to discharge areas and the Base boundary, (4) develop a better understanding of the vertical variability of contaminant concentrations and redox conditions, (5) evaluate the effects of temporal changes on concentrations in the plumes and source areas, and (6) determine whether intrinsic biodegradation is occurring at these sites.

The water-quality data indicate that intrinsic biodegradation is occurring at all three sites. The strongest indication of intrinsic biodegradation is the detection of tetrachloroethene and trichloroethene breakdown products within and downgradient of the source areas. The patterns of electron acceptors and metabolic by-products indicate that contaminant biodegradation has changed the prevailing geochemistry of the surficial aquifer, creating the strongly reducing conditions necessary for chlorinated solvent biodegradation. Geochemical changes include depleted dissolved oxygen and elevated ferrous iron and methane levels relative to concentrations in uncontaminated zones of the surficial aquifer. At Fire Training Area Three and the Rubble Area Landfill sites, natural attenuation appears to be adequate for controlling the migration of the contaminant plumes. At the third site, the Liquid Waste Disposal and Receiver Station Landfills, the plume is larger and the uncertainty about the effectiveness of natural attenuation in reducing contaminant concentrations and controlling plume migration is greater. Ground-water data indicate, however, that U.S. Environmental Protection Agency maximum contaminant levels were not exceeded in any point-of-compliance wells located along the Base boundary.

The information presented in this report led to the development of improved conceptual models for these sites, and to the recognition of four issues

that are currently unclear and may need further study. These issues include delineating the areal and vertical extent of the contaminant plumes in greater detail, determining the extent of intrinsic biodegradation downgradient of the Liquid Waste Disposal and Receiver Station Landfills, determining the fate of contaminants in the ground-water discharge areas, and determining the effect of temporal variability in source concentrations and ground-water flow patterns on the plume migrating from the Liquid Waste Disposal and Receiver Station Landfills. Some of these issues have been addressed with additional data collection since the January–March 2000 sampling round.

Introduction

Historical activities such as fire training and waste disposal in the East Management Unit (EMU) of Dover Air Force Base (DAFB), Delaware (figs. 1a and 1b) have resulted in subsurface contamination with organic chemicals. Previous investigations have shown that ground water contains detectable concentrations of a variety of volatile organic compounds (VOCs), including fuel hydrocarbons such as benzene, toluene, and xylenes, chlorinated solvents such as chlorinated ethenes and ethanes, and chlorinated benzenes (U.S. Army Corps of Engineers and Dames and Moore, Inc., 1997a; Bachman and others, 1998; Beman and others, 1999). Because some of these compounds were detected in ground water at concentrations exceeding maximum contaminant levels (MCLs) established by the U.S. Environmental Protection Agency (USEPA), considerable efforts have been made over the past decade to investigate the area, and to develop remedial alternatives (U.S. Army Corps of Engineers and Dames and Moore, Inc., 1997a, b). The selected remediation for Fire Training Area Three (FT03), the Rubble Area Landfill (LF13), the Liquid Waste Disposal Landfill (WP14), and the Receiver Station Landfill (LF15) in the EMU (fig. 2) is natural attenuation (U.S. Army Corps of Engineers and Dames and Moore, Inc., 1997b). As part of the selected remediation, the U.S. Geological Survey (USGS), in cooperation with the U.S. Air Force, is conducting a long-term monitoring program and an assessment of the effectiveness of natural attenuation in the surficial aquifer.

Whereas the steps used to document and quantify natural attenuation are the same for all sites, the level of effort needed to carry out each step varies substantially according to the complexity of the site (National Research Council, 2000, p. 173). The three basic steps, as defined by the National Research Council (2000, p. 204), are:

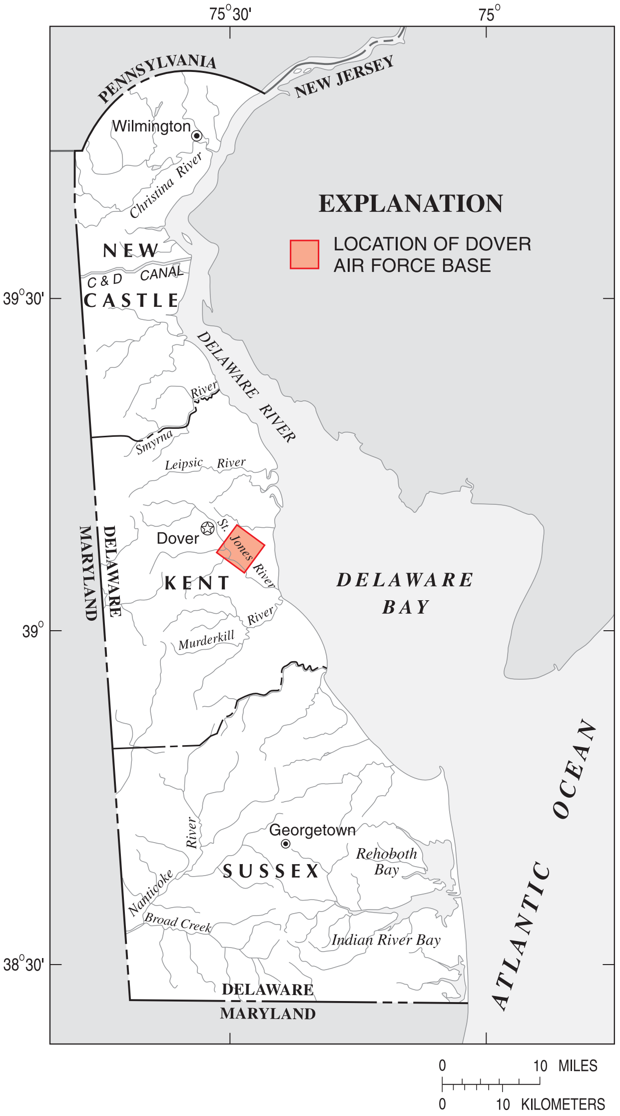


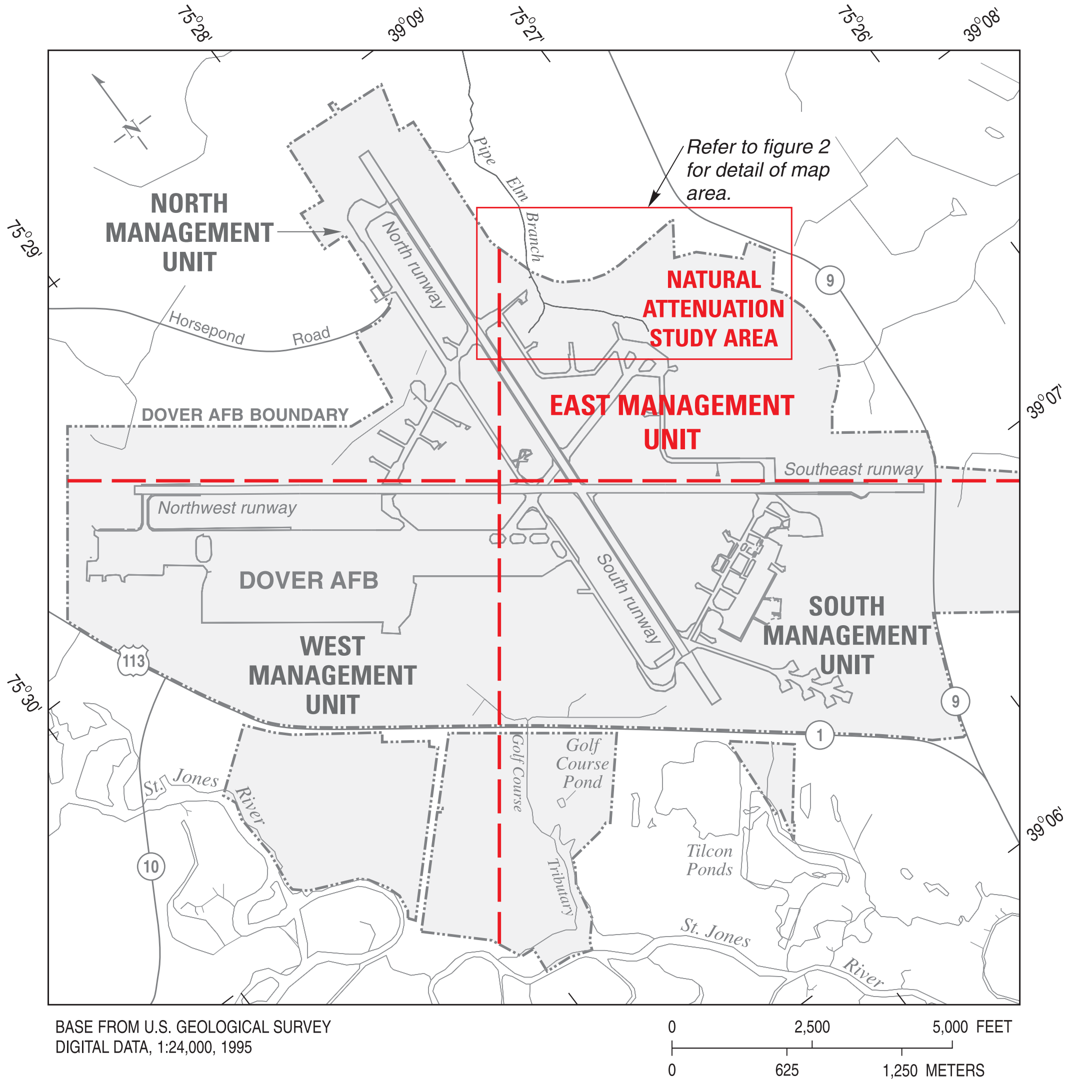
Figure 1a. Location of Dover Air Force Base, Dover, Delaware.

(1) Conceptual model development (hydrogeologic framework, plume and source-area delineation, and identification of attenuation processes).

(2) Analysis of ground-water samples to identify the characteristic geochemical changes or "footprints" associated with the relevant intrinsic biodegradation reactions.

(3) On-going site monitoring to determine if the documented processes continue to adequately control contaminant migration.

A historical data base that shows plume stabilization and/or contaminant mass loss over time provides the strongest evidence that natural attenuation is effective (Wiedemeier and others, 1999, p. 313).



BASE FROM U.S. GEOLOGICAL SURVEY
DIGITAL DATA, 1:24,000, 1995

Figure 1b. Location of the East Management Unit and the natural attenuation study area at Dover Air Force Base, Delaware.

The natural attenuation sites in the EMU are relatively complex. Complicating factors include a complex ground-water flow system, the presence of multiple source areas, and the presence of contaminant mixtures, predominantly fuel hydrocarbons and chlorinated solvents, in the source areas. The main compounds of concern at these sites, the chlorinated solvents, require specific geochemical conditions within the plumes that form downgradient of the source areas for efficient and sustainable intrinsic biodegradation. Accordingly, these sites require a relatively detailed level of site characterization and data analysis. A preliminary study by Bachman and others (1998) concluded that natural attenuation was reducing the concentrations of organic compounds as they migrated away from the source areas, and that off-site migration was unlikely. The presence of appropriate redox conditions and the formation of chlorinated-solvent breakdown products indicated that intrinsic biodegradation was the main attenuation mechanism. Whereas the preliminary results showed that natural attenuation was occurring at all three sites, uncertainties about the hydrogeologic framework and contaminant distributions also were identified.

Since 1995–96, when the data for the preliminary study were collected (Bachman and others, 1998), additional information has been obtained at these sites. The new results were used in the current assessment and include:

(1) Improved estimates of ground-water velocities in the EMU from hydraulic-conductivity values calculated from slug tests.

(2) Improved estimates of contaminant migration velocities from retardation factors calculated from sediment organic-carbon analyses.

(3) Improved understanding of ground-water flow directions and inferred contaminant migration

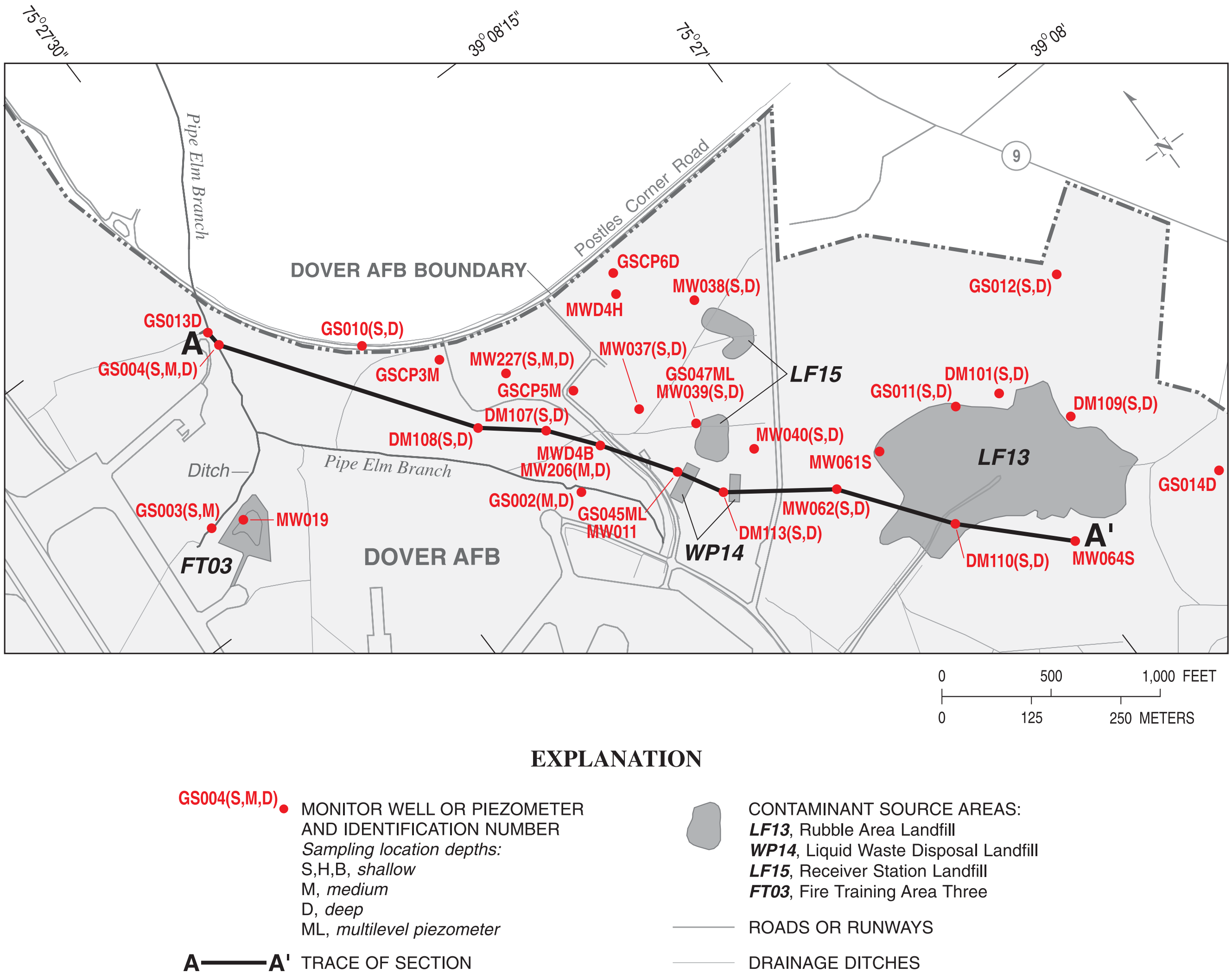


Figure 2. Location of the contaminant source areas, the monitor wells and piezometers sampled for water-quality constituents, and the trace of section A-A' in the natural attenuation study area, Dover Air Force Base, Delaware.

pathways from 2000 ground-water-level measurements.

(4) Better definition of the areal extent of contamination and the proximity of contaminants to discharge areas and the DAFB boundary from the results of comprehensive ground-water sampling performed in 2000.

(5) A better understanding of the vertical variability of contaminant concentrations and redox conditions from samples collected from multilevel piezometers.

(6) A better understanding of temporal changes in plume and source-area concentrations based on time-series plots using results from both the January–March 2000 and earlier sampling rounds.

Purpose and Scope

The purpose of this report is to present the results of an assessment of the effectiveness of natural attenuation in the EMU of DAFB. Monitor wells and newly installed multilevel piezometers completed in the surficial aquifer were sampled to determine the distributions of VOCs, electron acceptors, and metabolic by-products in the natural attenuation study area. Ground-water samples collected from January through March 2000 from 53 monitor wells and piezometers in the natural attenuation study area were analyzed. Analytical data from previous sample rounds also were used to determine temporal changes in VOC concentrations at selected wells in the plumes. Ground-water samples were analyzed for VOCs, total metals, dissolved metals, nitrate, ammonia, sulfate, sulfide, chloride, methane, dissolved oxygen (DO), total iron, and ferrous iron. The MCLs for metals were not exceeded in any sample collected during the January–March 2000 sampling round (K.C. Alexander and others, U.S. Geological Survey, written commun., 2000); therefore, the natural attenuation of metals will not be discussed in this report.

Hydraulic conductivities, hydraulic heads, and organic-carbon concentrations in aquifer sediment were measured to develop a better understanding of the hydrogeology of the surficial aquifer, and contaminant movement within this aquifer. Ten organic-carbon measurements, 15 hydraulic-conductivity measurements from slug tests on existing wells, ground-water-level measurements from surficial-aquifer wells in the EMU, and available geologic and geophysical well logs were used in this assessment.

Description of Study Area

DAFB is located in the Delmarva Peninsula, which is in the Atlantic Coastal Plain Physiographic Province. The surrounding area is primarily cropland and wetlands, with some residential development along the southwestern boundary of DAFB. The Base is underlain by a thick sequence of unconsolidated clastic deposits that form a regional aquifer system consisting of layered aquifers and confining units. Hinaman and Tenbus (2000, p. 7) provide a detailed description of the regional geologic framework and hydrogeology. The topographic relief on DAFB is relatively small. Land-surface elevations range from about 5 to 30 ft (feet) above sea level. Precipitation averages about 46 in/yr (inches per year), and is distributed uniformly throughout the seasons (Hinaman and Tenbus, 2000, p. 10).

The EMU is bounded on the south and west by runways, and on the north and east by cropland and light residential development. Four contaminant source areas have been identified in the area (fig. 2). Site FT03 is a 2- to 3-acre grassy area that was used for fire training until 1989. Waste oils and fuels were stored and periodically burned at the site. Site LF13 is an 8-acre landfill that has received construction rubble and small amounts of other refuse since the 1960s. Site WP14 is a former liquid-waste disposal area. It received liquid waste during the 1950s and early 1960s. Site LF15 is a former landfill site 200 ft east of WP14. During the 1960s, LF15 received general refuse and small quantities of shop wastes. For purposes of discussion, WP14 and LF15 are combined, and referred to as WP14/LF15. Some of the source material (contaminated soil) at FT03 was excavated during the early 1990s (U.S. Army Corps of Engineers and Dames and Moore, Inc., 1997b). Both FT03 and WP14/LF15 have received clean fill, and a part of FT03 is covered with a clay cap. Source materials, such as hydrocarbons and chlorinated solvents, probably are present in all four source areas in the EMU.

The surficial aquifer underlying DAFB consists of interbedded layers of sand and gravel with discontinuous layers of silt and clay (fig. 3). The sand consists of quartz with minor amounts of feldspar and mica (Bachman and others, 1998, p. 14). The orange color of the aquifer sediment indicates that ferric oxyhydroxide minerals are abundant. The aquifer is bounded on the top by the water table and on the bottom by the upper confining unit of the Calvert Formation. The saturated thickness of the surficial aquifer ranges from about 30 to 60 ft in the natural attenuation study area. The thickness is affected by seasonal fluctuations in the altitude of the water table. The surficial aquifer is thinnest in the northwest part of this area (fig. 3).

Ground water in the natural attenuation study area flows to the northwest. Flow is predominantly horizontal but vertical flow can occur near the fine-grained deposits and surface drainages (Hinaman and Tenbus, 2000, p. 16). Ground-water flow directions vary both spatially and temporally. Synoptic measurements taken during previous studies have shown a seasonal effect on the flow field, with a shallower water table and steeper hydraulic gradients during wetter conditions (Bachman and others, 1998, p. 14; Hinaman and Tenbus, 2000, p. 16). The natural attenuation study area is drained by Pipe Elm Branch and approximately 10 shallow drainage ditches. Drainage ditches that flow into Pipe Elm Branch drain surface water from source areas FT03 and WP14/LF15 (fig. 2). Drainage ditches that flow to the south, out of the natural attenuation study area, drain surface water from LF13. Strong upward hydraulic gradients in the nested streambed piezometers indicate that Pipe Elm Branch and the deep drainage ditch adjacent to FT03 (fig. 2) function as ground-water discharge boundaries.

Shallow ground water on the Delmarva Peninsula typically contains low total dissolved solids, pH in the range of 5 to 6.5, and detectable DO (Bachman and others, 1998, p. 23). Anaerobic conditions may be associated locally with clay lenses and organic-rich deposits in the aquifers, and with the organic-rich sediments commonly found in the discharge areas. Uncontaminated ground water in the surficial aquifer underlying DAFB typically contains low concentrations of nitrate (less than 1 mg/L, or milligram per liter, nitrate as N), variable concentrations of sulfate, and undetectable concentrations of iron and methane. Methane may be produced locally from microbial degradation of naturally occurring carbon in the organic-rich stream sediments, however.

