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Final Report: Hanover Environmental Site Investigation, 2009-2010
Volume 1: Main Text

Environmental Science Division

USDA
United States Department of Agriculture
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Final Report: Hanover Environmental Site Investigation, 2009-2010
Volume 1: Main Text

by
Applied Geosciences and Environmental Management Section
Environmental Science Division, Argonne National Laboratory

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United States Department of Agriculture

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Notation

AGEM	Applied Geosciences and Environmental Management
BE	barometric efficiency
BGL	below ground level
CAS	Corrective Action Study
CCC	Commodity Credit Corporation
CD	compact disc
CLP	Contract Laboratory Program
COC	chain of custody
cpm	count(s) per minute
DOE	U.S. Department of Agriculture
EPA	U.S. Environmental Protection Agency
FSA	Farm Service Agency
ft	foot (feet)
gal	gallon(s)
GC-ECD	gas chromatograph-electron capture detection
GC-MS	gas chromatograph-mass spectrometer
gpm	gallon(s) per minute
hr	hour(s)
IAEA	International Atomic Energy Agency
in.	inch(es)
IRIS	Integrated Risk Information System
KDHE	Kansas Department of Health and Environment
K_h	horizontal hydraulic conductivity
μg/kg	microgram(s) per kilogram
μg/L	microgram(s) per liter
$\mu g/m^3$	microgram(s) per cubic meter
MCL	maximum contaminant level
mi	mile(s)
min	minute(s)
ng	nanogram(s)
pCi/L	picocurie(s) per liter
PVC	polyvinyl chloride
QA/QC	quality assurance/quality control
ROI	radius of influence

RPD	relative percent difference
RWD	Rural Water District
SDG	sample delivery group
sec	second(s)
SF_i	inhalation slope factor
SIM	selected ion monitoring
SRE	site reconnaissance and evaluation
T	transmissivity
TOC	top of casing
TU	tritium unit(s)
USDA	U.S. Department of Agriculture
VI	vapor intrusion
VOC	volatile organic compound
yr	year(s)

Final Report: Hanover Environmental Site Investigation, 2009-2010

Executive Summary

The Commodity Credit Corporation (CCC), an agency of the U.S. Department of Agriculture (USDA), operated a grain storage facility at the northeastern edge of the city of Hanover, Kansas, from 1950 until the early 1970s. During this time, commercial grain fumigants containing carbon tetrachloride were in common use by the grain storage industry to preserve grain in their facilities. In February 1998, trace to low levels of carbon tetrachloride were detected in two private lawn and garden wells near the former grain storage facility at Hanover, as part of a statewide USDA private well sampling program that was implemented by the Kansas Department of Health and Environment (KDHE) near former CCC/USDA facilities. In July 2007, the CCC/USDA sampled indoor air at nine residences on or adjacent to its former facility to address the residents' concerns. Low levels of carbon tetrachloride were detected at four of the nine homes.

Consequently, the CCC/USDA has conducted investigations, under the direction of the KDHE, to determine the source and extent of the carbon tetrachloride contamination that might be associated with the former facility.

The Investigation

The CCC/USDA investigation at Hanover began in July 2007 with the preliminary indoor air study outlined above. Extensive studies continued at Hanover from January 2009 until June 2010. The primary technical objectives of the 2009-2010 program were as follows:

- Identify contaminant sources and the extent of soil contamination beneath the former CCC/USDA facility.
- Characterize the groundwater-bearing system.
- Delineate the vertical and lateral extent of the groundwater contamination.
- Determine groundwater flow patterns.

- Evaluate the hydraulic properties of the groundwater-bearing system.

- Determine the potential for vapor intrusion attributable to subsurface contamination.

The 2009-2010 investigations at Hanover were designed to generate specific information required to address these technical objectives. The 2009-2010 investigations were conducted in five phases. as follows:

- *Phase 1.* Identify potential contaminant sources, and determine the vertical and lateral distributions of potential soil contamination beneath the former CCC/USDA facility.

- *Phase 2.* Determine the potential vertical and lateral extents of groundwater contamination beneath the former CCC/USDA facility, and obtain data to accurately characterize the site lithology, hydrostratigraphy, and groundwater flow.

- *Phase 3.* Delineate the off-site vertical and lateral extents of contamination in groundwater emanating from any potential source areas identified on the former CCC/USDA facility, and develop a monitoring system to evaluate groundwater flow patterns.

- *Phase 4.* Install additional monitoring wells to augment data collected during Phases 1-3 and to establish a long-term monitoring network. Conduct hydrogeologic testing to evaluate aquifer properties.

- *Phase 5.* Conduct a vapor intrusion investigation.

The investigations in Phases 1-4 focused on the characterization of soil and groundwater and were guided by a work plan approved by the KDHE. The Phase 5 activities to identify potential vapor intrusion issues were implemented in accord with a separate KDHE-approved work plan.

The key technical findings of the comprehensive geologic, hydrologic, and geochemical site characterization studies; the aquifer hydraulic testing; and the vapor intrusion investigation programs conducted at the former CCC/USDA grain storage facility in Hanover are reported in detail in this document. These findings are summarized below.

Physical, Geologic, and Hydrostratigraphic Setting

- The geologic sequence in the Hanover area generally consists of unconsolidated Pleistocene eolian deposits (on upland areas) and alluvial sediments (in floodplains areas) overlying Permian bedrock. In the study area, a vertical sequence of nine primary lithostratigraphic units was recognized. In order of increasing depth, these units consist of (1) Pleistocene unconsolidated silt and clay with a lower section of sand and sandy silt, (2) Permian weathered shale, (3) interbedded limestone and shale, (4) gray shale, (5) an upper red shale, (6) an interval that varies laterally in facies from evaporitic deposits to soft gray shale with limestone, (7) gray dolostone and shale, (8) a lower red shale, and (9) a lower evaporitic deposit (Figure ES.1).

- A prominent erosional unconformity marks the top of the Permian bedrock section. Together with more recent topographic downcutting, this erosional unconformity has influenced the lateral extent of the shallow units in the lithostratigraphic sequence at this site. The complete sequence of units outlined above is present beneath a local upland area that extends southwestward from the former CCC/USDA property. On the eastern and western flanks of the upland area, erosion has progressively cut into, or locally removed, the shallower lithostratigraphic units. On the western flank of the uplift, Units 1-4 are completely absent, and erosion has partially removed Unit 5 (Figures ES.2 and ES.3).