Previous Studies

Investigations were performed in the EMU in 1984–85 (Science Applications International Corporation, 1986), the late 1980s (Science Applications International Corporation, 1989; Hazardous Waste Remedial Actions Program, 1990), and the early 1990s (Hazardous Waste Remedial Actions Program, 1993). In general, these studies included soil, sediment, ground-water, and surface-water sampling, as well as geophysical (magnetic, conductivity, and ground-penetrating radar) and soil-gas surveys. Additional sampling in support of the comprehensive Basewide Remedial Investigation (RI) was performed in 1993–94 (U.S. Army Corps of Engineers and Dames and Moore, Inc., 1997a). The purpose of the RI was to identify potential source areas and delineate contaminant distributions in soil and the surficial aquifer. In addition to geologic and hydrologic (ground-water level and slug test) data collection, this investigation included ground-water samples from available and new monitor wells, additional soil samples from borings and test pits, surface-water and sediment samples from drainage

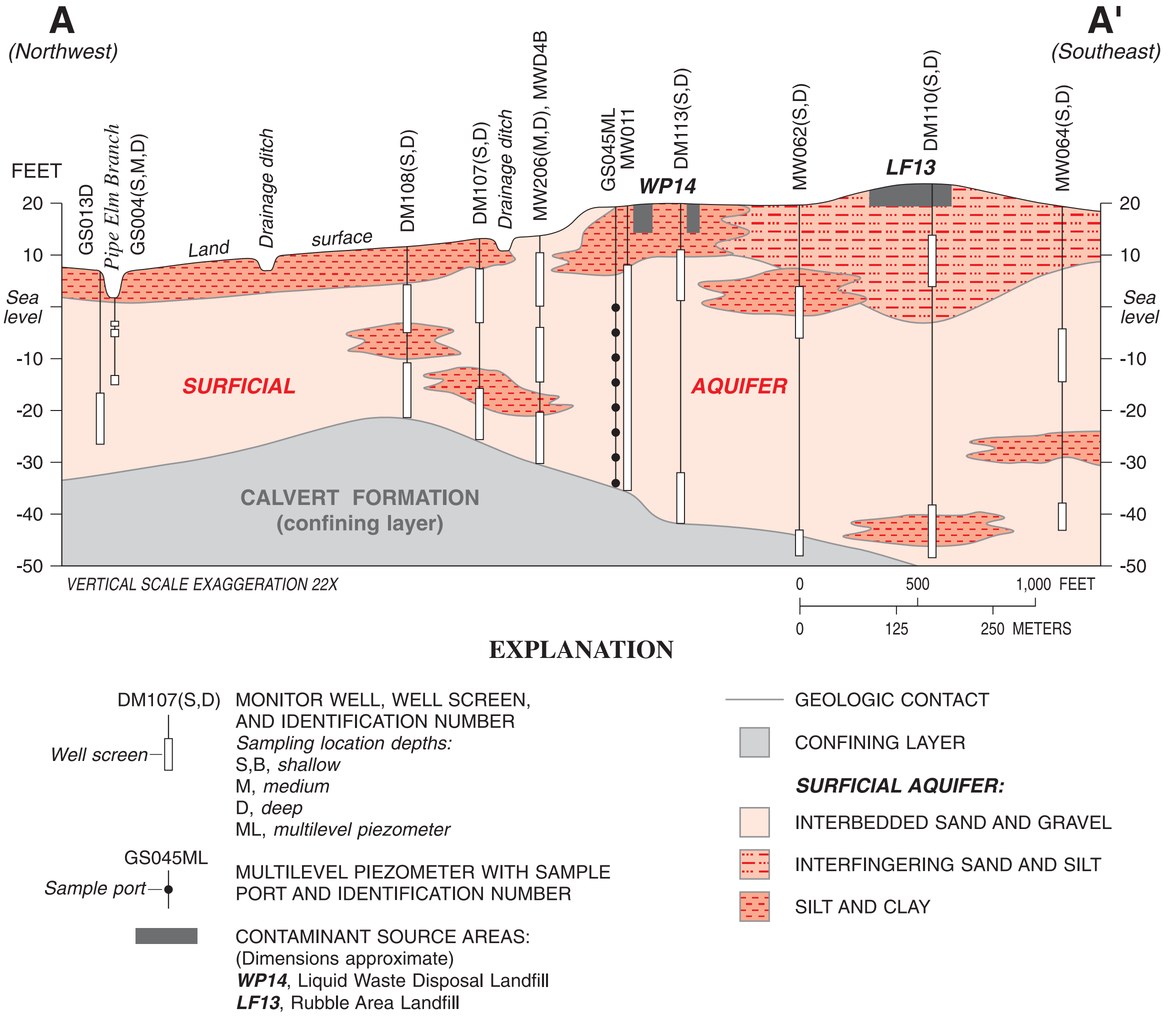


Figure 3. Hydrogeologic section A-A', Dover Air Force Base, Delaware. *(Trace of section shown in figure 2.)*

ditches, and geophysical and soil-gas surveys. Samples were analyzed for a comprehensive list of inorganic and organic constituents. The RI also contains summaries of the investigations performed prior to 1997.

The sizes and locations of the source areas discussed in this report (fig. 2) are taken from the RI report. The composition and amount of waste materials deposited in these areas is not known.

The preliminary USGS investigation to determine whether natural attenuation was occurring in the EMU took place in 1995–96 (Bachman and others, 1998; Beman and others, 1999). In 1997, the USEPA and the Delaware Department of Natural Resources and Environmental Control selected natural attenuation as the remedial measure for sites LF13, WP14/LF15, and FT03. In 1999, the USGS began semi-annual, long-term monitoring at these sites.

Acknowledgments

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Data-Collection Methods

The ground-water monitoring network, the methods used to characterize the hydrogeologic framework, and the methods used to collect hydrologic, aquifer sediment, and water-quality data are described in this section. The hydrogeologic framework is based on available lithologic and geophysical logs, hydraulic conductivity measurements from slug tests, and hydraulic-head measurements. Contaminant fate-and-transport interpretations are based on organic-carbon measurements in aquifer sediments and laboratory and field analyses on ground-water samples.

Monitoring Network

The ground-water monitoring network used in this study consists of 44 polyvinylchloride (PVC) monitor wells, 7 short-screened (3 ft or less), stainless-steel piezometers in the drainage ditches and Pipe Elm Branch, and 2 multilevel piezometers that were installed adjacent to long-screened wells. At many locations, well clusters installed during previous investigations were used to obtain data from varying depths in the surficial aquifer. Well locations and construction details are shown in figure 2 and table 1, respectively.

The monitoring network consists of a core group of 34 wells that are part of the current long-term monitoring program, plus a group of additional wells and piezometers that were sampled in an attempt to achieve better plume characterization. A list of the core group of wells was submitted to the USEPA in the external draft of the long-term monitoring plan (J. Williams and L.J. Bachman, U.S. Geological Survey, written commun., 1999).

The two multilevel piezometers, GS045ML and GS047ML, were installed by the USGS in 1999 to obtain better vertical resolution of contaminant distributions adjacent to two contaminated wells, MW011 and MW039S, that are located near the source areas. These piezometers are constructed with a series of 1/8-in. (inch) outer diameter (OD) Teflon sample tubes strapped to a 3/4-in. PVC center tube. The ends of the sample tubes are covered with nylon screen. Each piezometer contains multiple sample tubes spaced evenly over a given interval to obtain a vertical water-quality profile. GS045ML contains eight ports spaced at 5-ft intervals between 19.3 and 54.3 ft bgs (below ground surface). GS047ML contains five ports spaced at 2-ft intervals between 13.0 and 21.0 feet bgs.

Development of Hydrogeologic Framework

The hydrogeologic framework of the natural attenuation study area was developed primarily from geologic logs obtained by the USGS and other contractors during monitor well and piezometer installation, geophysical logs from selected wells, and interpretations from available reports (Hinaman and Tenbus, 2000, p. 7). The geophysical logs are included in the data report by Beman and others (1999, p. 82). The lithologic and geophysical logs (primarily gamma logs) were used to prepare a hydrogeologic section (fig. 3) parallel to the general direction of ground-water flow.

Hydrologic Data Collection

Fifteen wells in the area were slug-tested to obtain estimates of hydraulic conductivity in the surficial aquifer (fig. 4). Rising-head tests were done with an air-pressurized slug testing system (Greene and Shapiro, 1995). To obtain hydraulic conductivity values, the empirical Bouwer and Rice solution (Bouwer and Rice, 1976) for aquifers under unconfined conditions was applied to the rising-head data. Values range from 3 ft/d (feet per day) (GS003M) to 313 ft/d (MW037D), with a geometric mean of 43 ft/d (table 2). Most of the high values were obtained from tests on the wells that screen the base of the surficial aquifer. This result is consistent with the available geologic information, which indicates that the deposit that forms the surficial aquifer coarsens downward.

A synoptic round of water-level measurements was conducted on March 15–16, 2000 at most of the available wells in the EMU to determine ground-water flow directions and hydraulic-head gradients (Appendix A). These measurements were used to develop plan-view potentiometric-surface maps for the shallow and deep parts of the surficial aquifer, and a hydrogeologic section parallel to the general ground-water flow direction. Data from continuous recorders on wells in the natural attenuation study area indicated that water levels rose sharply during the 2-month period preceding this synoptic round of measurements, indicating that a spring recharge event was affecting the ground-water flow system when these measurements were taken.

Sediment Organic-Carbon Collection

Samples were collected from three boreholes to determine concentrations of organic carbon in the aquifer sediment (fig. 4). These data were used to estimate retardation factors for the organic contaminants in ground water. Ten samples were obtained from shallow, intermediate, and deep depth intervals within the surficial aquifer. Samples of aquifer sediment were obtained from cores collected with a Geoprobe direct-push drill rig. To obtain a sample, aquifer sediment was removed from a 1-ft section of core with a stainless-steel spatula. Sediment adjacent to the core-tube wall was discarded. After collection, samples were refrigerated until shipment to the University of Waterloo in Waterloo, Ontario, for analysis using the method described in Churcher and Dickhout (1987). Concentrations, expressed as the weight fraction of organic carbon (f_{oc}) on a dry weight basis (grams of naturally occurring carbon per gram of dry aquifer sediment), ranged from 0.00007 to 0.00087, with an arithmetic mean of 0.00029 (table 3). The method detection limit (MDL) for the analysis is 0.00004.

Ground-Water Sample Collection and Analysis

Ground-water and quality-control (QC) sample collection and analysis procedures for the January–March 2000 sampling round are described in detail in the data report prepared by Alexander and others (K.C. Alexander and others, U.S. Geological Survey, written commun., 2000).

To obtain representative ground-water samples, wells were purged of approximately three well volumes of water

Table 1. *Construction details for wells and piezometers sampled at Dover Air Force Base, Delaware, January–March 2000*

[ft, feet; ft bgs, feet below ground surface; ft s.l., feet above or below (negative altitude) sea level; in., inch; the last letter of a well or piezometer identification number indicates the following sampling location depths—S, H, or B, shallow; M, intermediate; D, deep; ML, multilevel piezometer]

Well and piezometer identification number	Screen length (ft)	Total depth (ft bgs)	Altitude of ground surface (ft s.l.)	Altitude of top of screen (ft s.l.)	Altitude of bottom of screen (ft s.l.)
DM101S	10	16.2	23.1	16.92	6.92
DM101D	10	53.0	22.9	-20.11	-30.11
DM107S	10	16.4	13.8	7.47	-2.53
DM107D	10	38.8	13.6	-15.15	-25.15
DM108S	10	16.9	11.7	4.75	-5.25
DM108D	10	32.8	11.5	-11.33	-21.33
DM109S	10	16.7	21.6	14.88	4.88
DM109D	10	43.9	21.4	-12.54	-22.54
DM110S	10	20.3	25.7	15.33	5.33
DM110D	10	73.4	25.4	-38.00	-48.00
DM113S	10	18.8	20.9	12.06	2.06
DM113D	10	63.6	20.9	-32.68	-42.68
GS002M	1	12.6	7.1	-4.49	-5.49
GS002D	3	23.0	7.4	-12.60	-15.60
GS003S	3	9.0	4.8	-1.28	-4.28
GS003M	3	14.9	4.4	-7.53	-10.53
GS004S	0.5	5.8	3.3	-2.03	-2.53
GS004M	1	9.8	3.8	-5.07	-6.07
GS004D	3	21.2	4.5	-13.73	-16.73
GS010S	5	25.2	16.9	-3.29	-8.29
GS010D	5	48.8	16.9	-26.89	-31.89
GS011S	5	17.4	20.1	7.73	2.73
GS011D	5	43.5	20.2	-18.34	-23.34
GS012S	10	15.4	21.0	15.53	5.53
GS012D	5	52.0	20.9	-26.09	-31.09
GS013D	10	34.8	6.8	-17.96	-27.96
GS014D	10	64.8	23.3	-31.51	-41.51
GSCP3M	3	22.8	16.8	-3.00	-6.00
GSCP5M	3	29.5	18.2	-8.34	-11.34
GSCP6D	3	40.5	18.8	-18.70	-21.70
MW011	44	55.0	19.8	8.74	-35.26
MW019	35	44.2	14.4	5.26	-29.74
MW037S	10	20.3	14.0	3.69	-6.31
MW037D	5	48.0	14.4	-28.61	-33.61
MW038S	10	29.9	17.2	-2.71	-12.71
MW038D	5	57.2	17.2	-34.96	-39.96
MW039S	10	19.6	17.0	7.41	-2.59
MW039D	5	58.0	18.3	-34.70	-39.70
MW040S	10	22.1	18.7	6.57	-3.43
MW040D	5	47.0	18.8	-23.27	-28.27
MW061S	10	27.5	24.7	7.21	-2.79
MW062S	10	25.0	19.5	4.49	-5.51
MW062D	5	67.7	19.8	-42.94	-47.94

Table 1. *Construction details for wells and piezometers sampled at Dover Air Force Base, Delaware, January–March 2000—Continued*

Well and piezometer identification number	Screen length (ft)	Total depth (ft bgs)	Altitude of ground surface (ft s.l.)	Altitude of top of screen (ft s.l.)	Altitude of bottom of screen (ft s.l.)
MW064S	10	34.8	21.7	-3.09	-13.09
MWD4H	3	9.5	19.0	12.47	9.47
MWD4B	10	12.9	14.2	11.25	1.25
MW206M	10	28.3	14.1	-4.22	-14.22
MW206D	10	44.3	14.3	-20.05	-30.05
MW227S	10	22.9	19.4	6.41	-3.59
MW227M	10	33.3	19.4	-3.98	-13.98
MW227D	10	46.2	19.4	-16.85	-26.85

Multilevel piezometer	Diameter of multilevel port (in.)	Depth (ft bgs)	Altitude of ground surface (ft s.l.)	Altitude of multilevel piezometer port (ft s.l.)
GS045ML		57.0	19.8	
Port H	0.125	19.3	19.8	0.45
G	0.125	24.3	19.8	- 4.5
F	0.125	29.3	19.8	- 9.5
E	0.125	34.3	19.8	-14.5
D	0.125	39.3	19.8	-19.5
C	0.125	44.3	19.8	-24.5
B	0.125	49.3	19.8	-29.5
A	0.125	54.3	19.8	-34.5
GS047ML		22.0	17.0	
Port E	0.125	13.0	17.0	4.0
D	0.125	15.0	17.0	2.0
C	0.125	17.0	17.0	0.0
B	0.125	19.0	17.0	- 2.0
A	0.125	21.0	17.0	- 4.0

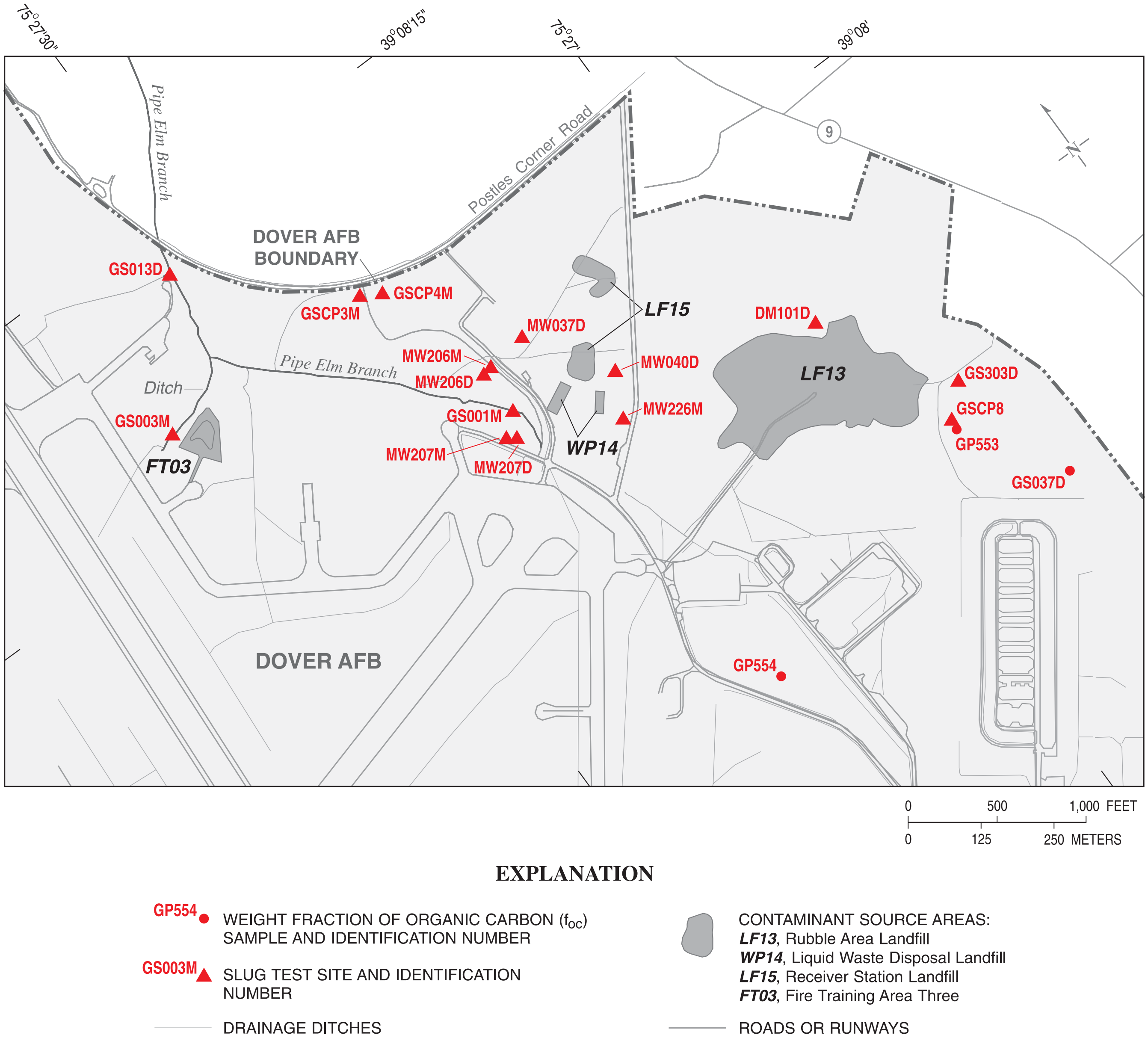


Figure 4. Location of slug tests and sediment organic-carbon samples, Dover Air Force Base, Delaware. *(See table 2 for slug-test results, and table 3 for organic-carbon results.)*

Table 2. *Hydraulic conductivity values from slug tests on wells screened in the surficial aquifer in the East Management Unit, Dover Air Force Base, Delaware*

[See figure 4 for location of slug-tested wells; ft, feet, ft bgs, feet below ground surface; ft/d, feet per day; *, arithmetic mean of values from two slug tests]

Well	**Screen length (ft)**	**Total depth (ft bgs)**	**Hydraulic conductivity (ft/d)**
DM101D	10	53.0	85 *
GS001M	1	6.5	4
GS003M	3	14.9	3
GS013D	10	34.8	30
GS303D	10	59.7	22
GSCP3M	3	22.5	24
GSCP4M	3	24.3	46 *
GSCP8	3	33.2	8 *
MW037D	5	48.0	313
MW040D	5	47.0	119
MW206D	10	44.3	110
MW206M	10	28.3	146
MW207D	10	47.5	138 *
MW207M	10	34.7	55 *
MW226M	10	46.9	130
		Geometric Mean [1]	**43**

[1] **Geometric Mean:**

$$\bar{K} = \sqrt[n]{K_1 K_2 \ldots K_n}$$

where

$\bar{K}$ = *geometric mean of the hydraulic conductivity,*

$K_1 K_2 \ldots K_n$ = *individual values of the hydraulic conductivity, and*

n = *number of values.*

prior to sample collection. Purging was stopped when temperature, pH, DO, and specific conductance stabilized. Measurements were made with field meters connected to a flow-through cell. A peristaltic pump was used for purging and sampling. Teflon tubing was used to collect ground-water samples. Each day, tubing was decontaminated in the laboratory with hot, soapy water and a triple rinse with deionized water. To minimize cross-contamination from sampling equipment and procedures, wells were sampled approximately in the order of least to most contaminated (as best known). The water-level measuring tape, electrodes, flow-through cell, and glassware also were rinsed with deionized water between wells.

Samples were collected from the discharge line of the peristaltic pump after the wells were purged. Severn Trent Laboratory in Arvada, Colorado provided pre-preserved sample bottles. Samples requiring laboratory analysis were placed on ice in coolers prior to shipment. Field analyses were done in a mobile laboratory immediately after sample collection.

The ground-water samples and equipment blanks discussed in this report were analyzed for VOCs (SW846 Method 8260), dissolved nutrients (sum of nitrate plus nitrite) (MCAWW Method 353.2) and ammonia as nitrogen (MCAWW Method 350.1), chloride (MCAWW Method 300.0A), and sulfate (MCAWW Method 300.0A) (U.S. Environmental Protection Agency, 1983, 1986). Trip and ambient blanks were analyzed for

Table 3. *Weight fractions of organic carbon (f_{oc}) in surficial-aquifer sediment samples collected in the East Management Unit, Dover Air Force Base, Delaware*

[See figure 4 for sample-collection locations; ft bgs, feet below ground surface; f_{oc}, weight fraction of organic carbon; g/g, grams of naturally occurring carbon per gram of dry aquifer sediment]

Location	Sample identification	Depth (ft bgs)	f_{oc} (g/g)
GP553	GSFOC-1	12–16	0.00083
GP553	GSFOC-2	32–35	.00020
GP553	GSFOC-3	42–44	.00008
GS037D	GSFOC-4	10–12	.00015
GS037D	GSFOC-5	12–16	.00014
GS037D	GSFOC-6	24–28	.00011
GS037D	GSFOC-7	40–44	.00007
GP554	GSFOC-8	12–16	.00087
GP554	GSFOC-9	24–28	.00039
GP554	GSFOC-10	28–30	.00008
		Arithmetic mean:	**0.00029**

VOCs only. Duplicate ground-water samples from all wells also were submitted to the USGS field laboratory at Aberdeen Proving Ground, Maryland for methane analysis using the procedure described in Baedecker and Cozzarelli (1992). Because of the potential for methane loss during and after sample collection, the highest concentration from each pair of replicate samples that contained methane was reported.

Temperature, pH, specific conductance, DO, ferrous and total iron, and sulfide were analyzed in the field. Temperature, pH, specific conductance, and DO were measured with meters (YSI Model 3000, Orion Model 260, or Hydrolab Model H20 multiprobe) connected to a flow-through cell on the discharge line of the peristaltic pump. When the DO concentration was 2 mg/L or less with the Hydrolab, a modified Winkler titration was used to determine the DO concentration. This method is more accurate and reproducible at low DO concentrations (Baedecker and Cozzarelli, 1992). The MDL for the modified Winkler titration is 0.2 mg/L DO.

Ferrous and total iron and sulfide were measured colorimetrically immediately after collection in the mobile field laboratory. Iron was analyzed with a Hach DR2000 spectrophotometer. Iron check standards were run daily along with ground-water samples. Sulfide was analyzed with a Chemetrics spectrophotometer. The spectrophotometers were zeroed with raw ground water before each sample was read in the instrument. The MDL for ferrous and total iron is 0.02 mg/L.

The QC samples presented in this report include nine laboratory duplicates, seven field blanks, three ambient blanks, six trip blanks, one equipment blank, and one source-water blank, denoted respectively by the extensions “DUP,” “FDB,” “AMB,” “TPB,” “EQB,” and “SWB” (K.C. Alexander and others, U.S. Geological Survey, written commun., 2000). Ground-water sample identifiers consist of the well name followed at most locations by an “S,” “M,” “D,” or “ML,” which represent shallow wells, intermediate wells, deep wells, and multilevel piezometers, respectively. Actual well depths are shown in table 1.

Assessment of Natural Attenuation

The hydrogeologic framework and the spatial and temporal concentration trends used to assess natural attenuation are presented in this section. The general approach used in this report to determine the effectiveness of natural attenuation is consistent with established protocols (Wiedemeier and others, 1999, p. 309; National Research Council, 2000, p. 150).

Evidence of Natural Attenuation

Natural attenuation refers to the reduction in concentration or mass of a dissolved constituent over time and distance from the source of contamination in response to naturally occurring physical, chemical, and biological processes. The main processes in a ground-water environment are intrinsic biodegradation, abiotic degradation, adsorption, and dispersion. Intrinsic biodegradation typically is the dominant natural attenuation process for organic compounds (Wiedemeier and others, 1999, p. 164).

Following initial conceptual model development, three broadly defined lines of evidence commonly are used at sites contaminated with chlorinated solvents to determine the extent of natural attenuation (Wiedemeier and others, 1999, p. 13):

(1) A historical data base of ground-water samples that shows whether the plume is stable or shrinking, and/or whether there has been a loss of contaminant mass over time. Demonstrating contaminant loss at the field scale is the strongest evidence of natural attenuation.

(2) Measurements of compounds in ground water to identify the characteristic geochemical changes, or footprints, of the intrinsic biodegradation reactions occurring at the site. These changes include the depletion of electron acceptors and production of metabolic by-products relative to background conditions, and the depletion of parent compounds and production of chlorinated-solvent breakdown products along ground-water flow paths. This line of evidence

is strongest when contaminant reductions and biodegradation reactions are linked quantitatively to show a cause-and-effect relation (National Research Council, 2000, p. 172).

(3) Laboratory microcosm data that demonstrate mass loss from biodegradation under the prevailing geochemical conditions in the aquifer.

In this report, concentration trends that show (1) the depletion of parent organic compounds, (2) the production of chlorinated-solvent breakdown products, and (3) the consumption of electron acceptors and production of metabolic by-products along generalized ground-water flow paths are used as the main lines of evidence of natural attenuation. Time-series graphs of VOC concentrations at selected wells within the plumes also are used in this assessment. The historical data base is currently inadequate for mapping the plumes, and laboratory microcosm data are not available.

Documentation of the disappearance of a contaminant is an important indication of natural attenuation, but this information alone is generally not sufficient (National Research Council, 2000, p. 11). Cause and effect must be established by linking the observed contaminant losses to natural-attenuation processes occurring in the aquifer. For natural attenuation to be acceptable as a remedial measure, it also must be shown that the remedial objective established for the site is met. For the sites in the EMU, the remedial objective is to attain cleanup levels (USEPA MCLs or site-specific background concentrations) for the compounds of concern in the area of attainment, defined as the zone inside the boundary of the contaminant plume (Hazardous Waste Remedial Actions Program, written commun., 1997). Point-of-compliance (POC) wells are used to determine concentrations at the DAFB boundary. The POC wells sampled in January–March 2000, GS004S, GS004M, GS004D, GS010S, GS010D, GS012S, GS012D, GS014D, GSCP3M, GSCP6D, MW227M, and MWD4H, are shown on figure 2.

Hydrogeologic Framework

The surficial aquifer may be conceptualized as a single, heterogeneous hydrostratigraphic unit that is bounded on the top by the water table and on the bottom by the regional Calvert confining unit (fig. 3). Ground water flows generally from southeast to northwest, toward Pipe Elm Branch, which is the major discharge boundary in the natural attenuation study area (figs. 5, 6, and 7). As noted by Bachman and others (1998, p. 14), flow systems in the surficial aquifer can be categorized with two scales. In the shallow flow system, ground water recharged at local topographically high areas flows under the influence of gravity along shallow flow paths to the nearest discharge area. The ground-water traveltimes in these shallow flow cells probably range from weeks to years. The deeper flow system apparently recharges near a local ground-water divide beneath LF13, and possibly further upgradient, and discharges to Pipe Elm Branch. The ground-water traveltimes in the deep flow system probably range from years to decades. Although hydraulic heads fluctuate seasonally, synoptic rounds of hydraulic-head measurements collected in 1993–94 (Hinaman and Tenbus, 2000, p. 25–26), in 1995–96 (Bachman and others, 1998, p. 14) and in March 2000 indicate that the general configuration of hydraulic heads in the surficial aquifer, and, therefore, ground-water flow paths, does not change substantially.

Near LF13, radial flow associated with a local ground-water divide occurs in the upper part of the surficial aquifer (fig. 5). This divide appears to be the main recharge boundary for the flow systems in the natural attenuation study area. Local water-table “highs” generally form above laterally extensive, fine-grained deposits in the surficial aquifer (Hinaman and Tenbus, 2000, p. 16). Hydrographs from well DM110 demonstrate that the high water table beneath LF13 persists throughout the year, although the magnitude of the downward vertical gradient decreases during the summer and fall (Hinaman and Tenbus, 2000, p. 16).

On March 15–16, 2000, hydraulic gradients varied substantially across the natural attenuation study area (figs. 5 and 6). Vertical gradients were measured in ground water beneath LF13 and Pipe Elm Branch (fig. 7). Near WP14/LF15, vertical gradients were relatively small and flow was predominantly horizontal; the horizontal gradient between wells DM107S and DM108S was 0.003 ft/ft (feet per feet) (fig. 7). Large horizontal gradients were observed, however, in the upper part of the surficial aquifer between the LF13 and WP14/LF15 source areas. These patterns are consistent with previous hydraulic-head distributions in this area (Bachman and others, 1998, p. 15; Hinaman and Tenbus, 2000, p. 26).

As shown on section A-A′, the surficial aquifer consists predominantly of sand and gravel with discontinuous lenses of silt and clay (fig. 3). The fine-grained deposits are more prevalent in the upper part of the aquifer. With the simplifying assumption of aquifer homogeneity, Darcy’s Law (Freeze and Cherry, 1979, p. 15) can be used to estimate a representative ground-water flow rate in the natural attenuation study area. Using the geometric mean hydraulic conductivity of 43 ft/d calculated from the 15 slug tests conducted in the area (table 2), and a horizontal gradient of 0.003, which is representative of the area between WP14/LF15 and Pipe Elm Branch, the specific discharge is 0.1 ft/d. Using an assumed effective porosity of 0.25 for sand and gravel (Wiedemeier and others, 1999, p. 129), the average ground-water velocity in the natural attenuation study area is 0.4 ft/d. At this velocity, the traveltime from source areas WP14/LF15 to Pipe Elm Branch at the Base boundary, a distance of 2,200 ft, is approximately 15 yrs (years). Using the highest and lowest measured hydraulic conductivities in this area (313 ft/d and 2.9 ft/d), and the representative horizontal hydraulic gradient of 0.003 ft/ft, traveltimes range from 2 yrs to 170 yrs. This is consistent with other estimates of traveltime in the surficial aquifer beneath DAFB (U.S. Army Corps of Engineers and Dames and Moore, Inc., 1997b; Hinaman and Tenbus, 2000, p. 63), and in other areas of the Delmarva Peninsula (Dunkel and others, 1992).

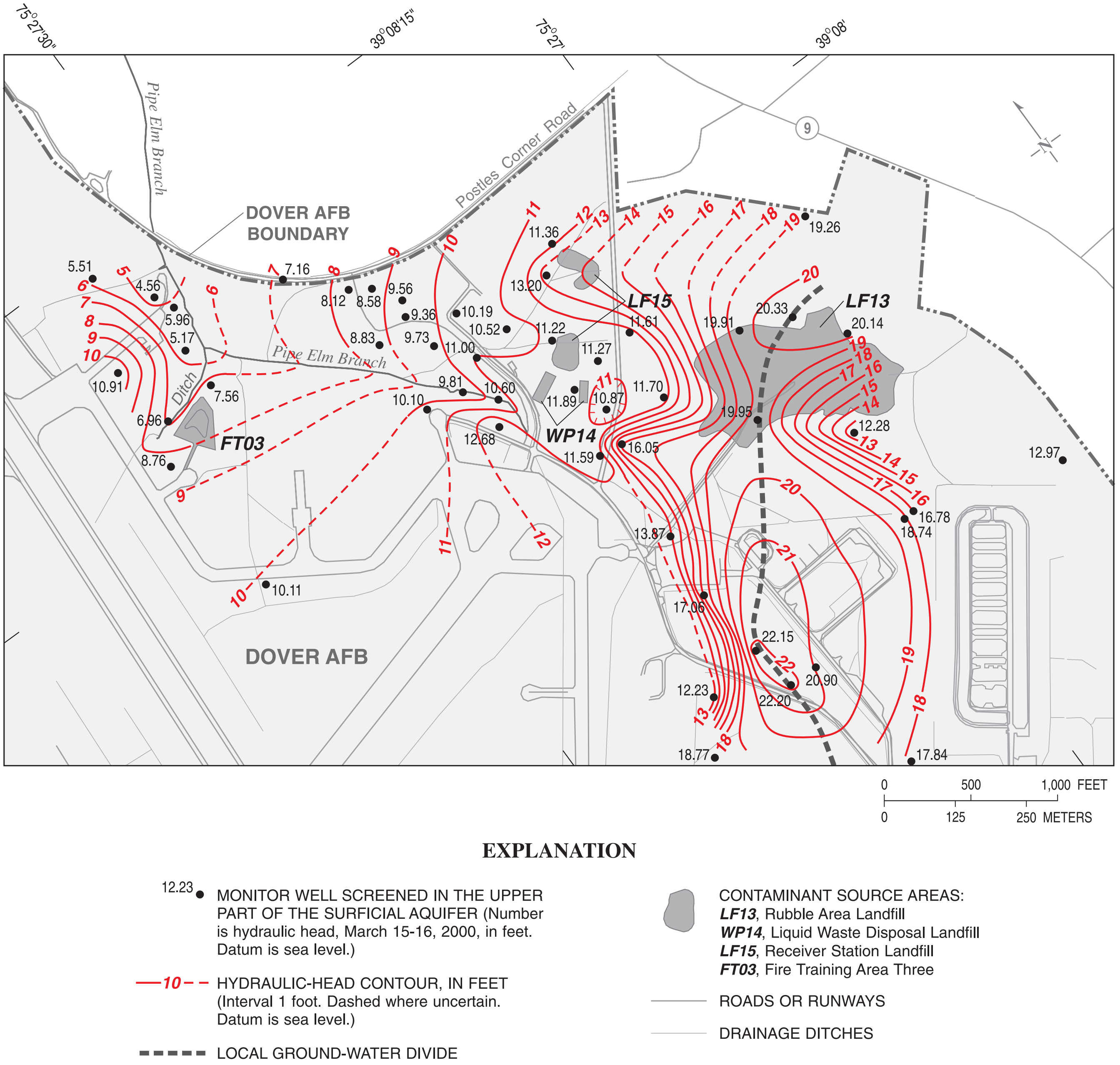


Figure 5. Hydraulic-head distribution in the upper part of the surficial aquifer, Dover Air Force Base, Delaware, March 15-16, 2000.

Dispersion, Adsorption, and Abiotic Degradation

Natural gradient experiments have shown that transverse dispersion is a weak mixing process in unconsolidated geologic deposits (Sudicky, 1986). At FT03, where the source area is close to adjacent surface-water discharge areas, dispersion probably has a negligible effect on the attenuation of the plume prior to discharge. At WP14/LF15 and LF13, flow paths are longer and the plume migrates through more aquifer heterogeneities, so dispersion may have a more substantial effect on contaminant distributions and on increased mass losses from aerobic biodegradation at the plume boundaries. The effects of dispersion cannot be determined with the information that is currently (2001) available, however.

To obtain a rough estimate of the effect of adsorption on contaminant migration velocities in the surficial aquifer, retardation factors were calculated for a selected group of organic compounds using a simple estimation procedure that is based on the organic-carbon content of the aquifer sediment. This procedure assumes that the association between the nonpolar organics and the natural organic matter in the sediment is the dominant adsorption mechanism. It should be noted that in sediments with low organic carbon contents (f_{oc} less than about 0.002), adsorption to mineral

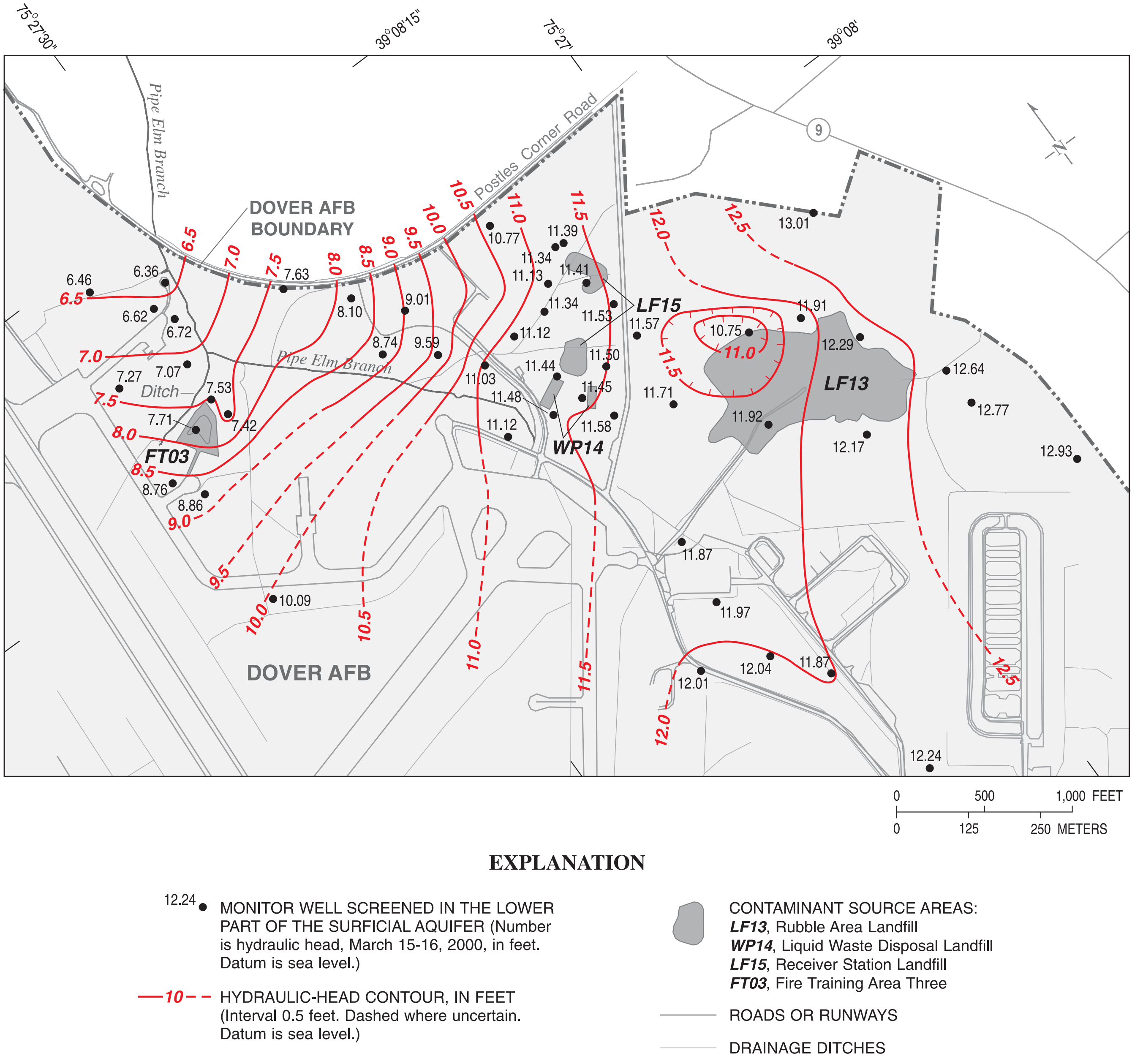


Figure 6. Hydraulic-head distribution in the lower part of the surficial aquifer, Dover Air Force Base, Delaware, March 15-16, 2000.

surfaces, particularly clays, might become significant (Schwarzenbach and others, 1993, p. 284). The importance of this sorption mechanism in the surficial aquifer cannot be determined with the information that is currently available.

The retardation factor is defined as $R = 1 + (\rho_b / n)\, K_d$,

where

ρ_b = the dry bulk density of the aquifer sediment in g/cm^3 (grams per cubic centimeter),

n = the total porosity, and

K_d = the distribution coefficient in mL/g (milliliters per gram) (Freeze and Cherry, 1979, p. 404).

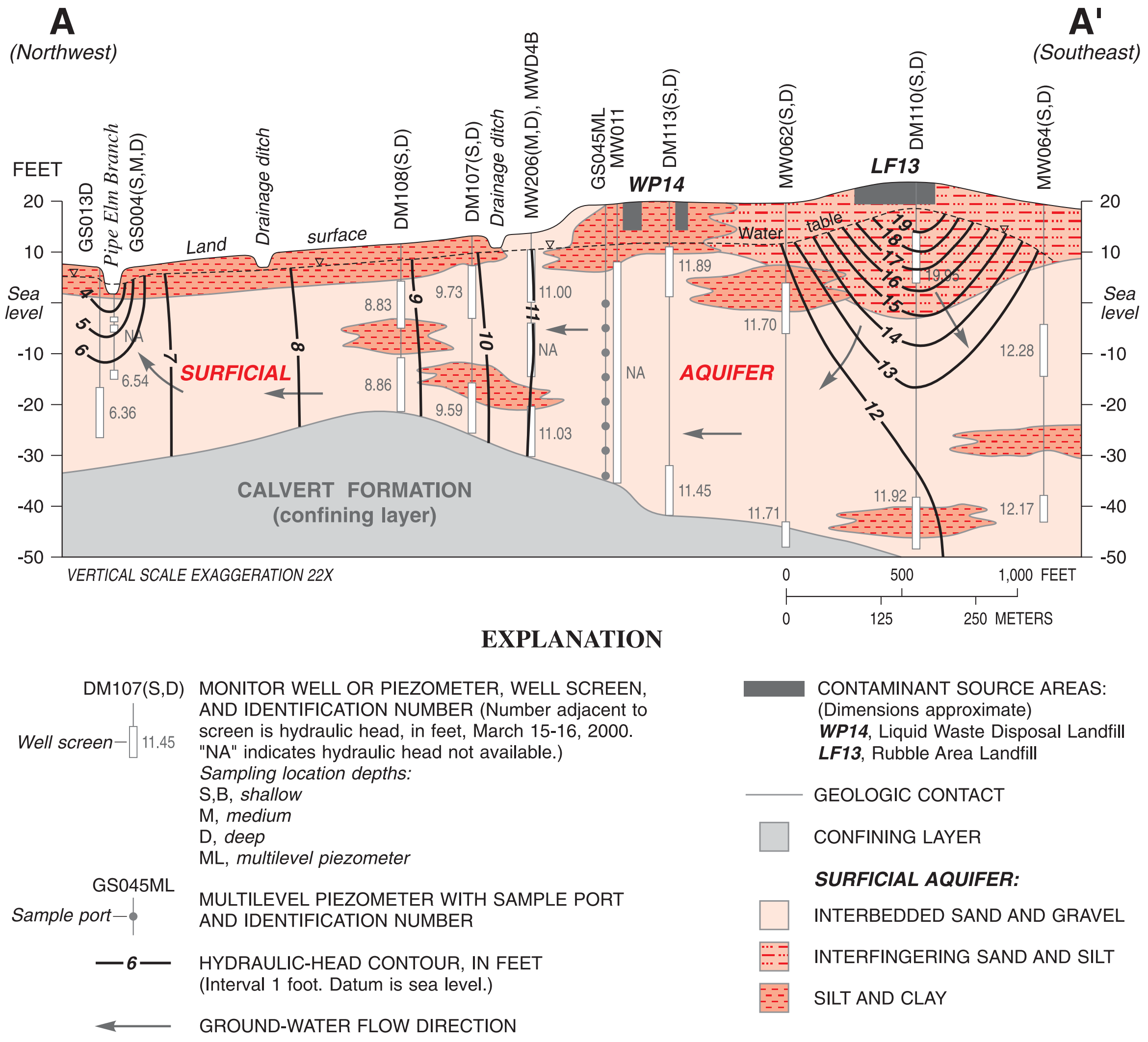


Figure 7. Vertical hydraulic-head distribution and ground-water flow direction along section A-A', Dover Air Force Base, Delaware. *(Trace of section shown in figure 2.)*

This equation is based on the assumption that adsorption is fast, reversible, and independent of the concentration of the organic constituent. Distribution coefficients were estimated from the relation $K_d = f_{oc} K_{oc}$,

where

f_{oc} = the mean weight fraction of organic carbon in the aquifer in g/g (grams of naturally occurring organic carbon per gram of dry aquifer sediment), and

K_{oc} = the organic-carbon distribution coefficient in mL/g (milliliters per gram).

Organic-carbon distribution coefficients were obtained from the published literature (table 4). Using assumed values for dry bulk density and porosity of 1.7 g/cm^3 and 0.35, respectively (Freeze and Cherry, 1979, p. 405), the measured arithmetic mean f_{oc} of the aquifer sediment of 0.00029, and the literature K_{oc} values, retardation factors ranging from 1.35 (PCE) to 1.00 vinyl chloride (VC) were calculated (table 4). Corresponding dimensionless relative velocities, defined as the migration velocity of the contaminant divided by the ground-water velocity, ranged from 0.74 (PCE) to 1.00 (VC). The low values for the distribution coefficients also indicate that the mass adsorbed to the aquifer solids is small relative to the mass in solution.

On the basis of the calculations presented above, adsorption to aquifer solids is not a strong natural attenuation mechanism in the surficial aquifer. The amount of adsorp-

Table 4. *Retardation factors and relative velocities for selected volatile organic compounds detected in the natural attenuation study area, Dover Air Force Base, Delaware*

[K_{oc}, organic carbon-based partition coefficient; K_d, distribution coefficient; R, retardation factor; v_c, velocity of contaminant front; v, average linear ground-water velocity; mL/g, milliliters per gram; --, dimensionless quantity]

Compound	log K_{oc} (mL/g)	Reference	K_d (mL/g)	R (--)	v_c/v (--)
Tetrachloroethene	2.4	Abdul and others, 1987	0.073	1.35	0.74
Trichloroethene	1.8	Abdul and others, 1987	0.018	1.09	0.92
cis-1,2-Dichloroethene	1.4	Wiedemeier and others, 1999, p. 145	0.0073	1.03	0.97
Vinyl chloride	0.39	Montgomery, 1996, p. 1,050	0.0007	1.00	1.00
1,1,2,2-Tetrachloroethane	2.07	Schwille, 1988, p. 130	0.034	1.16	0.86
Chlorobenzene	2.2	Walton and others, 1992	0.046	1.22	0.82
Benzene	1.7	Abdul and others, 1987	0.014	1.07	0.93

tion may be substantially greater in the finer-grained sediments around LF13 and the drainage ditches, which likely contain greater amounts of both organic carbon and clay. For the relatively coarse layers through which most of the contaminant migration occurs, however, both the clay and organic contents are low, and the effect of adsorption on migration velocities and bioavailable contaminant mass are expected to be small.