- Four groundwater-bearing intervals were identified in the bedrock sequence and designated as groundwater Zones 1-4 (Figures ES.1, ES.2, and ES.3). Groundwater Zone 1 — the uppermost water-bearing unit — consists of two to three discrete, thin, saturated horizons (total combined thickness of 1-3 ft) developed along bedding planes and fractures within the interbedded

limestones and shales of Unit 3. The areal extent of groundwater Zone 1 is bounded by the erosional limits of Unit 3. Semi-radial groundwater movement was identified in Zone 1, with flows to the northwest, west, southwest, and south originating from a localized groundwater high (groundwater divide) beneath the upland area at the former CCC/USDA facility. Preferential groundwater flow to the southwest is evident, along a relatively permeable zone underlying the upland. The estimated rate of groundwater flow in this direction is very low but greater by roughly one to two orders of magnitude than the rates of flow to the northwest, west, or south.

- Groundwater Zone 2 (Figure ES.1) consists of relatively thick saturated intervals (up to 5 ft in total) in the shale with limestone facies of Unit 6, or thin moist-wet intervals along bedding planes near the base of the upper red shale (Unit 5) where Unit 5 overlies the evaporitic facies of Unit 6. Zone 2 is laterally more extensive than Zone 1, since it is located deeper in the stratigraphic sequence and hence has been less severely truncated by erosion. Semi-radial groundwater flow was also identified in groundwater-bearing Zone 2, originating from a localized high beneath the former CCC/USDA facility. Groundwater movement to the west, southwest, south, and southeast is indicated; however, the observed contamination is associated with only the westerly flow direction.

- Groundwater Zone 3 (Figure ES.1) is hosted by the gray dolomitic shale near the base of Unit 7. The thin moist-wet intervals in this unit, which are difficult to identify, have a combined thickness of less than 2 ft. Groundwater Zone 4 is developed at the base of the lower red shale (Unit 8). The multiple thin, moist-wet intervals that form Zone 4 also have a total thickness of less than 2 ft. Continuous monitoring indicates that the groundwater levels in monitoring wells installed in Zone 3 and Zone 4 have yet to recover to the levels in the surrounding lithologies; therefore, the patterns of groundwater flow in these units cannot be determined from available data. The existing observations for these wells indicate, however, that the capacity of Zone 3 and Zone 4 to transmit groundwater to wells is very limited.

- Groundwater leakage from Zone 1 to Zone 2 is indicated in the area beneath the upland where groundwater mounding is observed in both Zone 1 and Zone 2. This downward vertical leakage, however, is minimal, as indicated by the much lower concentrations of carbon tetrachloride and nitrate observed in Zone 2 than in Zone 1. The apparent mixing ratio of Zone 1 groundwater flowing into Zone 2 is estimated at 10% or less, on the basis of concentration data for both carbon tetrachloride and nitrate in the upland area.

- Although equilibrium groundwater levels have not been achieved in Zone 3 or Zone 4, recent groundwater level measurements in Zones 1-4 indicate an upward hydraulic gradient from Zone 4 to Zone 3 (and also from Zone 4 to Zone 2). These observations suggest that a natural hydraulic barrier exists to downward migration of Zone 2 groundwater into the deeper parts of the flow system beneath the upland area.

Extent of the Contamination

- The residual concentrations of carbon tetrachloride and chloroform identified in soil were well below the KDHE Tier 2 standards for these contaminants (200 μg/kg and 960 μg/kg, respectively). Sampling of the soils beneath the former CCC/USDA facility was conducted at 38 locations. Carbon tetrachloride was detected at 8 locations only, at a maximum concentration of 35 μg/kg. Low levels of chloroform (≤ 44 μg/kg) were detected at 2 locations only.

- Carbon tetrachloride contamination was identified in the groundwater in Zone 1 at concentrations up to 617 μg/L (Figure ES.4). The highest concentrations of carbon tetrachloride (> 500 μg/L) were detected beneath the north central portion of the former CCC/USDA facility. Concentrations exceeding 100 μg/L generally underlie the topographic upland that extends to the south and southwest of the former facility, along the preferred groundwater flow pathway identified in this direction.

- Lateral variations in the carbon tetrachloride concentrations observed in Zone 1 (as a result of contaminant migration) show a close correlation to variations in the hydraulic conductivity (K_h) of the Zone 1 unit. Specifically, carbon tetrachloride concentrations > 100 μg/L are generally associated with the regions of highest K_h values in the unit (beneath the upland area), while progressively lower concentrations and K_h values are observed toward the margins of the upland.

- The elevated ratios of chloroform to carbon tetrachloride that are observed are evidence of degradation of carbon tetrachloride (by reductive dechlorination under anaerobic conditions) along the leading, downgradient margins of the contaminant distribution in groundwater Zone 1, as well as in groundwater Zone 2. Chloroform was found in groundwater Zone 1 at a maximum concentration of 18 μg/L. In the northern part of the former CCC/USDA facility, the relative abundance of chloroform to carbon tetrachloride was generally less than 2%. However, near the margins of the carbon tetrachloride distribution, the ratios of chloroform to carbon tetrachloride in Zone 1 increase locally to values of 13% to 64% or more. A similar increase (to values of 9% to 22%) is also evident in Zone 2.

- Carbon tetrachloride was identified in Zone 2 along a narrow pathway extending to the west and downgradient from the former CCC/USDA facility (Figure ES.5). The observed carbon tetrachloride concentrations ranged from 35 μg/L at the northern edge of the former facility to 11-28 μg/L near the downgradient toe of the distribution. Lower levels of carbon tetrachloride (1.5-7.8 μg/L) were also found in four private wells near the apparent western edge of this distribution. The private wells penetrate the deeper groundwater zones, with gravel packs extending to Zone 2 providing a conduit for contaminant migration to the deeper zones at these locations.

- No carbon tetrachloride was detected in groundwater Zone 3 or Zone 4 at monitoring wells completed exclusively in one of these zones. This observation is consistent with the interpretation that Zone 3 and Zone 4 receive little or no natural recharge via vertical infiltration from contaminated Zone 2.

Potential for Groundwater Production from Zone 1 and Zone 2

- The results of hydraulic characterization studies (slug tests, step-drawdown pumping tests, and constant-rate pump testing) conducted for groundwater-bearing Zone 1 indicate that the very limited groundwater production capacity of Zone 1 (mostly < 0.3 gpm in the short term) is restricted by the total effective thickness (1-3 ft) of the two-three discrete, thin horizons that form the interval; the heterogeneous hydraulic conductivity of the interval (ranging from 0.001 ft/day to 75 ft/day); and the generally limited availability of groundwater in Zone 1. The results further indicate that groundwater pumping (or injection) through the use of conventional wells does not represent a viable mechanism for hydraulic control or removal of the contaminated groundwater in Zone 1.

- The results of similar hydraulic testing conducted for groundwater-bearing Zone 2 indicate that this unit has a greater capacity than Zone 1 for groundwater production, because of the relatively greater total thickness (up to 5 ft) and generally less discrete nature of the Zone 2 water-bearing intervals, as well as the generally higher estimated K_h values of Zone 2 (ranging from 7.9 ft/day to 43 ft/day). Pumping tests conducted near the western (downgradient) margin of the Zone 2 contaminant distribution demonstrated that groundwater extraction appears feasible as a potential response technology in this portion of the Zone 2 water-bearing unit.

Vapor Intrusion

Carbon Tetrachloride and Chloroform

- In consultation with the KDHE, approximately 60 occupied residences were identified for possible vapor intrusion that might be linked to the carbon tetrachloride contamination identified in groundwater-bearing Zone 1 or in the western, more downgradient portion of Zone 2. Comprehensive indoor air testing was conducted in spring 2009 at all identified, accessible structures,

and confirmation air monitoring was performed in the summer and/or winter 2009-2010 at 17 homes identified as *potentially affected* by carbon tetrachloride contamination in groundwater Zone 1.

- Five homes, all overlying the documented contamination in groundwater-bearing Zone 1, were identified as *impacted* by carbon tetrachloride vapor intrusion at levels greater than the KDHE Tier 2 standard of 4.055 $\mu g/m^3$ for this contaminant in indoor air.

- With the approval of the KDHE, the CCC/USDA installed mitigation systems at each of the five homes determined to be impacted by vapor intrusion above the KDHE Tier 2 standard. Performance testing of the installed systems has demonstrated that they are effectively reducing indoor air contaminant concentrations to acceptable levels.

- At the request of the Hanover community, indoor air sampling was also conducted at the Hanover public school facility and St. John's School, which both lie outside the interpreted limits of the carbon tetrachloride distributions in groundwater Zone 1 and Zone 2. No carbon tetrachloride was detected at either facility.

Radon

- Radon analysis identified unacceptable levels of radon that exceed the EPA standard in 22 of 25 homes tested for this contaminant (Figure ES.6), as well as at selected locations in the Hanover public school facility and St. John's School.

- Radon is a naturally occurring substance that is unrelated to grain fumigation activities.

- Additional information about radon, including options for radon testing and mitigation, is available from the following sources:

- Toll free: 1-866-865-3233 — KDHE Bureau of Environmental Health

- Toll free: 1-800-693-5343 — Kansas Radon Hotline

- URL: http://www.epa.gov/radon/pubs/citguide.html — EPA publication, *A Citizen's Guide to Radon: The Guide to Protecting Yourself and Your Family from Radon*

- URL: http://www.epa.gov/radon/pdfs/hmbuygud.pdf — EPA publication, *Home Buyer's and Seller's Guide to Radon*

- URL: http://www.epa.gov/radon/rnxlines.html — EPA web page of radon hotlines and information

Assessment of Health Risk

The fundamental goal of the CCC/USDA site investigation efforts was the identification of potential contamination in the soils, groundwater, and surface waters, or in vapors intruding into indoor air, that might represent unacceptable health or environmental risks to the community of Hanover. The results of the investigations outlined above demonstrate the following:

- *Near-surface soils* at the former CCC/USDA facility pose no unacceptable health or environmental risks.

- Localized low, residual levels of carbon tetrachloride detected in the *subsurface soils* at the former CCC/USDA facility do not represent a potential continuing source of contamination to groundwater.

- No unacceptable health risks are associated with potential human exposure to the contaminated *groundwater* in Zone 1 or Zone 2, under current conditions at the site. No active private (or public) wells are known to be present within the area of Zone 1 contamination or are completed in this unit. Four existing private wells identified near the downgradient margin of the carbon

tetrachloride migration pathway in Zone 2 are used for lawn and garden purposes only.

- Field reconnaissance along the erosional limits of the Zone 1 and Zone 2 units (in the identified directions of contaminant migration) revealed no springs or seepage to suggest direct drainage from these intervals to the *surface waters* at Hanover.

- Only five homes, overlying the documented contamination in groundwater-bearing Zone 1, were identified as impacted by carbon tetrachloride *vapor intrusion* at levels greater than the KDHE Tier 2 standard for this contaminant in indoor air. Vapor mitigation systems were installed by the CCC/USDA and are operational in these five homes and will be inspected annually. Consequently, all risk associated with exposure to carbon tetrachloride vapor intrusion in the potentially affected areas of the community have been mitigated at this time.

- No carbon tetrachloride *vapor intrusion* was detected at either the Hanover public school facility or St. John's School, which both lie outside the interpreted limits of the carbon tetrachloride distributions in groundwater Zone 1 and Zone 2. No mitigation was required, and there is no associated health risk to the students and staff in the schools from carbon tetrachloride or chloroform vapors.

- *Vapor intrusion* of naturally occurring radon to indoor air at unacceptable health risk levels is a widespread phenomenon in Hanover and in Washington County generally. Radon is present at values exceeding the EPA action level (4.0 pCi/L) in the majority of the homes tested in Hanover (Figures ES.6 and ES.7). The occurrence of radon in the subsurface or indoor air is unrelated to the former CCC/USDA grain storage activities at Hanover.

Summary

- The results of the comprehensive investigation at Hanover indicate that no unacceptable risk to human health currently exists from exposure to surface and subsurface *soils* by either ingestion, inhalation or dermal contact.

- No risk is associated with potential exposure to contaminated *groundwater* at Hanover. No drinking water wells are known to exist in Hanover, and the drinking water supply comes from RWD #1 at Lanham, Kansas, located 6.5 mi north of Hanover.