The potential for abiotic degradation in the natural attenuation study area is discussed in detail in Bachman and others (1998, p. 31). In short, abiotic degradation of the chlorinated ethenes is not important because half-lives are very long (for example, in the range of 10^6 to 10^{10} yr) relative to the decadal residence times in the natural attenuation study area. Chlorinated ethanes, on the other hand, may undergo relatively rapid hydrolysis. Half-lives range from 0.01 to 72.0 yr (Bachman and others, 1998, p. 13). 1,1,2,2-TeCA (1,1,2,2-tetrachloroethane) degrades to trichloroethene under alkaline conditions (Jeffers and others, 1989). Because chlorinated ethanes have been detected periodically in the WP14/LF15 source area, TCE could be produced from abiotic degradation reactions. Based on information that is currently available, however, these compounds are not widespread in the natural attenuation study area, so the production of TCE by this mechanism is not expected to be important.

Intrinsic Biodegradation

Intrinsic biodegradation refers to contaminant transformation mediated by the indigenous microbial community in the aquifer. The anaerobic degradation pathways for the chlorinated ethenes and ethanes are shown in figure 8. The fuel hydrocarbons biodegrade relatively easily in ground water under both aerobic and anaerobic conditions. By depleting electron acceptors, they create the reducing conditions necessary for the efficient biodegradation of the chlorinated solvents. Converging lines of evidence from the spatial and temporal distributions of VOCs, electron acceptors, and metabolic by-products were used to assess the occurrence and extent of intrinsic biodegradation in the natural attenuation study area.

Areal Distribution of Electron Acceptors and Metabolic By-Products In response to the presence of biodegradable carbon, aquifer microorganisms will consume electron acceptors and produce metabolic by-products, causing changes in the prevailing geochemistry of the ground water. A well-defined sequence of microbially mediated oxidation-reduction reactions, based on free-energy yield, is observed in most contaminated aquifers. Dissolved-oxygen reduction occurs first, followed by nitrate reduction, manganese (IV) reduction, iron (III) reduction, sulfate reduction, and finally methane production (Weidemeier and others, 1999, p. 165; Chapelle and others, 1995). The consumption of electron acceptors is accompanied by the production of characteristic by-products. These by-products include reduced nitrogen, manganese and iron species, sulfide, methane, and carbon dioxide, leading to increased levels of dissolved inorganic carbon (DIC).

When chlorinated solvents are biodegraded, chloride ion also is produced as a metabolic by-product. Thus, under ideal conditions when background chloride concentrations are low, for example, elevated chloride concentrations can be used as evidence of chlorinated solvent degradation. The chloride results from the January–March 2000 sampling round (table 5) were inconclusive, however, and will not be

Table 5. *Concentrations of nutrients, sulfate, and chloride in ground water from wells screened in the surficial aquifer at sites FT03, LF13, and WP14/LF15, Dover Air Force Base, Delaware, January–March 2000*

[mg/L, milligrams per liter; N, nitrogen; DUP, duplicate sample; EQB, equipment blank; SWB, source-water blank; FDB, field blank; *B*, estimated result; result is less than the reporting limit; RL, reporting limit; ND, not detected; *Q*, elevated reporting limit; the reporting limit is elevated due to high analyte levels; *G*, elevated reporting limit; the reporting limit is elevated because of matrix interference]

Sample identification number	Collection date	Nitrate plus nitrite (mg/L as N)	Ammonia (mg/L as N)	Sulfate (mg/L)	Chloride (mg/L)
		RL: 0.10	0.10	5.0	3.0
DM101D	01/12/2000	0.30	ND	3.2 *B*	11.9
DM101S	01/12/2000	.63	ND	220 *Q*	6.3
DM107D	02/24/2000	.75	0.029 *B*	3.6 *B*	9.9
DM107S	02/24/2000	.16	.033 *B*	15.0	5.6
DM108D	02/24/2000	.20	.040 *B*	4.4 *B*	11.4
DM108D.DUP	02/24/2000	.53	.034 *B*	4.5 *B*	11.4
DM108S	02/24/2000	.55	.034 *B*	12.9	9.8
DM109D	01/19/2000	.066 *B*	.088 *B*	18.5	9.8
DM109S	01/19/2000	ND	ND	176 *Q*	16.6
DM110D	02/25/2000	1.1	.038 *B*	46.7	6.2
DM110D.DUP	02/25/2000	1.1	.091 *B*	49.0	6.1
DM110S	02/29/2000	.17	.29	94.5 *Q*	95.3 *Q*
DM110S.DUP	02/29/2000	.28	.37	97.1 *Q*	99.1 *Q*
DM113D	03/09/2000	2.1	.034 *B*	1.2 *B*	10.8
DM113S	03/09/2000	.33	.065 *B*	22.0	3.6
GS002D	02/16/2000	ND	.38 *B, G*	3.4	11.6
GS002M	02/10/2000	.41 *B, G*	.23 *B, G*	4.5 *B*	10.8
GS003M	02/23/2000	.46	.38	19.9	4.6
GS003S	02/23/2000	ND	.11	14.6	16.7
GS004D	02/25/2000	.013 *B*	.28	18.2	5.2
GS004D.DUP	02/25/2000	.021 *B*	.30	17.7	5.0
GS004M	02/15/2000	ND *G*	.17	16.7	10
GS004S	02/15/2000	ND *G*	.24	16.6	9.6
GS010D	02/17/2000	.20 *B, G*	.32 *B, G*	10	11.4
GS010S	02/17/2000	.26 *B, G*	1.2 *G*	36.2	18.9
GS010S.DUP	02/17/2000	.14 *B, G*	.68 *G*	35.8	19.1
GS011D	01/13/2000	.53	.65	16.2	12.2
GS011S	01/13/2000	ND	.44	416 *Q*	8.1
GS012D	02/17/2000	.38 *B, G*	.98 *B, G*	5.6	12.1
GS012S	02/17/2000	ND	.34 *B, G*	170 *Q*	78.0
GS013D	02/29/2000	.087 *B*	.42	14.4	5.0
GS014D	02/16/2000	1.0	.31 *B, G*	22.5	11.1
GS045MLA	03/13/2000	ND	.18	1.6 *B*	10.8
GS045MLB	03/13/2000	1.1	.035 *B*	3.2 *B*	12.5
GS045MLC	03/13/2000	1.7	.14	1.0 *B*	13.6
GS045MLD	03/13/2000	1.0	.030 *B*	2.8 *B*	5.6
GS045MLE	03/13/2000	ND	.047 *B*	9.1	11.6
GS045MLF	03/13/2000	ND	.085 *B*	10.9	4.0
GS045MLG	03/13/2000	ND	.066 *B*	13.4	4.8
GS045MLH	03/13/2000	ND	.060 *B*	12.9	5.6
GS045MLH.DUP	03/13/2000	ND	.064 *B*	13.0	5.8

Table 5. *Concentrations of nutrients, sulfate, and chloride in ground water from wells screened in the surficial aquifer at sites FT03, LF13, and WP14/LF15, Dover Air Force Base, Delaware, January–March 2000—Continued*

Sample identification number	Collection date	Nitrate plus nitrite (mg/L as N)	Ammonia (mg/L as N)	Sulfate (mg/L)	Chloride (mg/L)
		RL: 0.10	0.10	5.0	3.0
GS047MLA	03/14/2000	1.6	0.040 *B*	0.97 *B*	8.2
GS047MLB	03/14/2000	.90	.060 *B*	1.0 *B*	9.2
GS047MLC	03/14/2000	.14	.055 *B*	1.8 *B*	10.5
GS047MLD	03/14/2000	.10	.059 *B*	24.0	12.2
GS047MLE	03/14/2000	.16	.098 *B*	28.3	9.4
GSCP3M	02/15/2000	ND *G*	.24	3.4 *B*	14.4
GSCP5M	03/06/2000	ND	ND	7.1	14.2
GSCP6D	02/09/2000	ND *G*	.16	11.4	17.9
MW011	03/14/2000	.34 *B*	.078 *B*	12.1	5.9
MW011.DUP	03/14/2000	.73	.033 *B*	15.8	11.0
MW019	02/25/2000	.58	.38	9.9	8.0
MW037S	03/10/2000	.27	.035 *B*	22.4	6.2
MW037D	03/10/2000	.44	.030 *B*	10.2	10.2
MW038D	03/09/2000	.081 *B*	.038 *B*	5.5	9.8
MW038S	03/09/2000	ND	.055 *B*	26.7	6.3
MW039D	02/23/2000	1.1	.032 *B*	5.6	8.4
MW039S	03/14/2000	.73	.033 *B*	15.8	11.0
MW039S.DUP	03/14/2000	.55	.057 *B*	15.8	11.0
MW040D	03/07/2000	.88	.14	6.8	7.8
MW040S	03/07/2000	1.7	.030 *B*	10.7	8.0
MW061S	02/29/2000	.14	.28	11.9	175 *Q*
MW062D	03/10/2000	2.2	.034 *B*	.79 *B*	7.8
MW062S	02/11/2000	.25 *B*, *G*	1.2 *G*	5.5	19.5
MW064S	02/16/2000	ND *G*	.71 *G*	250 *Q*	32.8
MW206D	03/06/2000	.60	.036 *B*	2.2 *B*	10.7
MW206M	03/06/2000	.85	ND	8.9	8.6
MW206M.DUP	03/06/2000	.70	ND	8.7	8.7
MW227D	03/07/2000	.44	.032 *B*	10.2	8.6
MW227M	02/10/2000	.49	.044 *B*	15.2	5.9
MW227S	03/07/2000	ND	.14	49.7	40.5
MWD4B	03/06/2000	1.6	ND	16.4	4.6
MWD4H	03/15/2000	.029 *B*	.073 *B*	15.7	5.7
JAN0500.EQB	01/05/2000	ND	ND	ND	ND
JAN0500.SWB	01/05/2000	ND	ND	ND	ND
DM107S.FDB	02/24/2000	ND	.05 *B*	ND	ND
GS013D.FDB	02/29/2000	ND	.33	ND	ND
GSCP6D.FDB	02/09/2000	ND	3.7	ND	ND
MW011.FDB	03/14/2000	.025 *B*	.14	ND	.70 *B*
MW019.FDB	02/25/2000	ND	.032 *B*	ND	ND
MW064S.FDB	02/16/2000	.012 *B*	.33 *B*, *G*	ND	.79 *B*
MW227S.FDB	03/07/2000	ND	ND	0.97 *B*	.73 *B*

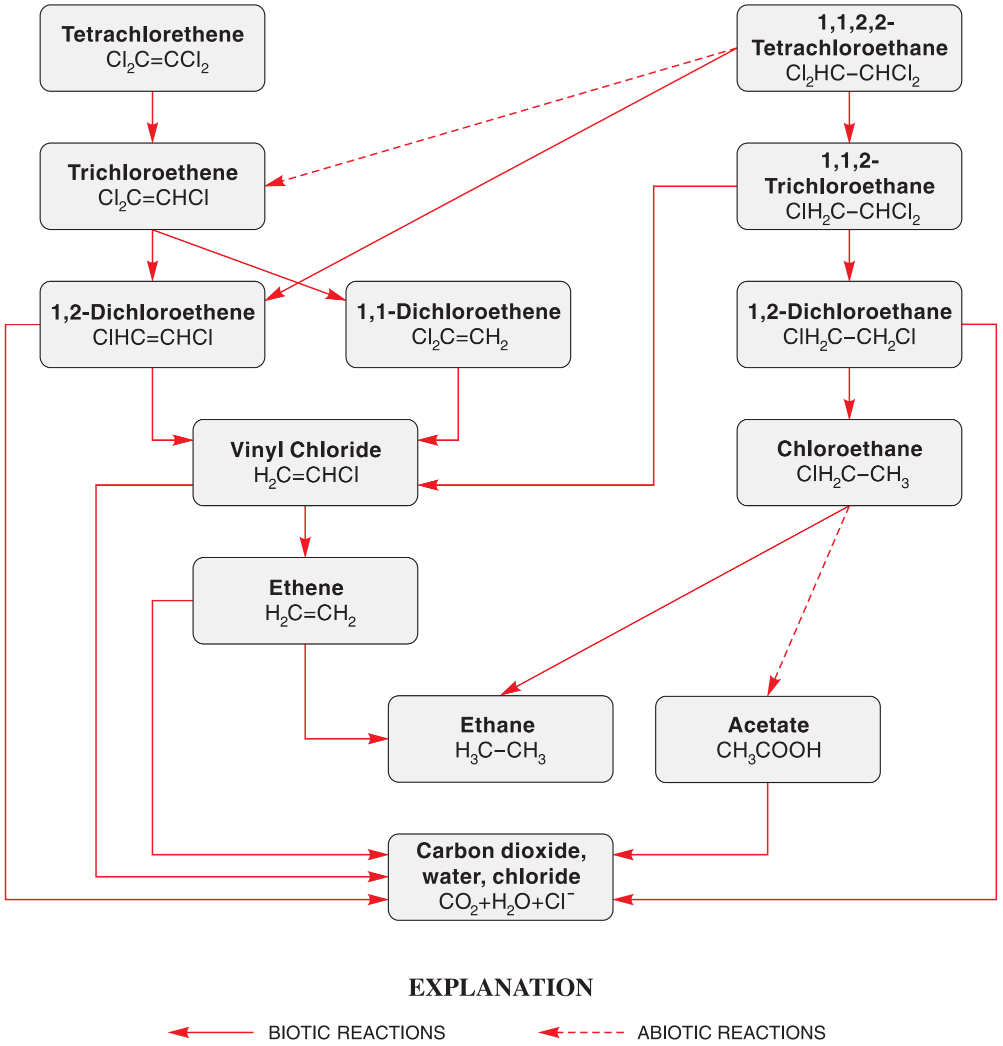


Figure 8. Possible biotic and abiotic reaction pathways for the chlorinated ethenes and ethanes (modified from Wiedemeier and others, 1999, p. 156, 246, and 268; and Lorah and others, 1997, p. 13).

discussed further in this report. This reaction footprint may have been difficult to observe because the concentrations of the chlorinated solvents in the plumes are low (less than 1 mg/L generally).

Nitrate and sulfate reduction do not appear to be important reactions in the natural attenuation study area. Because of a lack of nitrogen input to the surficial aquifer underlying DAFB, nitrate concentrations (nitrate plus nitrite as N in tables) in ground water are low (table 5). Sulfate concentrations were variable across the natural attenuation study area, and widespread sulfate depletion in contaminated ground water was not evident (table 5).

Based on the data collected for this study (table 6), oxygen reduction, iron reduction and methanogenesis are the dominant terminal electron-accepting processes (TEAPs) in the natural attenuation study area. For comparative purposes, the definitions provided by Bachman and others (1998, p. 23) of the three main TEAPs in the area are used in this discussion: aerobic conditions prevail when DO concentrations are greater than 1 mg/L; iron-reducing when DO concentrations are less than 1 mg/L and ferrous iron concentrations are greater than 1 mg/L; and mixed methanogenic and iron-reducing when DO concentrations are less than 1 mg/L, ferrous iron concentrations are greater than 1 mg/L, and dissolved methane concentrations are greater than 100 µg/L (micrograms per liter).

The areal distributions of DO, ferrous iron, and methane are shown in figures 9a, 9b, and 9c. For illustrative purposes, concentrations in ground water from wells and piezometers screened in the upper part of the surficial aquifer,

Table 6. *Concentrations of field constituents and methane in ground water from wells screened in the surficial aquifer at sites FT03, LF13, and WP14/LF15, Dover Air Force Base, Delaware, January–March 2000*

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter; °C, degrees Celsius; <, less than method detection limit; **>,** estimated result; concentration exceeded highest calibration standard; DUP, duplicate sample; FDB, field blank; NS, not sampled]

Sample identification number	Collection date	Ferrous iron (mg/L)	Total iron (mg/L)	Sulfide (mg/L)	Methane (µg/L)	Dissolved oxygen (mg/L)	pH (standard units)	Specific conductance (µS/cm)	Temperature (°C)
DM101D	01/12/2000	0.14	1.2	<0.01	42	0.81	7.6	159	12.6
DM101S	01/12/2000	< .02	.07	< .01	<10	4.5	5.6	625	11.7
DM107D	02/24/2000	.02	.02	< .01	21	3.1	5.4	61	14.6
DM107S	02/24/2000	< .02	.02	< .01	<9.2	4.7	5.2	55	11.3
DM108D	02/24/2000	.04	.19	< .01	58	.59	5.4	64	13.9
DM108D.DUP	02/24/2000	.05	.17	< .01	NS	.67	NS	NS	NS
DM108S	02/24/2000	.15	.20	< .01	<9.4	1.0	5.0	68	12.2
DM109D	01/19/2000	.28	1.2	< .01	<9.9	.76	7.7	122	11.9
DM109S	01/19/2000	< .02	.07	< .01	<8.8	3.7	5.4	430	11.8
DM110D	02/25/2000	.03	.08	< .01	<9.7	6.0	5.0	130	14.2
DM110D.DUP	02/25/2000	NS	NS	NS	<10	NS	NS	NS	NS
DM110S	02/29/2000	36	37	.15	8,700	< .20	5.9	724	11.3
DM113D	03/09/2000	< .02	< .02	< .01	<9.5	4.6	5.5	84	14.2
DM113S	03/09/2000	< .02	< .02	< .01	<9.5	4.6	5.0	88	11.8
GS002D	02/16/2000	1.0	1.4	< .01	47	1.5	5.3	73	14.2
GS002M	02/10/2000	8.0	8.4	< .01	<9.2	< .20	5.5	102	11.7
GS003M	02/23/2000	< .02	< .02	< .01	<9.5	5.9	5.5	72	12.9
GS003S	02/23/2000	10	10	< .01	1,500	< .20	6.1	206	12.8
GS004D	02/25/2000	4.4	4.6	.01	39	< .20	6.0	83	13.2
GS004M	02/25/2000	6.8	7.1	.01	<9.5	1.1	5.4	103	10.2
GS004S	02/15/2000	7.2	8.2	.03	<10	.52	5.2	101	8.1
GS010D	02/17/2000	< .02	< .02	< .01	<9.4	1.1	5.0	60	10.7
GS010S	02/17/2000	4.8	5.5	< .01	14	< .20	5.5	142	12.3
GS010S.DUP	02/17/2000	5.0	5.5	< .01	15	NS	NS	NS	NS
GS011D	01/13/2000	.31	.34	< .01	<10	2.2	4.3	108	13.6
GS011S	01/13/2000	12	14	< .01	30	< .20	5.2	1,270	12.4
GS012D	02/17/2000	3.1	4.0	< .01	15	< .20	5.5	74	11.0
GS012S	02/17/2000	1.9	4.2	< .01	13	.91	5.0	436	10.0
GS013D	02/29/2000	10	10	< .01	<9.5	< .20	6.4	136	14.1
GS014D	02/16/2000	.35	.37	< .01	<10	2.2	4.0	136	14.2
GS045MLA	03/13/2000	19	19	NS	14.2	1.5	NS	NS	NS
GS045MLB	03/13/2000	< .02	.03	NS	<9.4	4.1	NS	NS	NS
GS045MLC	03/13/2000	< .02	2.9	NS	<9.7	6.8	NS	NS	NS
GS045MLD	03/13/2000	< .02	< .02	NS	<10.1	3.4	NS	NS	NS
GS045MLE	03/13/2000	.34	.40	NS	<9.7	3.4	NS	NS	NS
GS045MLF	03/13/2000	2.8	.04	NS	<9.4	2.6	NS	NS	NS
GS045MLG	03/13/2000	2.3	2.4	NS	NS	2.7	NS	NS	NS
GS045MLH	03/13/2000	5.8	6.1	NS	481.9	2.2	NS	NS	NS
GS045MLH.DUP	03/13/2000	NS	NS	NS	NS	1.7	NS	NS	NS
GS047MLA	03/14/2000	.27	.39	NS	<8.9	1.8	NS	NS	NS
GS047MLB	03/14/2000	.37	.45	NS	13.4	.72	NS	NS	NS
GS047MLC	03/14/2000	1.0	1.1	NS	472.9	.59	NS	NS	NS
GS047MLD	03/14/2000	2.2	2.5	NS	704	.48	NS	NS	NS
GS047MLE	03/14/2000	1.6	2.4	NS	91.4	1.5	NS	NS	NS

Table 6. *Concentrations of field constituents and methane in ground water from wells screened in the surficial aquifer at sites FT03, LF13, and WP14/LF15, Dover Air Force Base, Delaware, January–March 2000—Continued*

Sample identification number	Collection date	Ferrous iron (mg/L)	Total iron (mg/L)	Sulfide (mg/L)	Methane (µg/L)	Dissolved oxygen (mg/L)	pH (standard units)	Specific conductance (µS/cm)	Temperature (°C)
GSCP3M	02/15/2000	11	11	0.01	170	0.58	6.0	126	11.4
GSCP5M	03/06/2000	3.6	5.4	< .01	111.8	.32	5.3	105	14.8
GSCP6D	02/09/2000	5.6	6.6	< .01	<8.4	< .20	4.9	126	13.2
MW011	03/14/2000	3.0	4.7	< .01	430	.29	5.6	116	13.7
MW019	02/25/2000	3.8	4.4	< .01	1,100	< .20	5.8	101	14.8
MW037D	03/10/2000	< .02	< .02	< .01	<9.4	2.2	5.1	85	15.8
MW037S	03/10/2000	.50	.72	< .01	<9.5	1.7	5.4	110	13.3
MW038D	03/09/2000	.49	.51	< .01	<9.3	.67	6.3	81	14.9
MW038S	03/09/2000	1.5	1.8	< .01	<10.0	.19	5.1	110	14.9
MW039D	02/23/2000	< .02	< .02	< .01	<9.2	5.7	5.5	58	13.7
MW039S	03/14/2000	< .02	< .02	< .01	370	1.0	5.5	131	12.8
MW040D	03/07/2000	< .02	< .02	< .01	<9.5	4.8	5.4	72	14.4
MW040S	03/07/2000	< .02	< .02	< .01	<9.3	3.9	5.2	96	13.1
MW061S	02/29/2000	36	37	.13	>9,200	< .20	6.0	1,206	14.4
MW062D	03/10/2000	< .02	< .02	< .01	<9.5	6.6	5.5	70	14.0
MW062S	02/11/2000	3.8	6.2	< .01	190	< .02	4.9	147	13.2
MW064S	02/16/2000	19	21	< .01	34	< .02	4.8	678	13.4
MW206D	03/06/2000	< .02	< .02	< .01	<9.4	2.3	5.3	73	14.3
MW206M	03/06/2000	.30	.28	< .01	142.9	.45	5.4	97	14.2
MW206M.DUP	03/06/2000	.30	.27	< .01	NS	NS	NS	NS	NS
MW227D	03/07/2000	< .02	< .02	< .01	<9.6	2.8	5.2	80	14.4
MW227M	03/07/2000	.14	.51	< .01	<9.6	2.5	3.4	85	13.5
MW227S	03/07/2000	2.5	3.0	< .01	<9.5	< .20	5.3	265	11.9
MWD4B	03/06/2000	< .02	< .02	< .01	<9.5	4.4	6.0	150	10.2
MWD4H	03/15/2000	< .02	.05	< .01	NS	NS	6.0	67	12.3
DM107S.FDB	02/24/2000	NS	NS	NS	<9.3	NS	NS	NS	NS
GS013D.FDB	02/29/2000	NS	NS	NS	<9.6	NS	NS	NS	NS
GSCP6D.FDB	02/09/2000	NS	NS	NS	<9.5	NS	NS	NS	NS
MW011.FDB	03/14/2000	NS	NS	NS	<9.1	NS	NS	NS	NS
MW019.FDB	02/25/2000	NS	NS	NS	<9.5	NS	NS	NS	NS
MW064.FDB	02/16/2000	NS	NS	NS	<9.5	NS	NS	NS	NS
MW227S.FDB	03/07/2000	< .02	< .02	< .01	<9.5	NS	NS	NS	NS