- Limited potential risk was identified due to exposure to *indoor air* contaminated with carbon tetrachloride, but this risk has been mitigated, thereby removing this threat to human health.

- Radon is prevalent in the community, at concentrations exceeding the level at which the EPA recommends additional measures (testing and/or mitigation). The recommended testing and mitigation (if needed) are the responsibility of the homeowners.

- *In the current condition in which no private wells are used for drinking water in the affected area, no unacceptable human health risk from carbon tetrachloride is associated with the identified impacted media at the Hanover site.*

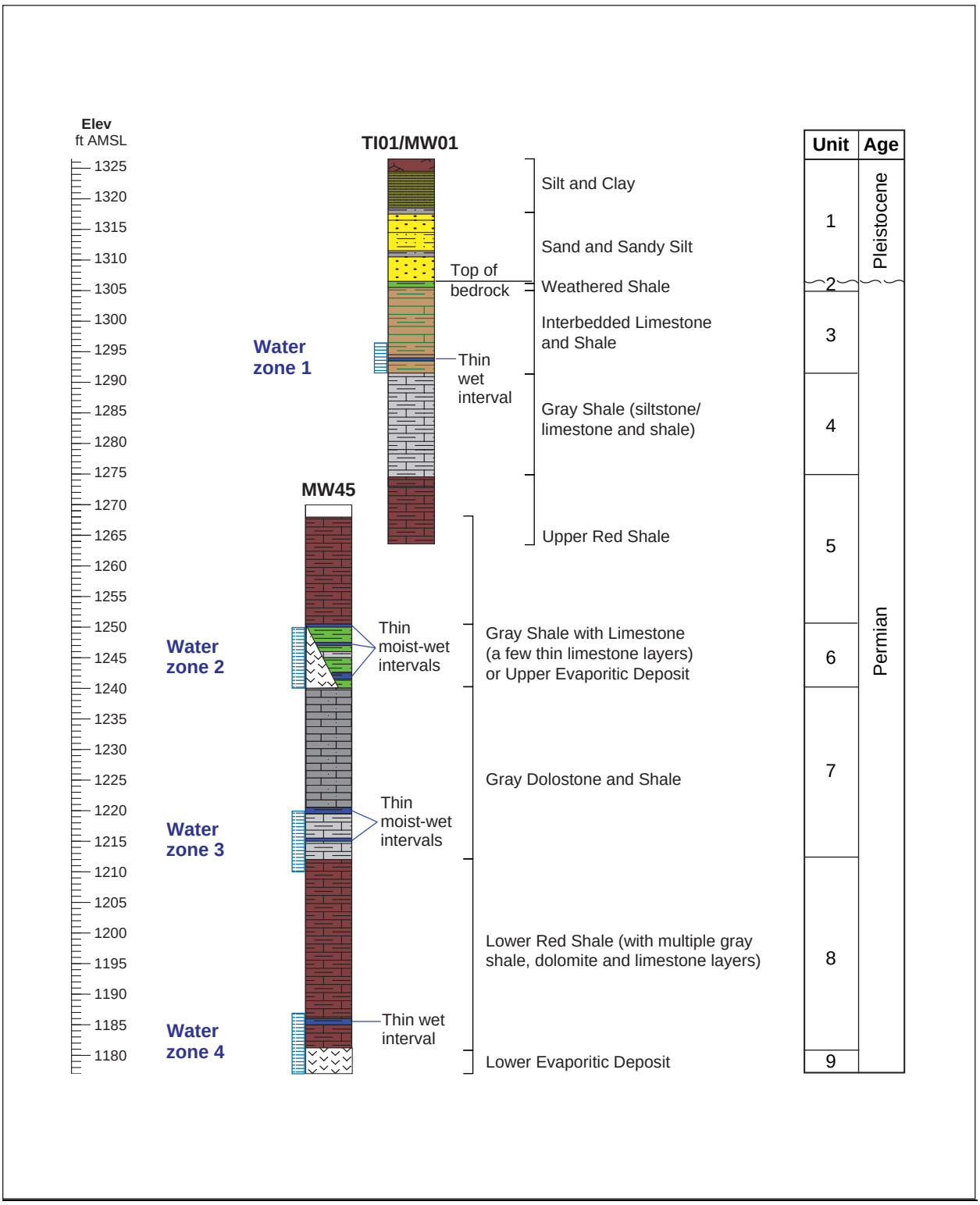

FIGURE ES.1 General stratigraphic section in the investigation area at Hanover

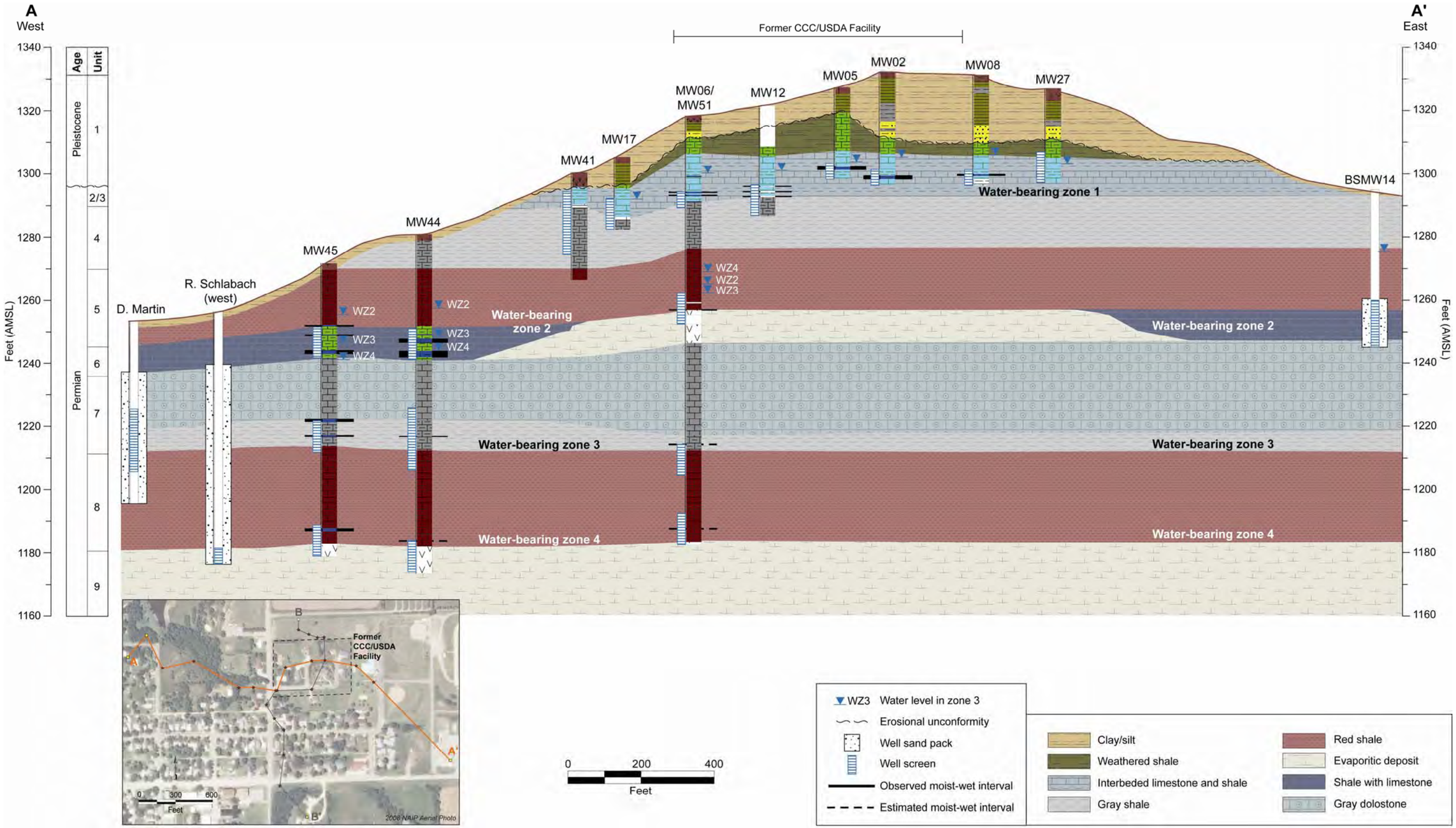

FIGURE ES.2 Interpretive west-to-east hydrogeologic cross section A-A'.

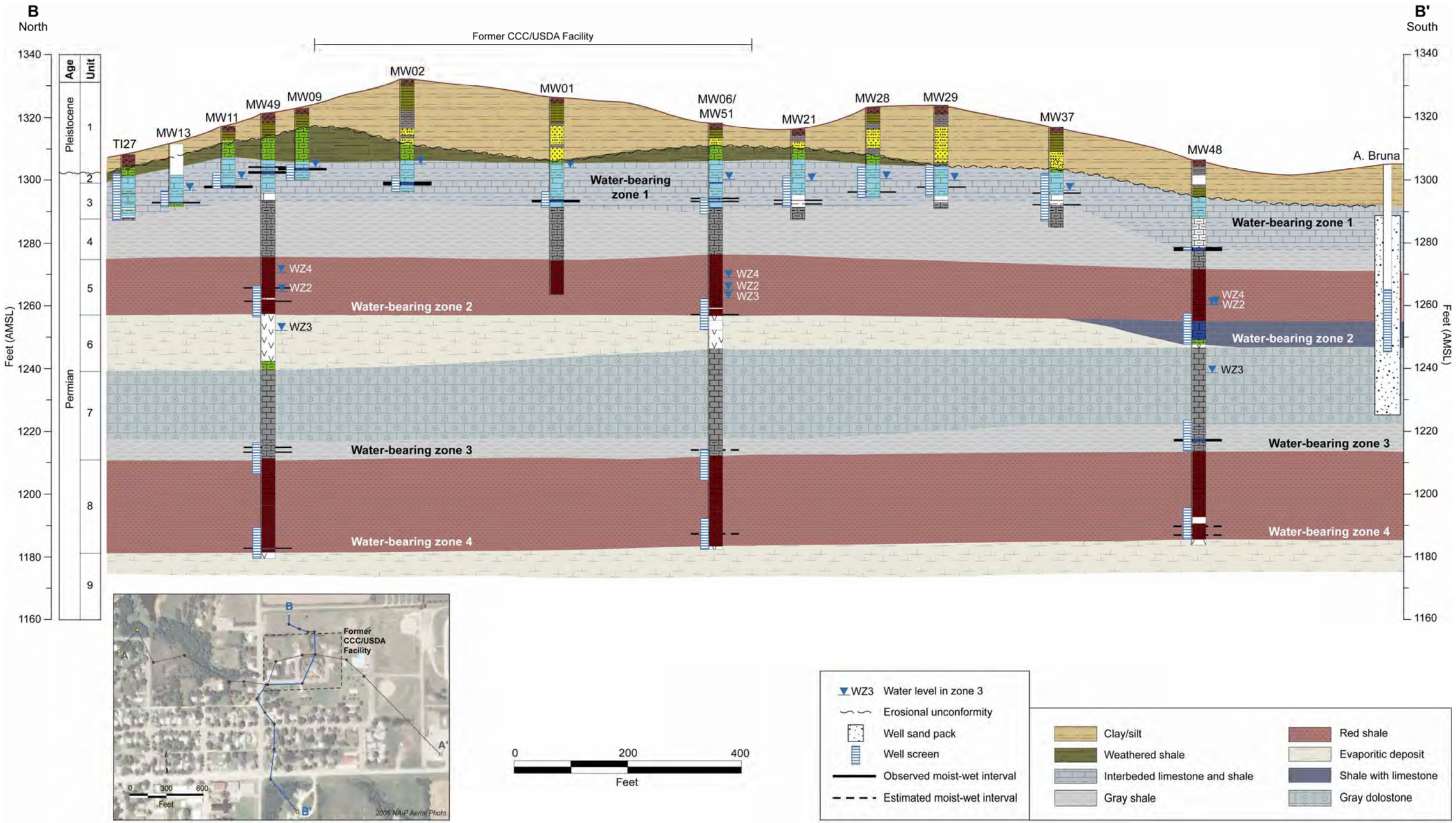

FIGURE ES.3 Interpretive north-to-south hydrogeologic cross section B-B'.

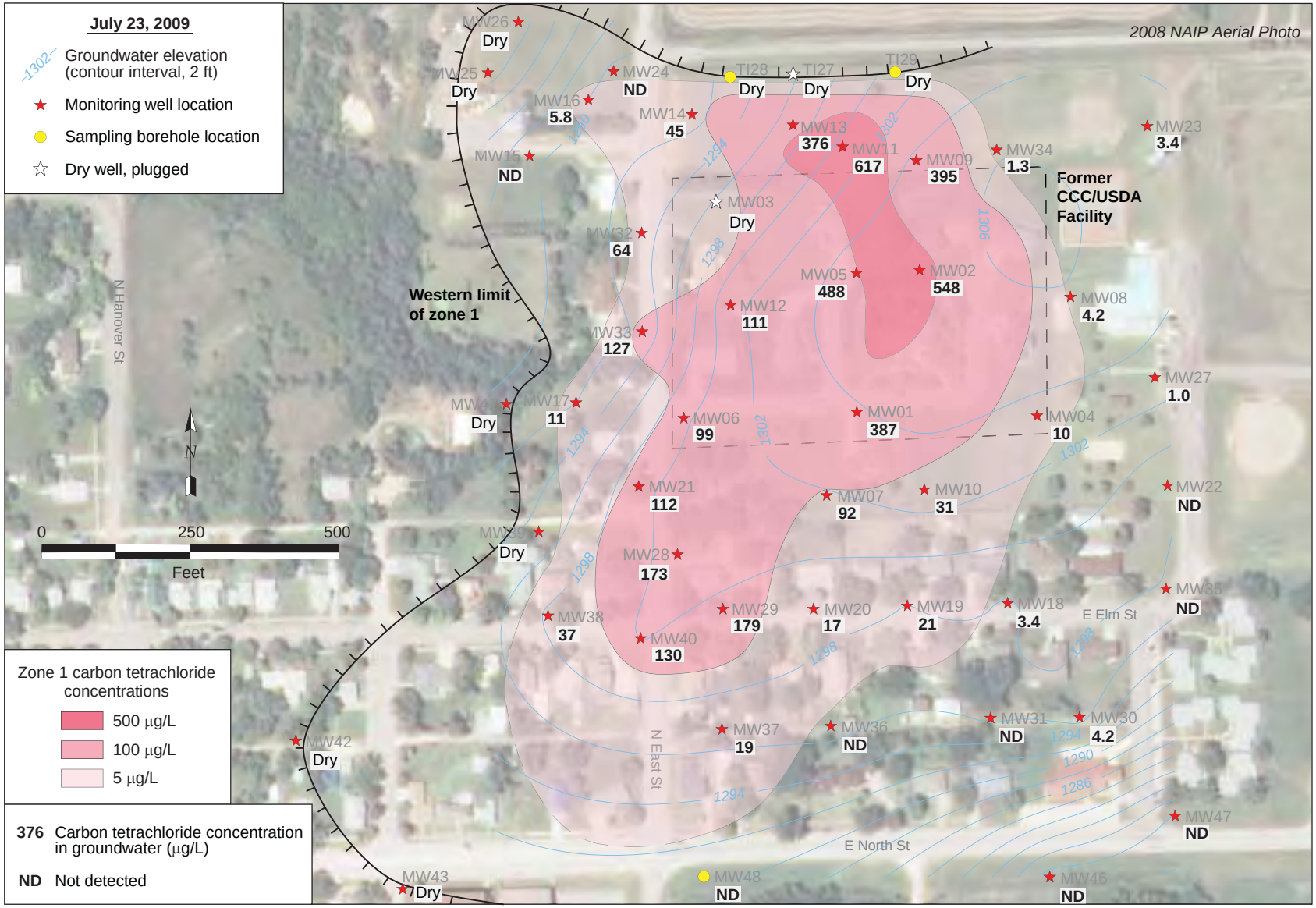

FIGURE ES.4 Carbon tetrachloride concentrations in groundwater Zone 1, with the interpreted lateral extent of the carbon tetrachloride contamination, the potentiometric surface, and the estimated western limits of groundwater Zone 1.