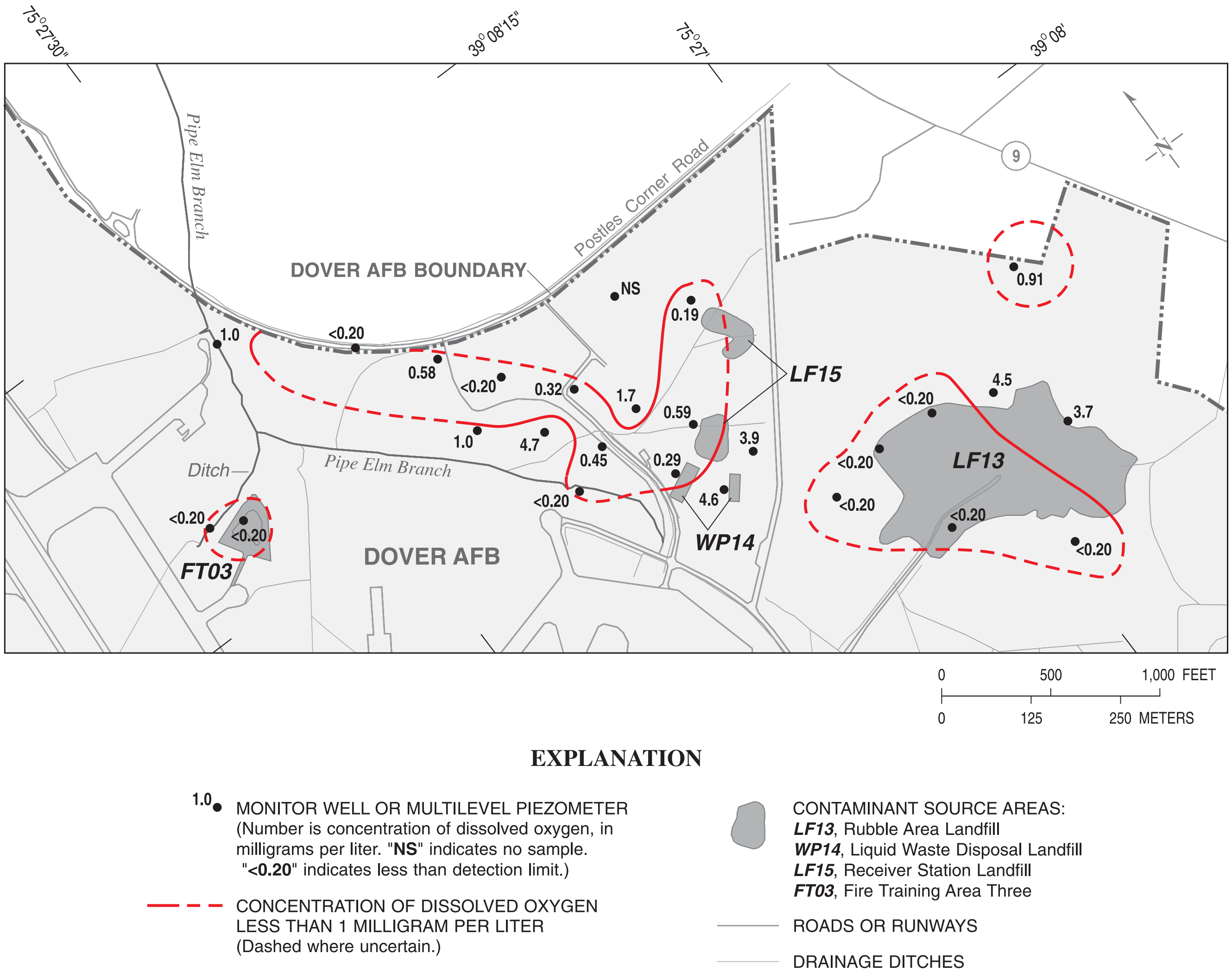


Figure 9a. Distribution of dissolved oxygen in the upper part of the surficial aquifer, Dover Air Force Base, Delaware, January-March 2000.

the most heavily contaminated vertical interval, are plotted on these figures. These figures show the zones where DO is less than 1 mg/L, ferrous iron is greater than 1 mg/L, and methane is greater than 100 µg/L. Three discrete zones with depleted DO and elevated iron and methane coincide with the three source areas and the area downgradient of WP14/LF15.

Using the TEAP definitions given above, mixed methanogenic/iron-reducing conditions have formed beneath all three source areas (fig. 10). Zones with iron reduction as the dominant TEAP surround the methanogenic zones beneath the WP14/LF15 and LF13 source areas. With the exception of higher methane concentrations at some of the wells downgradient of WP14/LF15, the distribution of dominant TEAPs is similar to the distribution in 1995–96 (Bachman and others, 1998, p. 24). This distribution indicates that the spatial patterns of redox conditions have not changed substantially.

The apparent co-existence of ferrous iron and methane is attributed to the length of the well screens. Long well screens, defined in this report as screens greater than 3 ft in length, likely produce samples that are a mixture of waters from vertically stratified redox environments (Smith and others, 1991). In actuality, the anaerobic reactions that produce ferrous iron and methane probably occur in discrete, narrow intervals that are controlled by the heterogeneity of the aquifer. Some ground-water samples also contain appreciable amounts of DO as well as ferrous iron and methane. This apparent redox disequilibrium also is attributed to a mixing of different redox environments. On a larger scale, however, the spatial patterns of depleted oxygen and elevated reduced species such as iron and methane are fairly consistent (figs. 9a, 9b, and 9c).

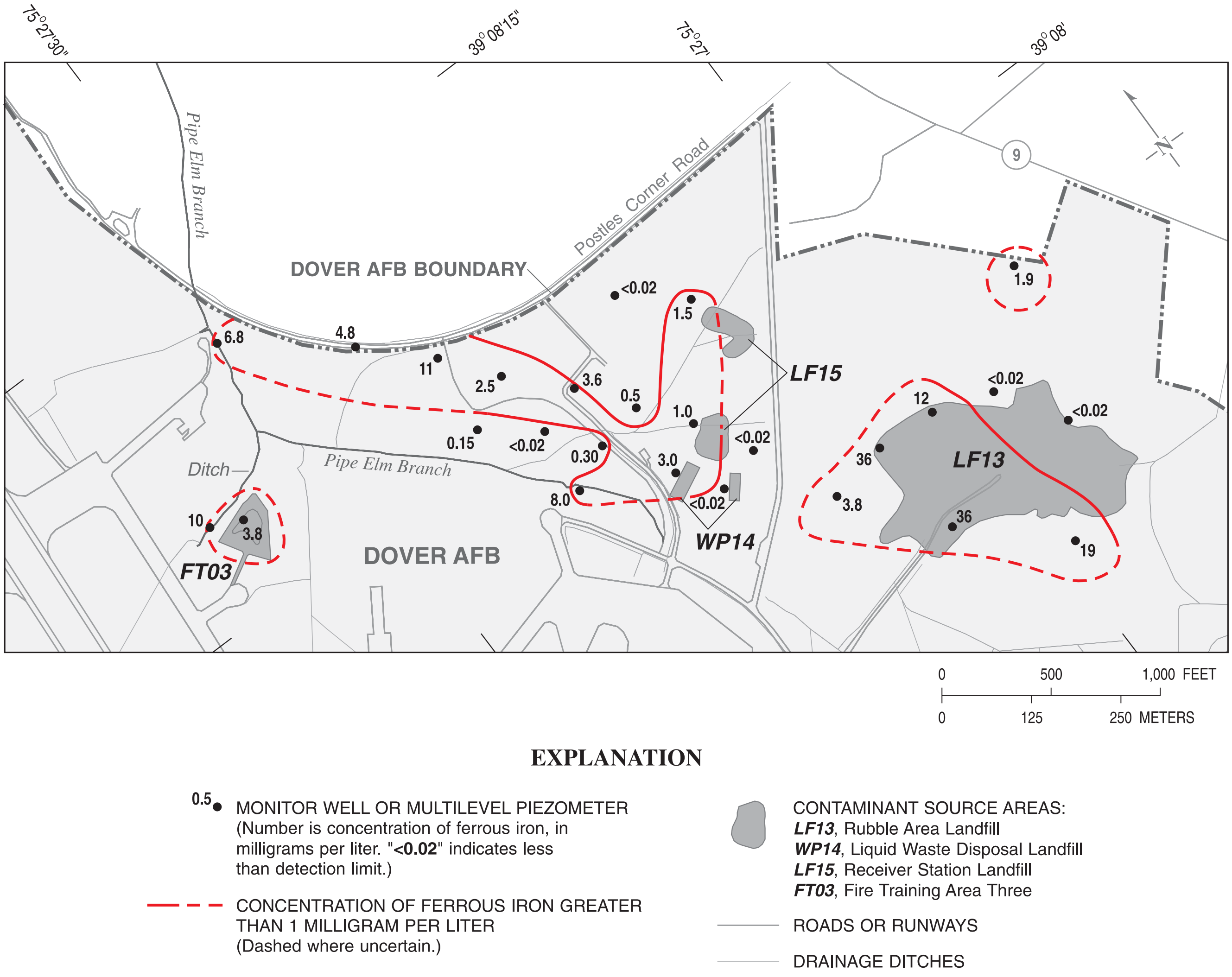


Figure 9b. Distribution of ferrous iron in the upper part of the surficial aquifer, Dover Air Force Base, Delaware, January-March 2000.

The presence of high concentrations of methane indicates that fermentation occurs near all of the contaminant source areas. Methane production often is used as an indicator of active fermentation because the hydrogen produced by the fermentation process is used as an electron donor by methanogens. If fermentable substrate is abundant within the plume, fermentation reactions will continue downgradient. On the basis of methane concentrations from samples downgradient of WP14/LF15 and LF13, fermentation is restricted to a zone that extends roughly 500 ft downgradient of the sources (fig. 9c). The available information indicates, therefore, that the dominant TEAP grades from methanogenic/iron-reducing to iron-reducing with distance from the source, and that the strongly reducing conditions required for dechlorination are present in ground water beneath the source areas.

The reaction footprints discussed in this section indicate that electron acceptors are consumed in microbially mediated reactions with reactive organic contaminants. Aerobic conditions in the surficial aquifer indicate that the naturally occurring carbon is not sufficiently reactive to rapidly deplete the DO. As oxygenated water flows through the source areas, DO is consumed rapidly in reactions with labile compounds such as benzene, toluene, ethylbenzene, and the xylene isomers (BTEX), the most abundant soluble compounds of fuel hydrocarbons. If reactive carbon in the source areas is abundant, competing anaerobic electron acceptors also will be depleted and fermentation will be the dominant process. Fermentation reactions yield substantially less energy in comparison to oxidation reactions, so fermentation (and methane production) generally occur only when other electron acceptors are not available (Wiedemeier and others, 1999, p. 249). Benzene, toluene, ethylbenzene and the xylene isomers are known to biodegrade under a

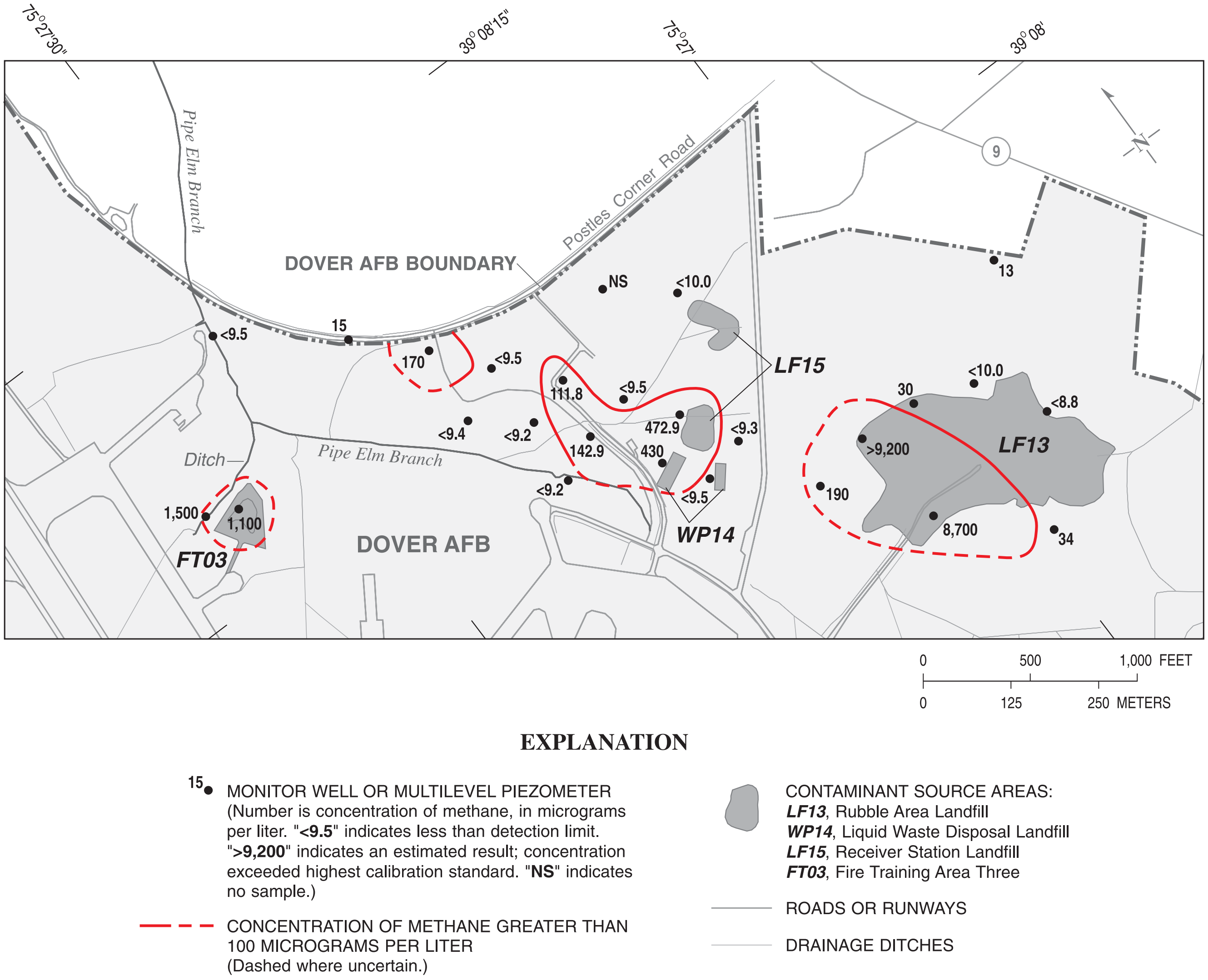


Figure 9c. Distribution of methane in the upper part of the surficial aquifer, Dover Air Force Base, Delaware, January-March 2000.

wide range of anaerobic conditions, including methanogenic conditions (Grbic-Galic and Vogel, 1987; Cozzarelli and others, 1990).

Areal Distribution of Fuel Hydrocarbons Fuel hydrocar-bons are susceptible to natural attenuation and consequently form relatively short plumes (typically less than 400 ft) (Wiedemeier and others, 1999, p. 10). Thus, their main importance at the sites in the EMU is to create the strongly reducing conditions that are required for the biodegradation of the chlorinated solvents. The fermentation of the soluble fuel compounds produces hydrogen, which is a required electron donor for the halorespiring bacteria that carry out reductive dechlorination (Wiedemeier and others, 1999, p. 247). If the hydrocarbon source becomes depleted, hydrogen production from fermentation may cease, allowing the solvent plumes to resume downgradient migration (National Research Council, 2000, p. 73).

Soluble fuel compounds were detected in low concentrations in all three source areas, and in some downgradient locations. Benzene was detected in samples collected from wells GS003S (1.9 µg/L), GSCP3M (2.7 µg/L) and MW061S (8.5 µg/L) (table 7). The MCL for benzene (5 µg/L) was exceeded only at well MW061S, which is located in LF13. The other common soluble fuel compounds toluene, ethylbenzene, and the xylene isomers, were not detected in ground-water samples collected during January–March 2000. The MCLs for the soluble fuel compounds were not exceeded in any of the POC wells along the Base boundary.

Two processes may account for the sparse detections of BTEX in the natural attenuation study area. First, through the process of dissolution, the non-aqueous phase liquid

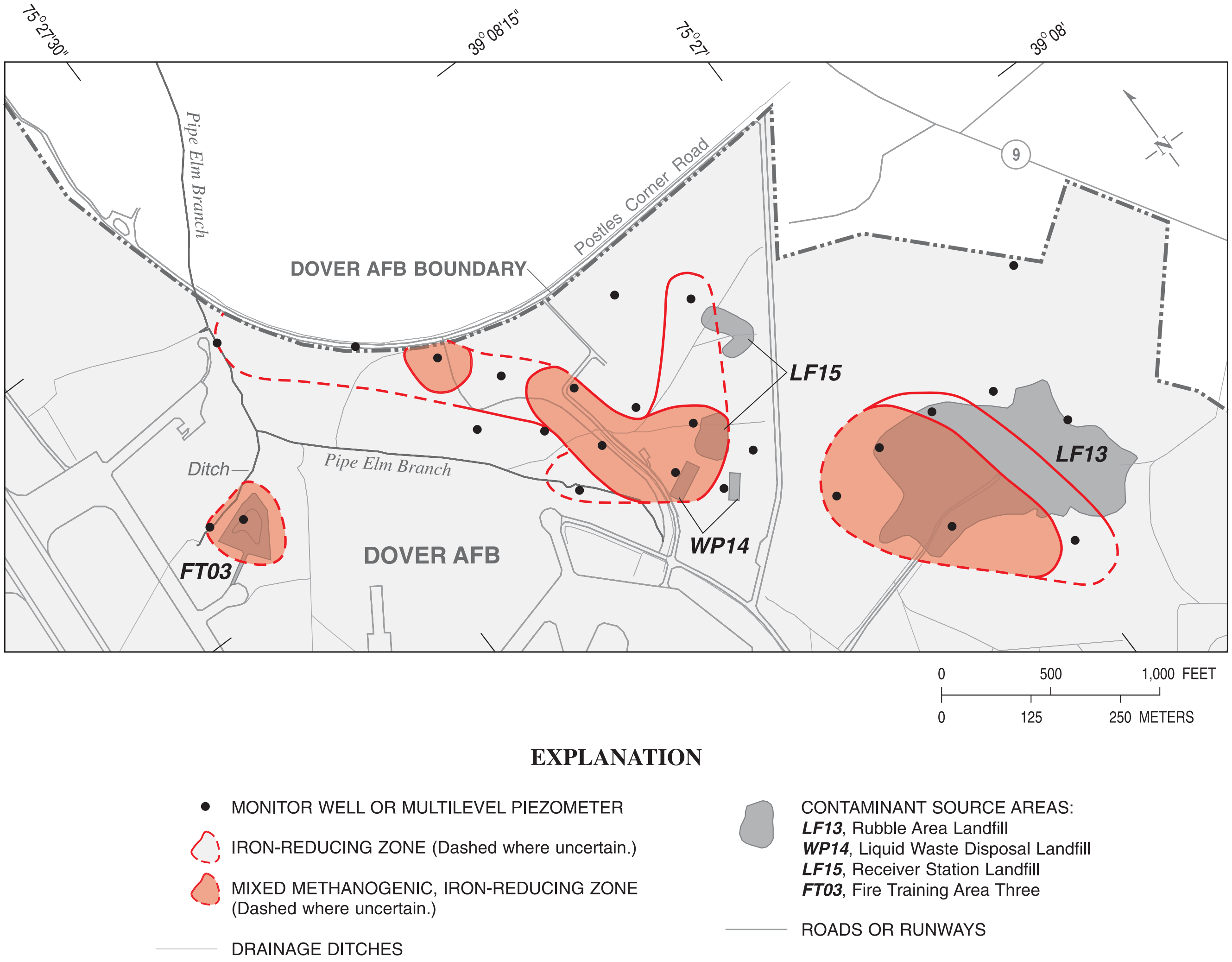


Figure 10. Distribution of terminal electron-accepting processes in the upper part of the surficial aquifer, Dover Air Force Base, Delaware, January-March 2000.

(NAPL) presumed to be present in the source areas may have become depleted in these compounds. Measurements of a floating hydrocarbon layer in well MW013, located 140 ft southeast of well MW011, show that NAPL is present in WP14/LF15 (U.S. Army Corps of Engineers and Dames and Moore, Inc., 1997a). The monitoring network does not indicate that NAPL is present at the other two sites, but considering historical disposal practices, its presence is a possibility in the natural attenuation study area. The more water-soluble compounds of a multicomponent organic liquid such as jet fuel will partition relatively quickly to the ground water, so that the remaining NAPL consists mainly of the insoluble fraction (Borden and Kao, 1992). As NAPLs dissolve, the mass flux (mass per unit time) of contaminants to ground water will gradually decline. The rate of the decline depends on site-specific factors and cannot be determined with the available information. Because waste fuels and solvents have not been placed in these source areas recently, it is reasonable to expect that substantial depletion of BTEX in the source material has occurred.

Second, most of the BTEX mass that partitions to ground water may undergo biodegradation over short distances (tens of feet) from the source areas. These constituents are known to biodegrade under both iron-reducing and methanogenic conditions (Wiedemeier and others, 1999, p. 192), the two main anaerobic TEAPs at the site. Thus, rapid anaerobic biodegradation also may explain the low number of detections of BTEX in the contaminant plumes.