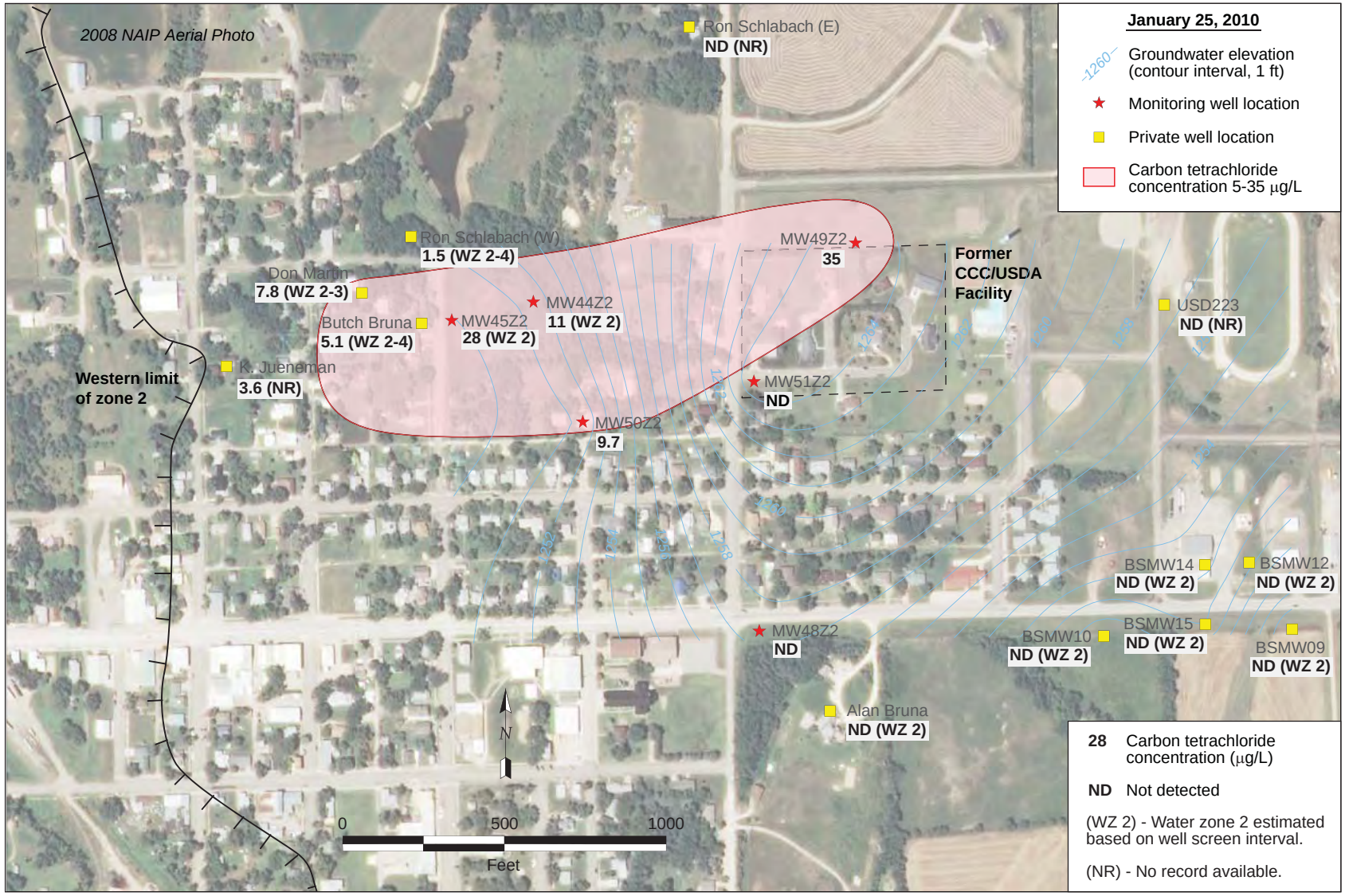

FIGURE ES.5 Carbon tetrachloride concentrations in groundwater Zone 2, with the interpreted lateral extent of the carbon tetrachloride contamination, the potentiometric surface, and the estimated western limits of groundwater Zone 2.

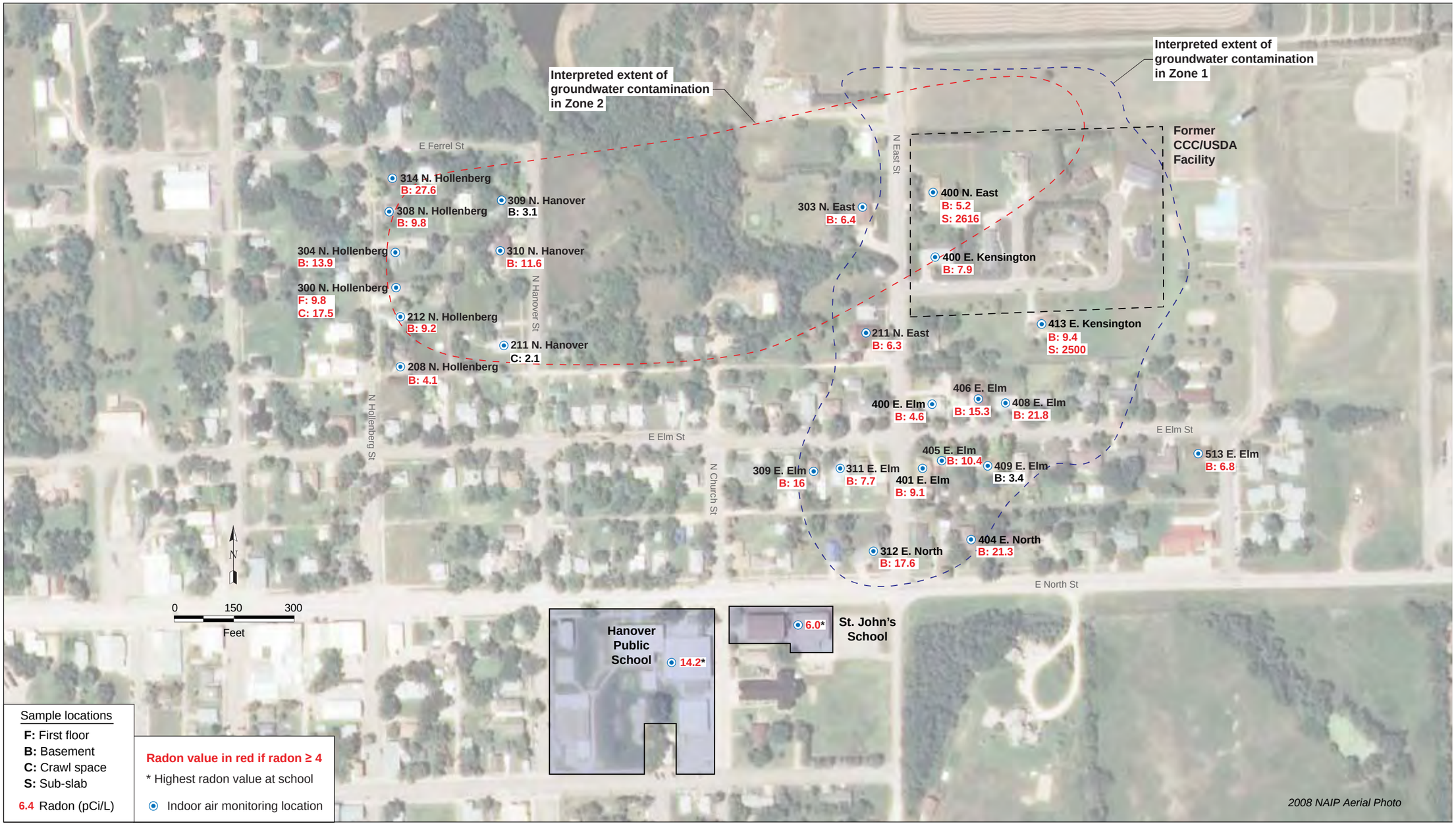

FIGURE ES.6 Radon concentrations detected in indoor air of the schools and the tested homes.