Areal Distribution of Chlorinated Solvents

Chlorinated solvents were detected in ground water beneath all three source areas, as well as downgradient of the WP14/LF15 area. Because of their relatively widespread distribution, only the PCE → TCE → *cis*-1,2-DCE → VC reduction sequence is discussed here in detail; other chlorinated com-pounds such as chlorobenzene, 1,1,2,2-

TeCA, 1,2-dichloro-ethane (1,2-DCA), *trans*-1,2-dichloroethene (*trans*-1,2-DCE), and methylene chloride were detected less frequently in the natural attenuation study area

Table 7. *Concentrations of selected volatile organic compounds in ground water from wells screened in the surficial aquifer at sites FT03, LF13, and WP14/LF15, Dover Air Force Base, Delaware, January–March, 2000*

[µg/L, micrograms per liter; ND, not detected; RL, reporting limit; *J*, estimated result; result is less than the reporting limit; MCL, maximum contaminant level; PCE, tetrachloroethene; TCE, trichloroethene; *cis*-1,2-DCE, *cis*-1,2-dichloroethene; VC, vinyl chloride; 1,2-DCA, 1,2-dichloroethane; 1,1,2,2-TeCA, 1,1,2,2-tetrachloroethane; concentration listed in **bold** when MCL exceeded; DUP, duplicate sample; AMB, ambient blank; TPB, trip blank; FDB, field blank; EQB, equipment blank; SWB, source-water blank]

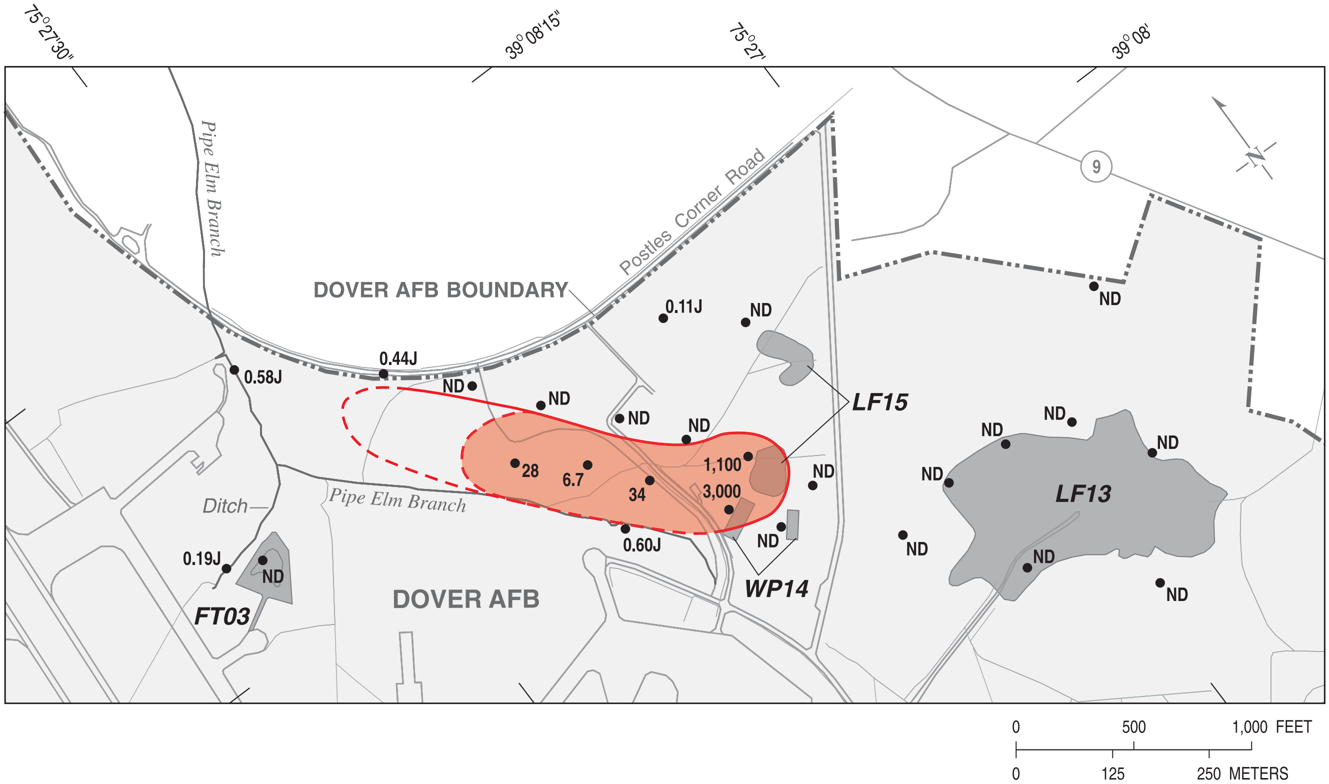
Sample identification number	Collection date		Benzene (µg/L)	Chlorobenzene (µg/L)	PCE (µg/L)	TCE (µg/L)	*cis*-1,2-DCE (µg/L)	VC (µg/L)	1,1,2,2,-TeCA (µg/L)	1,2-DCA (µg/L)	Methylene chloride (µg/L)
		RL	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**2.0**	**1.0**	**1.0**	**1.0**
		MCL	**5**	**100**	**5**	**5**	**70**	**2**	**--**	**5**	**5**
DM101D	01/12/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
DM101S	01/12/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
DM107D	02/24/2000		ND	ND	**15**	**21**	2.8	0.20 *J*	ND	**12**	ND
DM107S	02/24/2000		ND	ND	**6.7**	**7.5**	1.9	ND	ND	1.3	ND
DM108D*	02/24/2000		0.24 *J*	ND	**40**	**110**	16	1.6 *J*	5.6	**55**	0.67 *J*
DM108D.DUP*	02/24/2000		ND	ND	**32**	**88**	13	1.0 *J*	4.6	**41**	.60 *J*
DM108S*	02/24/2000		ND	ND	**28**	**84**	16	ND	7.2	ND	.41 *J*
DM109D	01/19/2000		ND	0.29 *J*	ND	ND	ND	ND	ND	ND	ND
DM109S	01/19/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
DM110D	02/25/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
DM110D.DUP	02/25/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
DM110S*	02/29/2000		3.7 *J*	47	ND	1.4 *J*	**270**	**130**	ND	ND	5.0 *J*
DM110S.DUP*	02/29/2000		3.4 *J*	45	ND	1.4 *J*	**270**	**120**	ND	ND	**5.2** *J*
DM113D	03/09/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
DM113S	03/09/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
GS002D	02/16/2000		.18 *J*	ND	**8.3**	**24**	5.6	.31 *J*	1.9	**27**	.46 *J*
GS002M	02/10/2000		ND	ND	.60 *J*	.83 *J*	.24 *J*	ND	ND	ND	.22 *J*
GS003M	02/23/2000		ND	ND	.30 *J*	ND	6.6	ND	ND	ND	ND
GS003S	02/23/2000		1.9	ND	.19 *J*	1.1	15	**8.8**	ND	ND	ND
GS004D	02/25/2000		ND	ND	ND	.17 *J*	.78 *J*	ND	ND	ND	ND
GS004D.DUP	02/25/2000		ND	ND	ND	.14 *J*	.78 *J*	ND	ND	ND	ND
GS004M	02/15/2000		.16 *J*	ND	.58 *J*	.29 *J*	1.4	ND	ND	.22 *J*	ND
GS004S	02/15/2000		.20 *J*	ND	.41 *J*	.48 *J*	1.1	ND	ND	ND	ND
GS010D	02/17/2000		ND	ND	.38 *J*	4.2	2.6	ND	2.1	ND	ND
GS010S	02/17/2000		.61 *J*	ND	.44 *J*	2.9	2.5	ND	.90 *J*	ND	ND
GS010S.DUP	02/17/2000		.63 *J*	ND	.42 *J*	2.8	2.5	ND	.95 *J*	ND	ND
GS011D	01/13/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND

Table 7. *Concentrations of selected volatile organic compounds in ground water from wells screened in the surficial aquifer at sites FT03, LF13, and WP14/LF15, Dover Air Force Base, Delaware, January–March, 2000—Continued*

Sample identification number	**Collection date**		**Benzene (µg/L)**	**Chlorobenzene (µg/L)**	**PCE (µg/L)**	**TCE (µg/L)**	***cis*-1,2-DCE (µg/L)**	**VC (µg/L)**	**1,1,2,2,-TeCA (µg/L)**	**1,2-DCA (µg/L)**	**Methylene chloride (µg/L)**
		RL	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**2.0**	**1.0**	**1.0**	**1.0**
		MCL	**5**	**100**	**5**	**5**	**70**	**2**	**--**	**5**	**5**
GS011S	01/13/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
GS012D	02/17/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
GS012S	02/17/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
GS013D	2/29/20000		ND	ND	ND	ND	ND	ND	ND	ND	ND
GS014D	02/16/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
GS045MLA	03/13/2000		ND	ND	**12**	**15**	6.3	ND	ND	ND	ND
GS045MLB	03/13/2000		ND	ND	0.88 *J*	1.1	1.8	ND	ND	ND	ND
GS045MLC	03/13/2000		ND	ND	.50 *J*	0.45 *J*	0.23 *J*	ND	ND	ND	ND
GS045MLD	03/13/2000		ND	ND	.34 *J*	.36 *J*	.20 *J*	ND	ND	ND	ND
GS045MLE	03/13/2000		ND	ND	3.6	2.9	.79 *J*	ND	ND	ND	ND
GS045MLF	03/13/2000		ND	ND	2.2	1.9	.68 *J*	ND	ND	ND	ND
GS045MLG*	03/13/2000		0.54 *J*	ND	**63**	**49**	43	0.73 *J*	ND	ND	ND
GS045MLH*	03/13/2000		ND	ND	**1,100**	**600**	**400**	ND	ND	ND	ND
GS045MLH.DUP*	03/13/2000		ND	ND	**960**	**520**	**340**	ND	ND	ND	ND
GS047MLA*	03/14/2000		ND	ND	**180**	**45**	18	ND	ND	ND	2.6 J
GS047MLB*	03/14/2000		ND	ND	**430**	**110**	46	ND	ND	ND	**11**
GS047MLC*	03/14/2000		ND	ND	**1,100**	**290**	**130**	**12** *J*	ND	**17** *J*	**20**
GS047MLD*	03/14/2000		4.6 *J*	ND	**430**	**160**	**79**	**16** *J*	ND	**21**	4.5 *J*
GS047MLE	03/14/2000		ND	ND	1.9	1.6	1.3	ND	ND	ND	1.2
GSCP3M	02/15/2000		2.7	ND	ND	.56 *J*	.12 *J*	ND	ND	0.24 *J*	ND
GSCP5M	03/06/2000		ND	ND	ND	**7.2**	4.5	.85 *J*	5.1	.39 *J*	ND
GSCP6D	02/09/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
MW011*	03/14/2000		ND	ND	**3,000**	**1,400**	**450**	ND	ND	ND	**42** *J*
MW011.DUP*	03/14/2000		ND	ND	**2,900**	**1,200**	**420**	ND	ND	ND	**43** *J*
MW019	02/25/2000		ND	ND	ND	ND	6.9	**11**	ND	.39 *J*	ND
MW037D	03/10/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
MW037S	03/10/2000		ND	ND	ND	1.5	1.1	ND	.95 *J*	ND	.20 *J*
MW038D	03/09/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
MW038S	03/09/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
MW039D	02/23/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
MW039S*	03/14/2000		ND	ND	**310**	**120**	51	**9.1** *J*	ND	**7.5** *J*	4.0 *J*
MW039S.DUP*	03/14/2000		ND	ND	**300**	**110**	49	**8.9** *J*	ND	**7.3** *J*	**11**

Table 7. *Concentrations of selected volatile organic compounds in ground water from wells screened in the surficial aquifer at sites FT03, LF13, and WP14/LF15, Dover Air Force Base, Delaware, January–March, 2000—Continued*

Sample identification number	Collection date		Benzene (µg/L)	Chlorobenzene (µg/L)	PCE (µg/L)	TCE (µg/L)	*cis*-1,2-DCE (µg/L)	VC (µg/L)	1,1,2,2,-TeCA (µg/L)	1,2-DCA (µg/L)	Methylene chloride (µg/L)
		RL	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**2.0**	**1.0**	**1.0**	**1.0**
		MCL	**5**	**100**	**5**	**5**	**70**	**2**	**--**	**5**	**5**
MW040D	03/07/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
MW040S	03/07/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
MW061S*	02/29/2000		**8.5**	75	ND	ND	0.30 *J*	ND	ND	0.89 *J*	0.42 *J*
MW062D	03/10/2000		ND	ND	ND	ND	ND	ND	ND	ND	.20 *J*
MW062S	02/11/2000		ND	0.46 *J*	ND	ND	ND	ND	ND	ND	ND
MW064S	02/16/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
MW206D	03/06/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
MW206M	03/06/2000		0.18 *J*	ND	**34**	**34**	26	0.32 *J*	ND	**10**	ND
MW206M.DUP	03/06/2000		.20 *J*	ND	**38**	**37**	28	.38 *J*	ND	**12**	ND
MW227D	03/07/2000		ND	ND	1.3	**7.5**	4.3	ND	2.8	ND	.21 *J*
MW227M	02/10/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
MW227S	03/07/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
MWD4B	03/06/2000		ND	ND	0.11 *J*	ND	ND	ND	ND	ND	ND
MWD4H	03/15/2000		ND	ND	ND	ND	ND	ND	ND	ND	.23 *J*
JAN0500.EQB	01/05/2000		ND	ND	ND	ND	ND	ND	ND	ND	2.0
JAN0500.SWB	01/05/2000		ND	ND	ND	ND	ND	ND	ND	ND	1.8
JAN1300.TPB	01/13/2000		ND	ND	ND	ND	ND	ND	ND	ND	.28 *J*
FEB1500.TPB	02/15/2000		ND	ND	ND	ND	ND	ND	ND	ND	.34 *J*
FEB2300.TPB	02/23/2000		ND	ND	ND	ND	ND	ND	ND	ND	.35 *J*
FEB2900.TPB	02/29/2000		ND	ND	ND	ND	ND	ND	ND	ND	.54 *J*
MAR0600.TPB	03/06/2000		ND	.21 *J*	ND	ND	ND	ND	ND	.30 *J*	.67 *J*
MAR1400.TPB	03/14/2000		ND	ND	ND	ND	ND	ND	ND	ND	.72 *J*
DM108D.AMB	02/24/2000		ND	ND	ND	ND	ND	ND	ND	ND	.30 *J*
DM110D.AMB	02/25/2000		ND	ND	ND	ND	ND	ND	ND	ND	.38 *J*
MW039S.AMB	03/14/2000		ND	ND	ND	ND	ND	ND	ND	ND	.92 *J*
DM107S.FDB	02/24/2000		ND	ND	ND	ND	ND	ND	ND	ND	.34 *J*
GSCP6D.FDB	02/09/2000		ND	ND	ND	ND	ND	ND	ND	ND	.59 *J*
GS013D.FDB	02/29/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND
MW011.FDB	03/14/2000		ND	ND	ND	ND	ND	ND	ND	ND	1.1
MW019.FDB	02/25/2000		ND	ND	ND	ND	ND	ND	ND	ND	.22 *J*
MW064S.FDB	02/16/2000		ND	ND	ND	ND	ND	ND	ND	ND	.44 *J*
MW227S.FDB	03/07/2000		ND	ND	ND	ND	ND	ND	ND	ND	ND



EXPLANATION

28● MONITOR WELL OR MULTILEVEL PIEZOMETER (Number is concentration of tetrachloroethene, in micrograms per liter. "**J**" indicates an estimated result. "**ND**" indicates not detected.)

CONCENTRATION OF TETRACHLOROETHENE GREATER THAN 1 MICROGRAM PER LITER (Dashed where uncertain.)

CONCENTRATION OF TETRACHLOROETHENE GREATER THAN THE MAXIMUM CONTAMINANT LEVEL (MCL) OF 5 MICROGRAMS PER LITER (Dashed where uncertain.)

CONTAMINANT SOURCE AREAS:
LF13, Rubble Area Landfill
WP14, Liquid Waste Disposal Landfill
LF15, Receiver Station Landfill
FT03, Fire Training Area Three

ROADS OR RUNWAYS

DRAINAGE DITCHES

Figure 11a. Distribution of tetrachloroethene in the upper part of the surficial aquifer, Dover Air Force Base, Delaware, January-March 2000.

volatile organic compounds in ground water from wells screened in the surficial aquifer at sites
F15, Dover Air Force Base, Delaware, January–March, 2000—Continued

Chlorobenzene (µg/L)	PCE (µg/L)	TCE (µg/L)	*cis*-1,2-DCE (µg/L)	VC (µg/L)	1,1,2,2-TeCA (µg/L)	1,2-DCA (µg/L)	Methylene chloride (µg/L)
1.0	1.0	1.0	1.0	2.0	1.0	1.0	1.0
100	5	5	70	2	--	5	5

ese samples are elevated due to high analyte levels.

and others, U.S. Geological Survey, written commun., 2000). With the exception of 1,1,2,2-TeCA, which was detected in well GS010D at a concentration of 2.1 µg/L, these compounds were not detected in the POC wells near the DAFB boundary.

Distributions of PCE, TCE, *cis*-1,2-DCE, and VC in the upper part of the surficial aquifer, the most heavily contaminated vertical interval, are shown in figures 11a, 11b, 11c, and 11d. The measured concentrations of these constituents throughout the full thickness of the aquifer ranged from 3,000 µg/L PCE in well MW011 (table 7) to below the reporting limit of 1.0 µg/L. The zones in the upper part of the surficial aquifer where the compounds were detected above 1 µg/L, and above their respective MCLs, are shown in figures 11a through 11d.

In general, VOC concentrations were highest beneath source areas and declined sharply with distance from the sources. The parent compounds PCE and TCE are prevalent only in the WP14/LF15 source area and plume. Both of these compounds were detected in wells substantial dis-

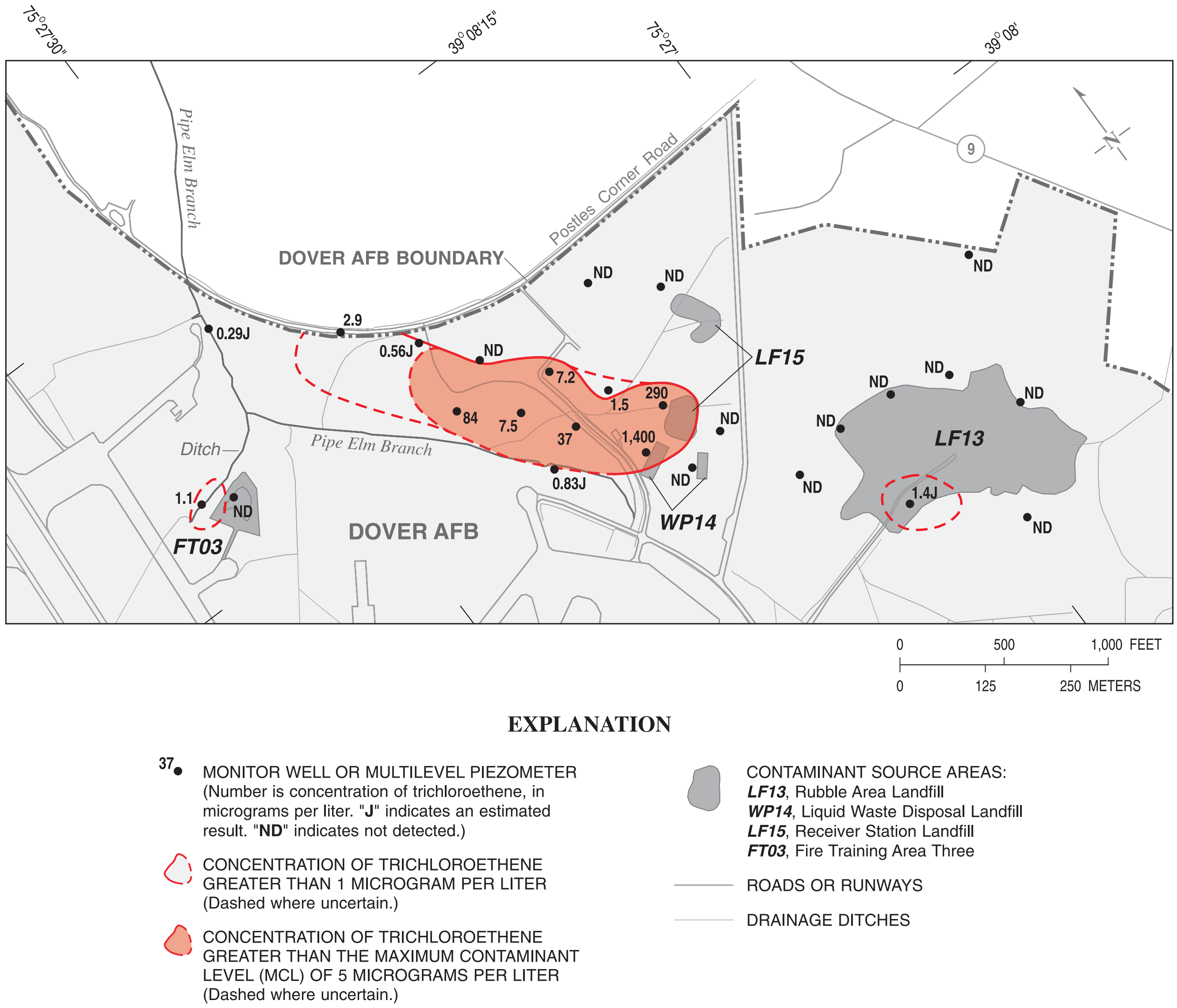


Figure 11b. Distribution of trichloroethene in the upper part of the surficial aquifer, Dover Air Force Base, Delaware, January-March 2000.

tances (thousands of feet) downgradient of the known source areas. For example, PCE was detected at 28 µg/L in well DM108S, which is located 1,000 feet downgradient of the source areas. TCE was detected at 2.9 µg/L in well GS010S and at 4.2 µg/L in well GS010D. This well cluster is located 1,800 ft downgradient of WP14/LF15. The MCL of 5 µg/L for TCE was not exceeded at these wells. With the exception of low concentrations in the GS003 well cluster, PCE and TCE were not detected in FT03 or LF13. By comparison, the breakdown products *cis*-1,2-DCE and VC were detected in all three source areas. The distribution of *cis*-1,2-DCE in the WP14/LF15 area is similar to that of TCE, although samples with concentrations exceeding the MCL of 70 µg/L are confined to the source area. VC was detected only in the monitor wells in the immediate vicinity of the source areas.

Site FT03—The three ground-water samples collected in FT03 indicate that ground water is reducing, and that dechlorination reactions are occurring in this area. The concentrations of the breakdown products *cis*-1,2-DCE and VC are substantially higher than the parent compounds (table 7). The MCL of 2 µg/L for VC was exceeded in samples from wells GS003S and MW019. Shallow ground water in FT03 migrates over relatively short flow paths of approximately 100 to 500 ft before reaching the adjacent drainage ditch or Pipe Elm Branch (fig. 5). Flow paths could be shorter depending on the specific location of the source area. Using the calculated mean ground-water flow velocity of 0.4 ft/d, traveltimes over 100–500 ft range from 250 d (days) to 3.4 yrs.

Intrinsic biodegradation in combination with the proximity of hydrologic discharge boundaries appears to be effective in controlling contaminant migration at this site.

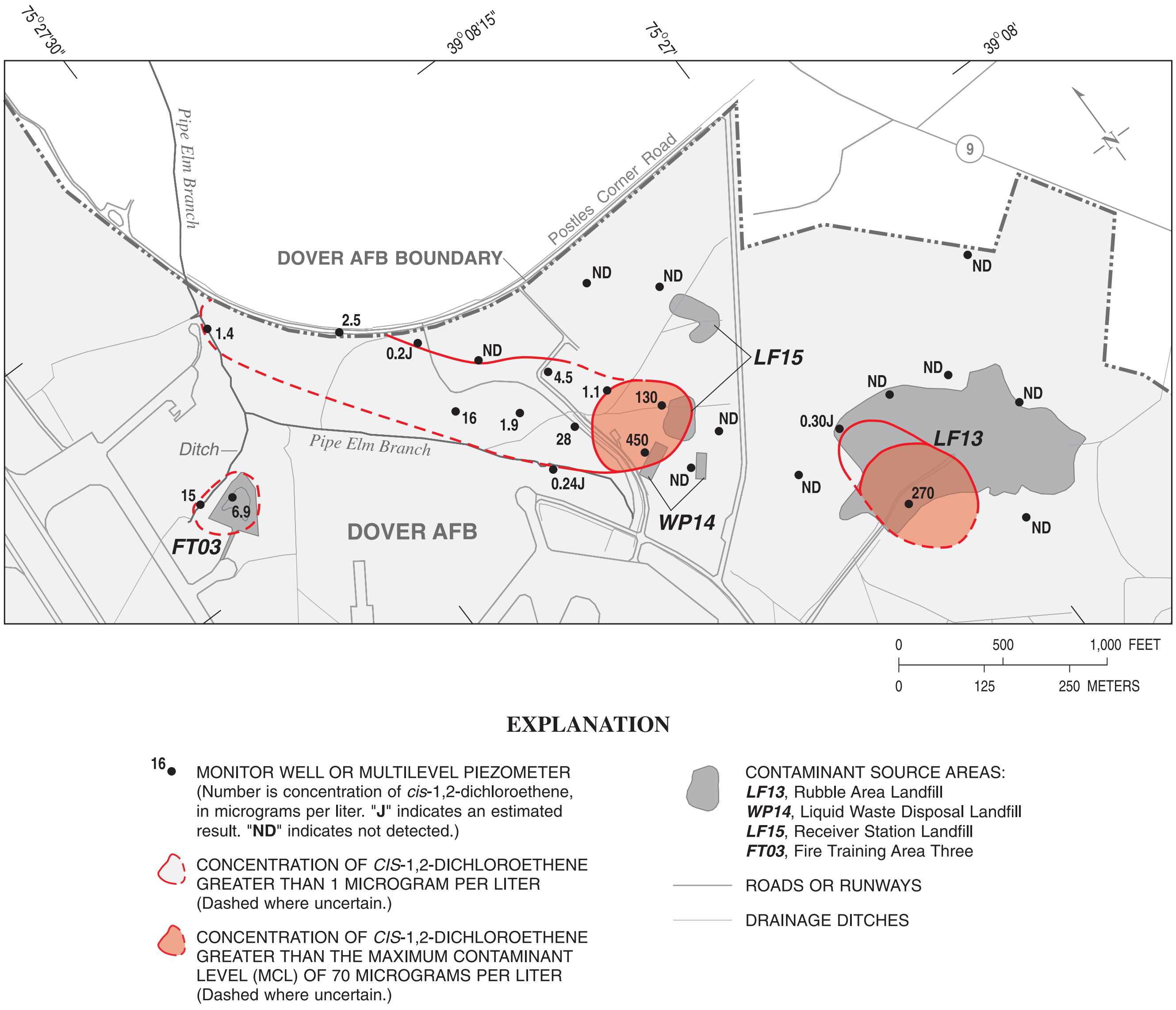


Figure 11c. Distribution of *cis*-1,2-dichloroethene in the upper part of the surficial aquifer, Dover Air Force Base, Delaware, January-March 2000.

The fate of contaminated water in the discharge areas is not well understood, however. Samples from the piezometers installed in the drainage ditch (GS003S and GS003M) contain parent compounds and breakdown products, indicating that the plume reaches the discharge area prior to complete dechlorination at this location. Because piezometer GS003S is screened 6 to 9 ft below the streambed (table 1), it is not known whether the contaminated water actually discharges to surface water, or migrates under the drainage ditch. If the plume does discharge to the drainage ditch, as indicated by upward hydraulic-head gradients, further anaerobic biodegradation may occur during migration through the anaerobic organic-rich deposits that underlie the ditch. If the contaminants reach the streambed surface-water interface, additional aerobic biodegradation of *cis*-1,2-DCE and VC may occur in this environment. Consequently, degradation reactions in the discharge areas may strongly affect the fate of contaminated water at this site.

Site LF13—With the exception of well DM110S, the wells along the perimeter of LF13 did not contain VOCs. High concentrations of methane, ferrous iron, chloride, and the breakdown products *cis*-1,2-DCE and VC in the sample from well DM110S indicate that extensive dechlorination is occurring near this well. However, the location of the source area within the landfill and the direction of plume migration currently are not well understood. The direction of plume migration in the upper part of the surficial aquifer could vary by 180 degrees (fig. 5), depending on the specific location of the source area. The steep downward vertical gradients in this area (fig. 7) also indicate that a plume migrating from a shallow source area has a downward trajectory along the first part of the flow path. If the plume migrating from the vicinity of well DM110S flows in a

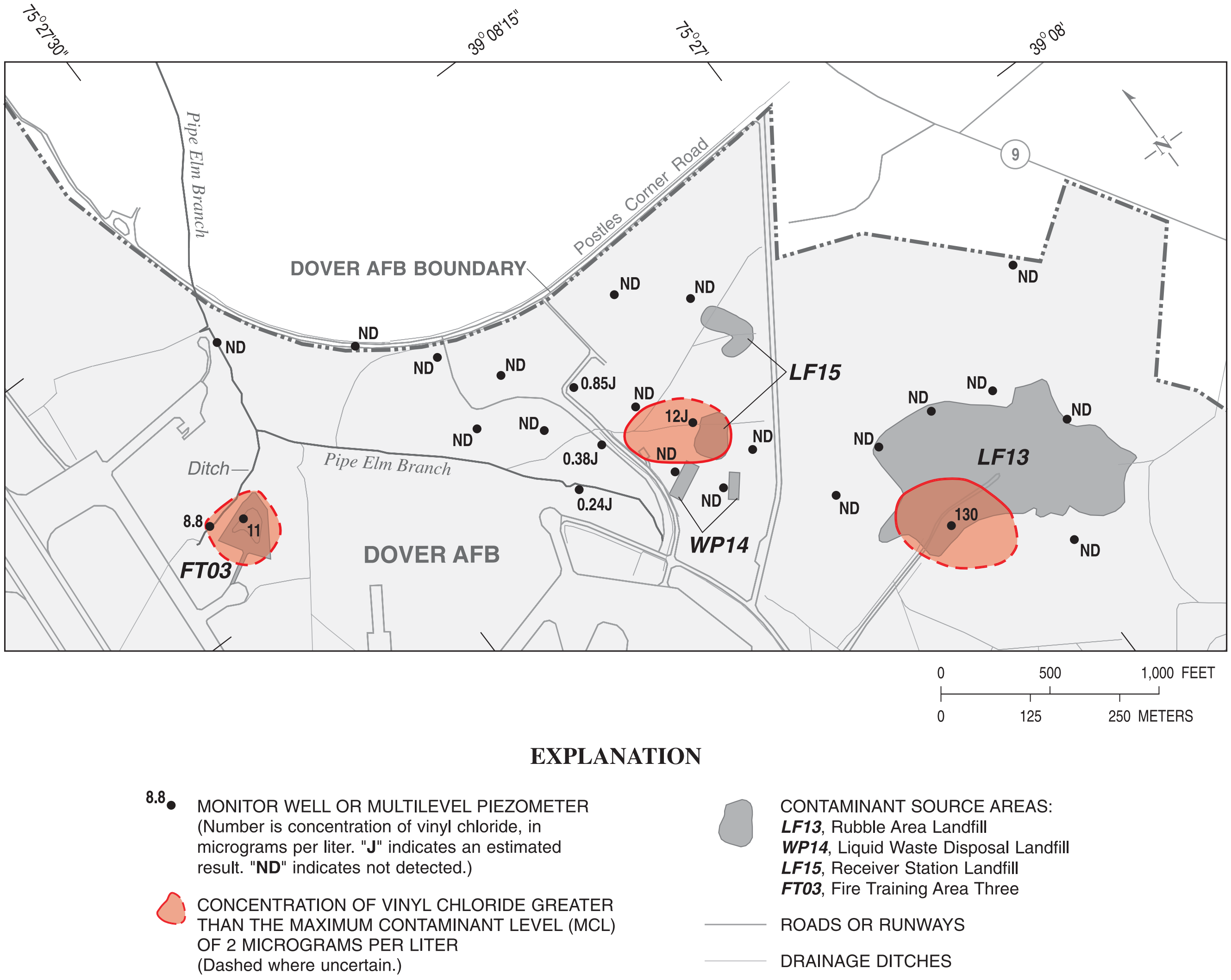


Figure 11d. Distribution of vinyl chloride in the upper part of the surficial aquifer, Dover Air Force Base, Delaware, January-March 2000.

northerly direction (the regional flow direction), wells MW062 and DM113, and possibly MW040, are located downgradient of the source area. Results from the January–March 2000 sampling indicate that the plume has not reached these locations. Another possibility is that the plume flows to the south, toward well cluster MW064. Considering the possible ground-water flow directions and the location of LF13 relative to the site boundary, it is unlikely that this plume migrates toward the DAFB boundary under either flow scenario described above.

Despite the incomplete knowledge of ground-water flow directions and contaminant distributions, analysis of the hydrologic and geochemical data collected at this site indicates that natural attenuation is adequate for controlling off-site migration of contaminated water. This conclusion is based on the following factors: (1) potential plume migration directions relative to the DAFB boundary, (2) the presence of methanogenic conditions, (3) the formation of chlorinated-solvent breakdown products, and (4) declining contaminant concentrations in well DM110S (fig. 12).

Site WP14/LF15—Results of ground-water samples show that intrinsic biodegradation of the chlorinated solvents is occurring at WP14/LF15. This conclusion is based on the presence of chlorinated-solvent breakdown products within and downgradient of the source areas, concentration reductions in the general direction of ground-water flow, and the presence of the reducing conditions required for reductive dechlorination. Concentrations still decrease sharply downgradient of the source areas, as documented in 1995–96 (Bachman and others, 1998, p. 37). For example, the concentration of PCE drops from 1,100 µg/L in piezometer GS047MLC to 40 µg/L in well DM108D. MCLs were not exceeded at any POC well along the DAFB boundary.

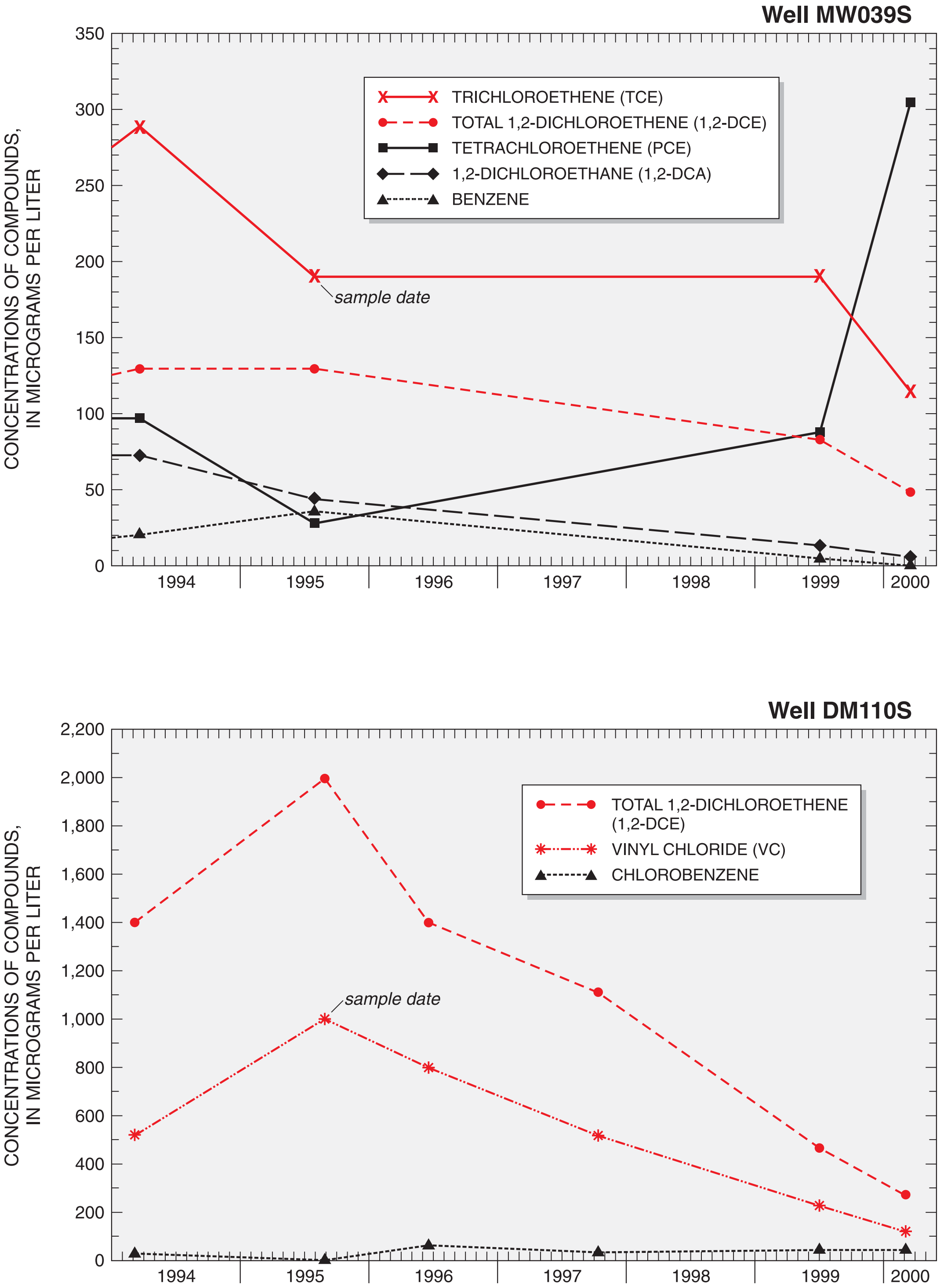


Figure 12. Concentrations of selected volatile organic compounds in ground-water samples collected from wells MW039S and DM110S, 1994-2000, Dover Air Force Base, Delaware. *(Refer to figure 2 for well locations.)*

Despite concentration decreases, three observations based on the January–March 2000 monitoring data raise concerns about the effectiveness of natural attenuation for controlling off-site migration at this site.

First, redox conditions downgradient of the source areas may not be appropriate for reductive dechlorination of the chlorinated solvents. Conditions generally are mixed between iron-reducing and methanogenic (fig. 10). As discussed previously, the appearance of mixed conditions probably results from sampling a relatively small number of long-screened wells. Reductive dechlorination of the highly chlorinated parent compounds (PCE and TCE) is known to occur in the anaerobic core of a plume, but not in the less-reducing zones near the plume fringes (Wiedemeier and others, 1999, p. 242). Moreover, reductive dechlorination depends on a continuous supply of electron donors in the contaminant plume. Because a viable electron donor has not yet been identified and the distribution of redox conditions has not been defined in sufficient detail, it currently is not possible to determine the sustainability of reductive dechlorination in this plume. If reductive dechlorination is not occurring downgradient of the source areas, the parent compounds may persist. Other anaerobic biodegradation processes such as oxidation under iron-reducing conditions are possible, but have not been clearly demonstrated under field conditions. Moreover, these oxidation reactions are favorable only for the breakdown products. C*is*-1,2-DCE and VC potentially biodegrade under both iron-reducing and aerobic conditions (Bradley and Chapelle, 1998; Bradley, 1997). Thus, the spatial distributions of redox conditions and specific reaction mechanisms probably have an effect on intrinsic biodegradation in this plume.

Second, detections of low levels of contaminants in the streambed piezometers and monitor wells near Pipe Elm Branch indicate that contaminated water is reaching and potentially discharging to this hydrologic boundary along the entire length of the plume. As reported in Bachman and others (1998, p. 14), and shown by the configuration of the potentiometric surface in the upper part of the surficial aquifer during March 2000, shallow contamination from WP14 migrates over a short flow path in the shallow flow system and discharges into adjacent Pipe Elm Branch. Contamination from LF15, on the other hand, migrates over a longer flow path, potentially discharging to Pipe Elm Branch further north near the DAFB boundary. The fate of the contaminated water in these discharge areas probably affects plume length and the potential for off-site movement.

Third, temporal variability in source concentrations may occur and affect contaminant concentrations in the plume. In some locations, for example, contaminant concentrations increase with distance downgradient of the source. These increases may result from collecting samples from wells with long screens, or from comparing concentrations near the center of the plume to concentrations on the fringe of the plume. For example, concentrations of PCE and TCE at the DM108 well cluster are higher than concentrations at the DM107 well cluster, even though well DM108 appears to be further downgradient, indicating that well DM107 is located closer to the fringe of the plume. Alternatively, this concentration distribution could occur when the source concentrations change over time. Under this scenario, higher concentrations intermittently leached from the source area would migrate downgradient as slugs of high-concentration water. These slugs may influence the effectiveness of natural attenuation in reducing contaminant concentrations.

Temporal Variability The record of reliable VOC data in the EMU extends back only to the early 1990s, when the majority of the wells were installed for previous investigations. Available VOC concentration data from selected source-area wells are shown on figure 12. Sampling done at a WP14/LF15 source-area well, MW039S, shows no clear concentration trends over the period 1994–2000. PCE concentrations were sharply higher in samples collected during the most recent sampling event (January–March 2000), however. In contrast, time-series sampling at well DM110S

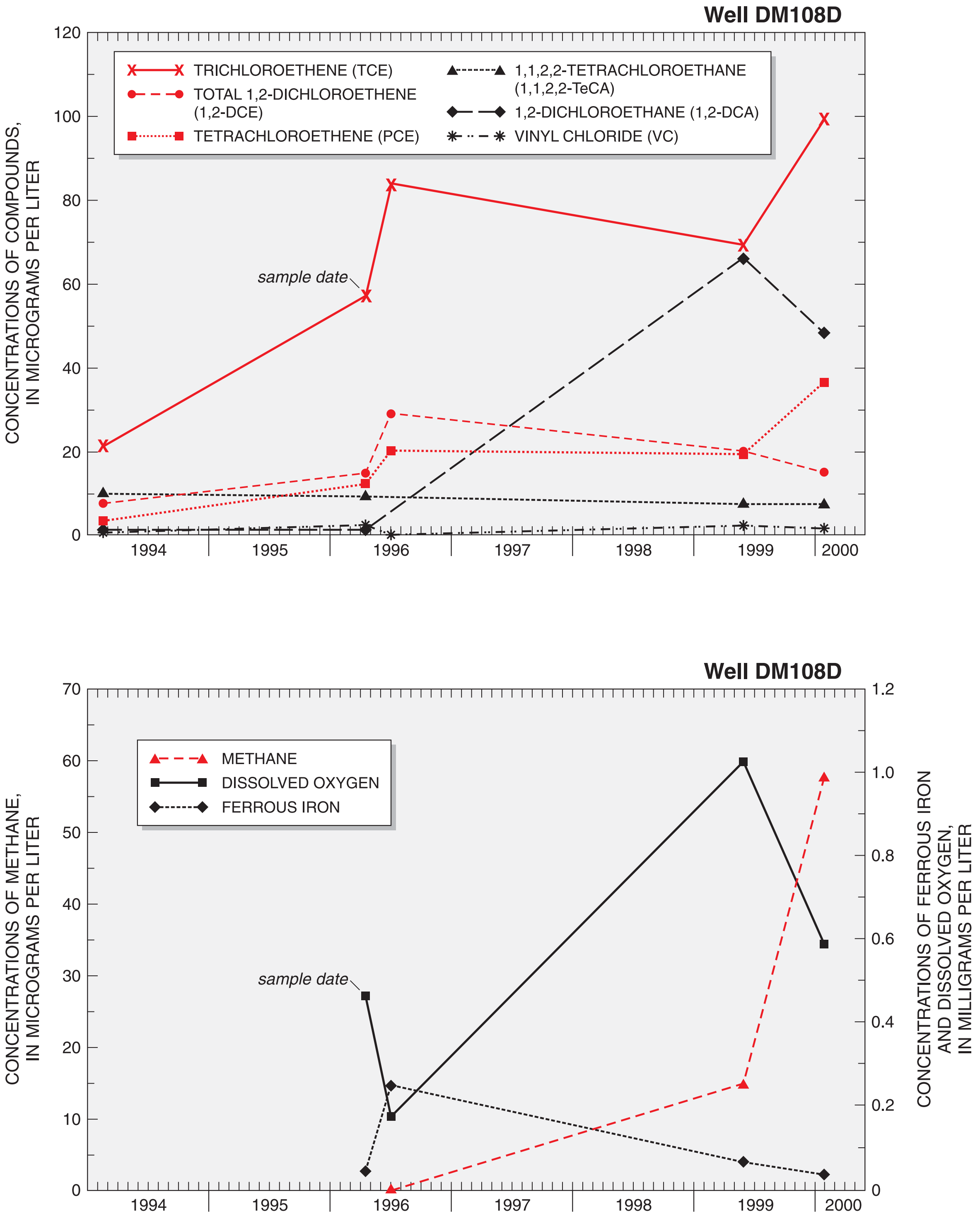
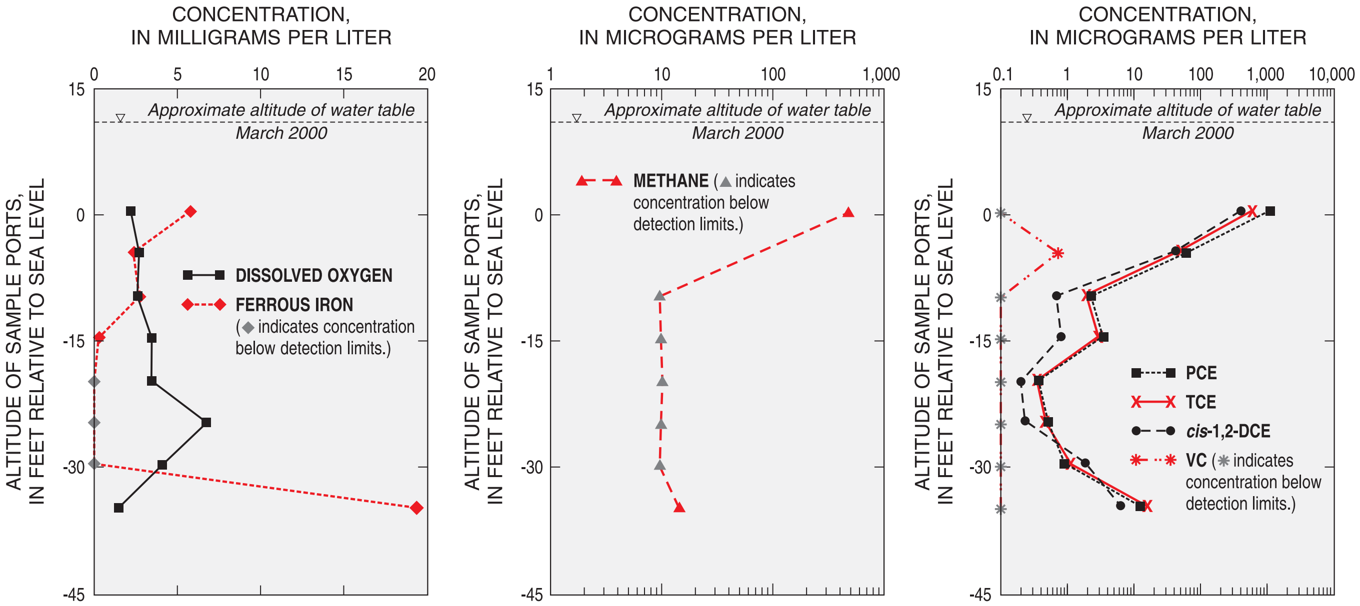
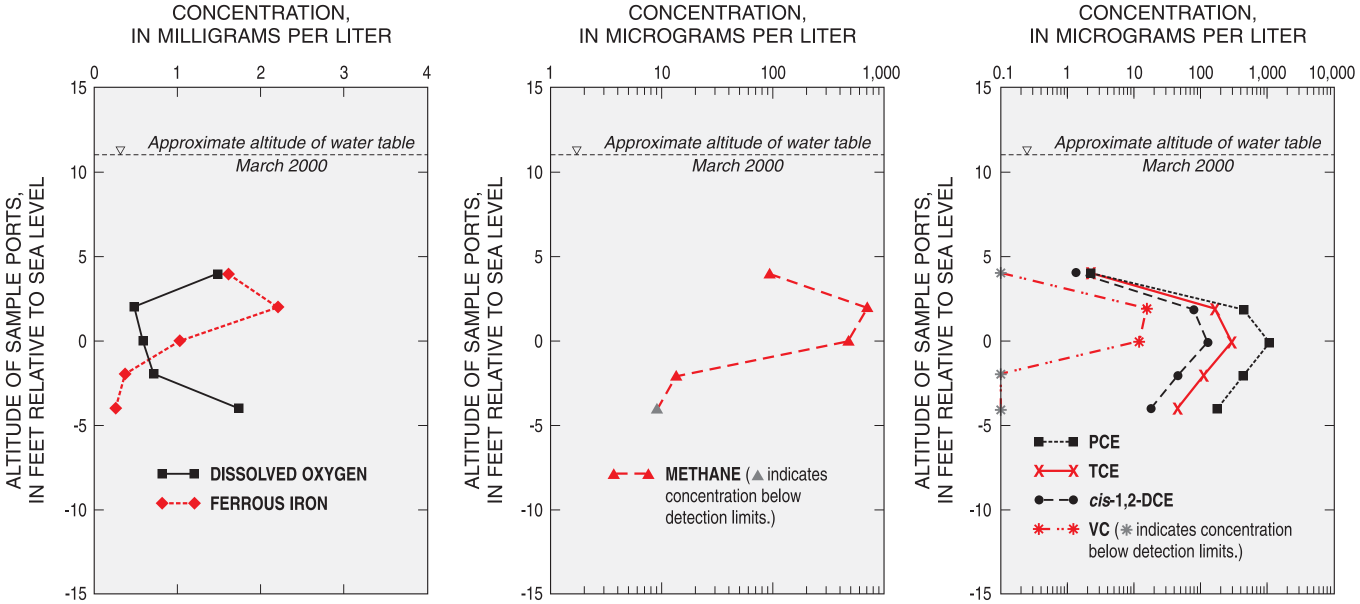


Figure 13. Concentrations of selected volatile organic compounds, electron acceptors, and metabolic by-products in ground-water samples collected from well DM108D, 1994-2000, Dover Air Force Base, Delaware. *(Refer to figure 2 for well location.)*

Multilevel Piezometer GS045ML



Multilevel Piezometer GS047ML

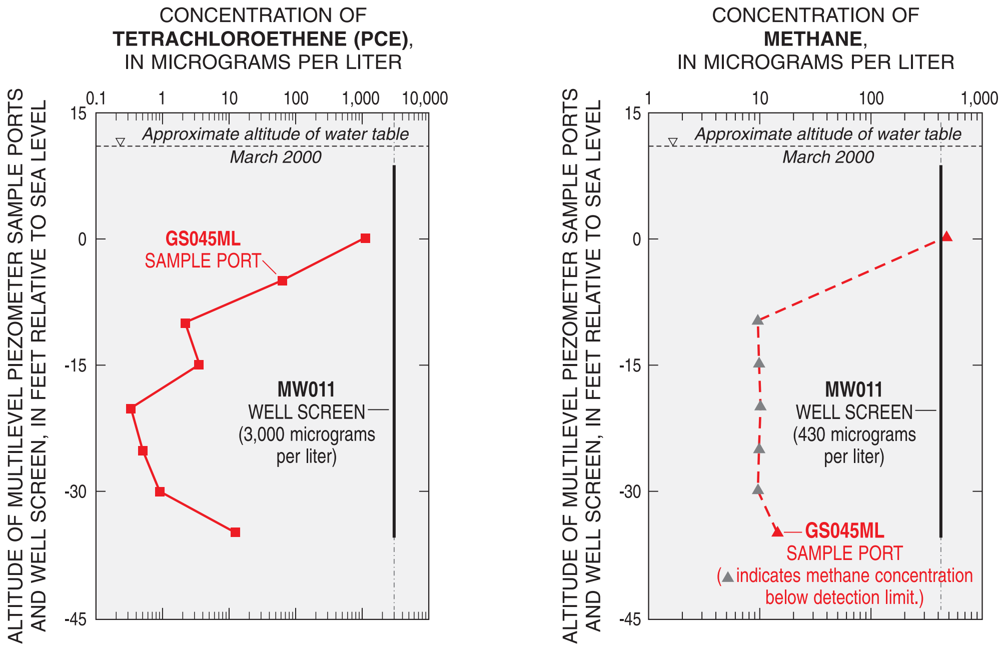


EXPLANATION

PCE	TETRACHLOROETHENE
TCE	TRICHLOROETHENE
VC	VINYL CHLORIDE
***cis*-1,2-DCE**	*CIS*-1,2-DICHLOROETHENE

Figure 14. Vertical distribution of selected volatile organic compounds, electron acceptors, and metabolic by-products in ground-water samples collected from multilevel piezometers GS045ML and GS047ML, Dover Air Force Base, Delaware. *(Refer to figure 2 for piezometer locations.)*

Multilevel Piezometer GS045ML and Well MW011



Multilevel Piezometer GS047ML and Well MW039S

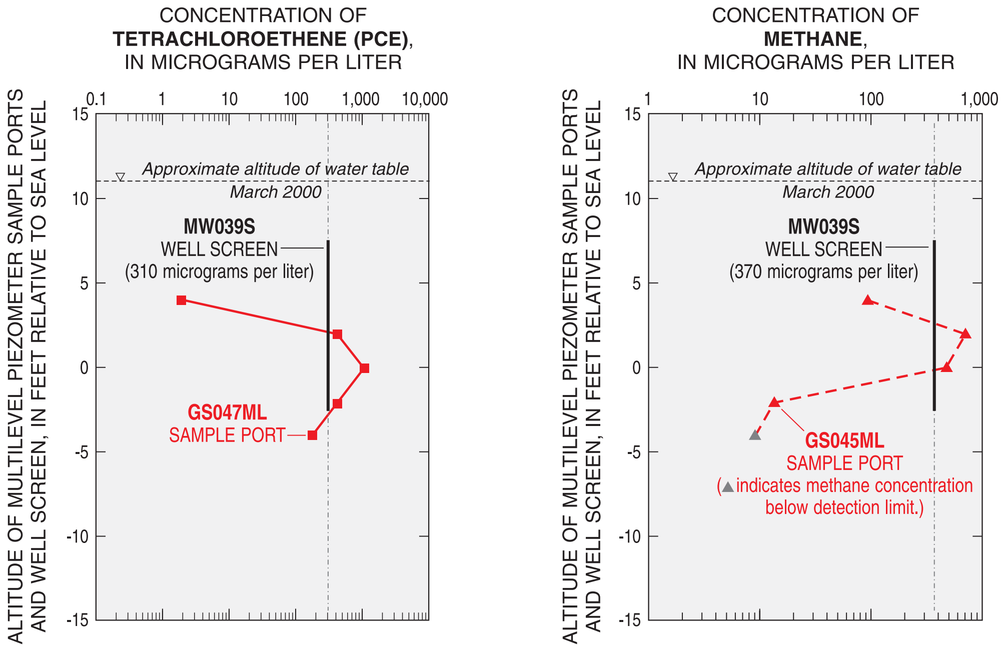


Figure 15. Concentrations of tetrachloroethene and methane in ground-water samples collected from multilevel piezometers GS045ML and GS047ML, and the adjacent long-screened wells MW011 and MW039S, Dover Air Force Base, Delaware. *(Refer to figure 2 for well and piezometer locations.)*

(3) What is the fate of contaminants migrating from FT03 and WP14/LF15 at the ground-water discharge boundaries? Do contaminants discharge to surface water or biodegrade extensively in the streambed sediments prior to discharge? Does deeper contamination migrate past these discharge areas? Hydrologic boundaries may be important at these sites by physically intercepting contaminant plumes and preventing off-site movement in ground water.

(4) Has temporal variability in source concentrations and ground-water flow patterns occurred in WP14/LF15? If so, what is the magnitude of the variability and the effect on the fate of contaminants migrating from WP14/LF15? Is seasonal variation in heads an important factor in controlling contaminant concentrations and migration pathways?

Summary and Conclusions

Fire training and waste disposal in the East Management Unit of Dover Air Force Base, Delaware have resulted in subsurface contamination with chlorinated solvents and fuel hydrocarbons. Four source areas, Fire Training Area Three, the Rubble Area Landfill, the Liquid Waste Disposal Landfill, and the Receiver Station Landfill, are present in the East Management Unit. Natural attenuation of ground-water contamination is the remediation method selected by the U.S. Environmental Protection Agency and the Delaware Department of Natural Resources and Environmental Control. As part of the selected remediation, the U.S. Geological Survey, in cooperation with the U.S. Air Force, is conducting a long-term monitoring program and an assessment of the effectiveness of natural attenuation in the surficial aquifer. This report presents the first assessment of the effectiveness of natural attenuation since long-term monitoring began in 1999. The conclusions in this report are based on ground-water samples collected from January through March 2000, previous analytical results from selected wells, available geologic and geophysical well logs, and newly acquired information such as sediment organic-carbon measurements, hydraulic-conductivity measurements from slug tests on wells in the natural attenuation study area, and water-level measurements from wells screened in the surficial aquifer. The results of this assessment are in general agreement with the results of a preliminary study by Bachman and others in 1998.

Contamination occurs in the surficial aquifer, which is a single hydrostratigraphic unit bounded on the top by the water table and on the bottom by a regional confining unit, the Calvert Formation. Ground water contains chlorinated solvents, such as chlorinated ethenes and ethanes, and fuel hydrocarbons. Ground water in the natural attenuation study area recharges at topographically high areas and discharges to Pipe Elm Branch and local drainage ditches. The general ground-water flow direction is to the northwest. Hydraulic-conductivity values in the natural attenuation study area range from 3 feet per day to 313 feet per day, with a geometric mean value of 43 feet per day. The ground-water velocity in the area is approximately 0.4 feet per day. The residence time for ground water in the natural attenuation study area ranges from weeks to decades, depending on the length of the flow path.

The organic-carbon content of the surficial aquifer sediment is low, with an arithmetic mean value of 0.00029 grams of carbon per gram dry sediment. To estimate the effect of adsorption on contaminant migration velocities, the organic-carbon results were used to calculate retardation factors for the compounds that are prevalent in ground water. The retardation factors range from 1.00 for vinyl chloride to 1.35 for tetrachloroethene, indicating that contaminant velocities are similar to ground-water velocities, and that adsorption to aquifer solids is not a strong natural-attenuation mechanism. Similarly, abiotic reactions and dispersion also are not expected to be important mechanisms. Consequently, the most important natural attenuation mechanism in the surficial aquifer is intrinsic biodegradation.

Fifty-three monitor wells and multilevel piezometers completed in the surficial aquifer were sampled to determine the distributions of volatile organic compounds, electron acceptors, and metabolic by-products in the natural attenuation study area. The water-quality data indicate that intrinsic biodegradation is occurring at all four sites in the East Management Unit. This conclusion is based on the spatial distributions of volatile organic compounds, electron acceptors, and metabolic by-products in ground water. The strongest evidence for intrinsic biodegradation is the detection of tetrachloroethene and trichloroethene breakdown products within and downgradient of the source areas. The distributions of electron acceptors and metabolic by-products indicate that contaminant biodegradation has changed the prevailing geochemistry of the surficial aquifer, creating the strongly reducing conditions necessary for chlorinated-solvent biodegradation. Geochemical changes include depleted dissolved oxygen and elevated ferrous iron and methane relative to concentrations in uncontaminated zones of the surficial aquifer. Redox conditions are mixed methanogenic/iron-reducing near the source areas. Iron-reducing conditions appear to dominate further downgradient.

Natural attenuation appears to be adequate for controlling the migration of the contaminant plumes at Fire Training Area Three and the Rubble Area Landfill. The potential for off-site migration is low at these sites because reductive dechlorination reduces contaminant concentrations and plume lengths, and the sources are relatively far from the Dover Air Force Base boundary. At Fire Training Area Three, geochemical and hydrologic results indicate that intrinsic biodegradation in combination with the proximity of hydrologic discharge boundaries limits contaminant migration. At this site, contaminated ground water migrates over relatively short flow paths (tens to hundreds of feet) to nearby discharge boundaries where further biodegradation may occur. At the Rubble Area Landfill, geochemical results indicate that reductive dechlorination of the chlorinated solvents is extensive, and that source-area concentrations have been declining steadily since 1995. These observations in combination with the potential ground-water flow directions relative to the Base boundary indicate that off-site migration is unlikely.

In the Liquid Waste Disposal Landfill and Receiver Station Landfill area, intrinsic biodegradation is occurring, but the plume is larger, and the uncertainty about the effectiveness of natural attenuation in reducing contaminant concentrations and controlling plume migration is greater. Maximum contaminant levels were not exceeded in any of the January–March 2000 samples collected from point-of-compliance wells, however. Three observations from the January–March 2000 ground-water data raise concerns about the effectiveness of natural attenuation at this site. First, redox conditions downgradient of the source area may not be appropriate for reductive dechlorination. Second, contaminated water potentially is discharging to Pipe Elm Branch. Third, temporal variability in source concentrations may occur and have an effect on the fate of contaminants migrating from the source area.

The new results presented in this report led to the development of improved conceptual models for Fire Training Area Three, the Rubble Area Landfill, the Liquid Waste Disposal Landfill, and the Receiver Station Landfill, and to the recognition of four issues that currently are unclear and may need further study. These issues include delineating the areal and vertical extent of the contaminant plumes in greater detail, determining the extent of intrinsic biodegradation downgradient of the Liquid Waste Disposal and Receiver Station Landfills, determining the fate of contaminants in the ground-water discharge areas, and determining the effect of temporal variability in source concentrations and ground-water flow patterns on the plume migrating from the Liquid Waste Disposal and Receiver Station Landfills. Some of these issues have been addressed with an additional study performed since the January–March 2000 sampling round. In this study, ground-water samples were collected with a Geoprobe direct-push drilling rig and a mini-piezometer to map the contaminant plumes in greater detail and measure contaminant concentrations in the ground-water discharge areas. This study, and the ongoing long-term monitoring program, also provided information on temporal variability in the source areas and plumes. Further study is planned to better understand the fate of the volatile organic compounds in the ground-water discharge areas, and the spatial distribution of redox conditions and reaction mechanisms in the contaminant plumes.

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Appendix A. *Hydraulic-head measurements from wells screened in the surficial aquifer, Dover Air Force Base, Delaware, March 15–16, 2000*

[ft, feet; ft s.l., feet above sea level; total depth measured from top of well casing to bottom of well]

Appendix A. *Hydraulic-head measurements from wells screened in the surficial aquifer, Dover Air Force Base, Delaware, March 15–16, 2000—Continued*

Well identification number	Top of casing (ft s.l.)	Total depth (ft)	Screen length (ft)	Depth to water (ft)	Hydraulic head (ft s.l.)
DM02S	26.24	21.80	10	14.01	12.23
DM03S	24.88	16.77	10	6.11	18.77
DM04S	26.87	16.66	10	4.67	22.20
DM05S	24.36	15.68	10	7.58	16.78
DM06S	24.12	16.06	10	5.38	18.74

Appendix A. *Hydraulic-head measurements from wells screened in the surficial aquifer, Dover Air Force Base, Delaware, March 15–16, 2000—Continued*

Well identification number	Top of casing (ft s.l.)	Total depth (ft)	Screen length (ft)	Depth to water (ft)	Hydraulic head (ft s.l.)
DM101D	25.84	55.95	10	13.93	11.91
DM101S	25.70	18.78	10	5.37	20.33
DM102D	21.44	61.56	10	8.51	12.93
DM102S	21.59	18.72	10	8.62	12.97
DM103D	26.80	77.97	10	14.56	12.24
DM103S	27.00	21.89	10	9.16	17.84
DM104D	24.68	82.11	10	12.71	11.97
DM104S	24.71	19.58	10	7.65	17.06
DM105D	21.65	82.16	10	9.78	11.87
DM105S	21.44	19.59	10	7.57	13.87
DM106D	26.07	84.92	10	14.03	12.04
DM106S	26.05	20.12	10	3.90	22.15
DM107D	15.96	41.11	10	6.37	9.59
DM107S	16.38	18.91	10	6.65	9.73
DM108D	13.80	35.13	10	5.06	8.74
DM108S	13.99	19.24	10	5.16	8.83
DM109D	23.87	46.41	10	11.58	12.29
DM109S	24.18	19.30	10	4.04	20.14
DM110D	29.43	77.43	10	17.51	11.92
DM110S	29.36	24.03	10	9.41	19.95
DM111D	20.32	43.85	10	10.23	10.09
DM111S	20.20	19.29	10	10.09	10.11
DM113D	23.34	66.02	10	11.89	11.45
DM113S	23.20	21.14	10	11.31	11.89
DM114D	26.51	81.17	10	14.50	12.01
DM115DA	24.58	85.88	10	12.71	11.87
DM115S	24.56	18.89	10	3.66	20.90
DM116D	19.70	48.67	10	12.43	7.27
DM116S	20.02	17.69	10	9.11	10.91
DM117D	16.95	45.56	10	9.88	7.07
DM117S	16.52	17.69	10	11.35	5.17
DM118D	16.42	44.76	10	9.70	6.72
DM118S	16.55	20.05	10	10.59	5.96
DM119D	17.27	41.34	10	10.65	6.62
DM119S	15.72	20.31	10	11.16	4.56
GS001D	13.59	28.68	3	2.53	11.06
GS001M	15.82	19.16	1	5.22	10.60
GS001S	14.26	8.54	.50	4.56	9.70
GS002D	10.79	26.39	3	1.00	9.79
GS002M	10.36	15.85	1	.55	9.81
GS003M	8.27	18.80	3	1.31	6.96
GS003S	7.56	11.84	3	1.05	6.51
GS004M	10.33	16.40	1	3.03	7.30
GS010D	16.48	48.37	5	8.85	7.63
GS010S	16.46	24.75	5	9.30	7.16
GS011D	21.77	45.11	5	11.02	10.75

Appendix A. *Hydraulic-head measurements from wells screened in the surficial aquifer, Dover Air Force Base, Delaware, March 15–16, 2000—Continued*

Well identification number	Top of casing (ft s.l.)	Total depth (ft)	Screen length (ft)	Depth to water (ft)	Hydraulic head (ft s.l.)
GS011S	22.59	19.86	5	2.68	19.91
GS012D	22.83	53.92	5	9.82	13.01
GS012S	23.08	17.45	10	3.82	19.26
GS013D	9.34	37.30	10	2.98	6.36
GS014D	22.97	64.48	10	10.20	12.77
GS303D	22.19	59.40	10	9.55	12.64
GSCP3D	16.26	45.75	3	8.16	8.10
GSCP3M	16.30	22.30	3	8.18	8.12
GSCP4M	18.33	23.15	3	9.75	8.58
GSCP5M	17.92	29.26	3	7.73	10.19
GSCP6D	18.44	40.14	3	7.67	10.77
MW010	22.38	59.02	46	10.90	11.48
MW011	21.76	57.02	44	10.49	11.27
MW012	21.81	57.08	44	10.37	11.44
MW018	19.73	50.21	38	10.87	8.86
MW019	16.27	46.01	35	8.59	7.68
MW020	12.34	42.11	33	4.92	7.42
MW021	18.03	62.03	50	6.69	11.34
MW022	20.19	62.03	50	8.78	11.41
MW023	21.39	59.09	47	9.86	11.53
MW036D	17.53	56.64	8	6.40	11.13
MW037D	16.28	49.89	5	5.16	11.12
MW037S	16.29	22.60	10	5.77	10.52
MW038D	19.64	59.60	5	8.30	11.34
MW038S	19.05	31.76	10	7.69	11.36
MW039D	19.55	59.25	5	8.27	11.28
MW039S	19.57	22.16	10	8.35	11.22
MW040D	20.51	48.78	5	9.01	11.50
MW040S	20.68	24.11	10	9.41	11.27
MW041D	23.45	65.00	5	11.88	11.57
MW041S	23.61	25.01	10	12.00	11.61
MW042P	19.41	59.99	33	8.02	11.39
MW043D	14.06	22.37	5	6.53	7.53
MW043S	14.15	44.64	10	6.59	7.56
MW044D	20.99	52.92	5	12.23	8.76
MW044S	20.61	24.76	10	11.80	8.81
MW061S	26.77	29.56	10	14.55	12.22
MW062D	22.14	70.08	5	10.43	11.71
MW062S	22.27	27.78	10	10.57	11.70
MW064D	23.92	66.40	5	11.75	12.17
MW064S	24.14	37.23	10	11.86	12.28
MW206D	16.85	46.90	10	5.82	11.03
MW207D	20.75	50.23	10	9.63	11.12
MW207M	20.82	37.46	10	9.71	11.11

Appendix A. *Hydraulic-head measurements from wells screened in the surficial aquifer, Dover Air Force Base, Delaware, March 15–16, 2000—Continued*

Well identification number	Top of casing (ft s.l.)	Total depth (ft)	Screen length (ft)	Depth to water (ft)	Hydraulic head (ft s.l.)
MW226D	24.31	79.30	10	12.73	11.58
MW226M	24.71	49.22	10	13.09	11.62
MW226S	24.81	22.28	10	13.94	10.87
MW227D	22.86	49.71	10	13.85	9.01
MW227M	21.45	35.43	10	12.46	8.99
MW227S	21.39	24.98	10	11.83	9.56
MWD4A	20.93	17.21	10	8.25	12.68
MWD4B	17.29	16.04	10	6.29	11.00
MWD4C	18.81	16.81	10	5.61	13.20
MWD4D	23.34	16.99	10	7.29	16.05
MWD4E	24.01	20.13	3	12.42	11.59
MWD4F	20.38	17.13	3	10.28	10.10
MWD4G	21.68	18.36	3	12.32	9.36
MWD4I	21.87	25.32	3	14.33	7.54