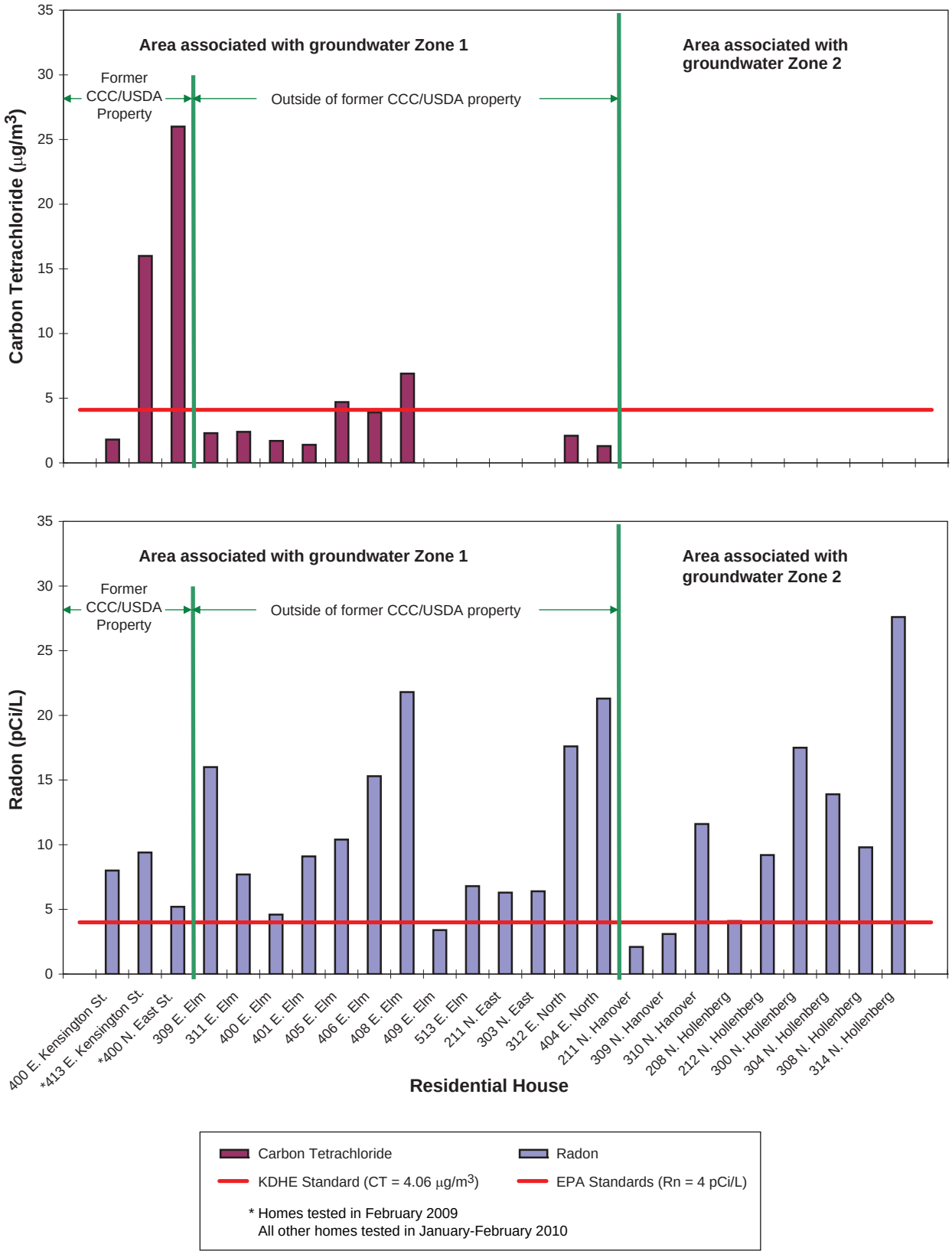

FIGURE ES.7 Qualitative correlation between radon and carbon tetrachloride in basement indoor air of homes tested.

1 Introduction

The Commodity Credit Corporation (CCC), an agency of the U.S. Department of Agriculture (USDA), operated a grain storage facility at the northeastern edge of the city of Hanover, Kansas, from 1950 until the early 1970s. During this time, commercial grain fumigants containing carbon tetrachloride were in common use by the grain storage industry to preserve grain in their facilities. In February 1998, trace to low levels of carbon tetrachloride were detected in two private lawn and garden wells near the former grain storage facility at Hanover, as part of a statewide USDA private well sampling program that was implemented by the Kansas Department of Health and Environment (KDHE) near former CCC/USDA facilities. No public water supply wells were identified within 1 mi of the town by the KDHE in 1998.

In July 2007, the CCC/USDA sampled indoor air at nine residences on or adjacent to its former facility to address the residents' concerns regarding vapor intrusion (VI). Low levels of carbon tetrachloride were detected at four of the nine homes.

Because carbon tetrachloride found in private wells and indoor air at Hanover might be linked to historical use of fumigants containing carbon tetrachloride at its former grain storage facility, the CCC/USDA has conducted investigations to determine the source and extent of the carbon tetrachloride contamination that may be associated with the former facility. The investigations were performed by the Environmental Science Division of Argonne National Laboratory in accordance with the intergovernmental agreement between the KDHE and the Farm Service Agency (FSA) of the USDA. Argonne is a nonprofit, multidisciplinary research center operated by UChicago Argonne, LLC, for the U.S. Department of Energy (DOE).

This report presents the findings of the investigations at Hanover, conducted from January 2009 to June 2010.

1.1 Background and Previous Investigations

Hanover, Kansas, is a rural city located in northeastern Washington County, in Section 9, Township 2 South, Range 5 East, approximately 78 mi northwest of Manhattan, Kansas, and 90 mi southwest of Lincoln, Nebraska (Figure 1.1). Hanover is a state historic site known for the Hollenberg Pony Express Station. The city has numerous small businesses, the Farmers

Cooperative Association, and a hospital. It also has public and private schools, churches, a library, a weekly newspaper, and a recreation facility.

The 2000 Census recorded 653 people in 329 housing units in the city of Hanover. The residents of the city have been served since February of 1974 by a public water supply system that obtains water from the Washington County Rural Water District (RWD) #1, which has a well field located 6.5 mi north of the town, outside the investigation area (Figure 1.1).

Prior to February of 1974, the city had its own wells in the Little Blue River valley, on the southwest side of the city, taping water from the alluvial aquifer. These wells have been abandoned. The water from the old city wells had a hardness of 99 grains per gallon (RWD 2009), which is "very hard" (Water Quality Association 2010). "Very hard" water can cause serious problems, including clogging of the delivery piping system, interference with all cleaning tasks, and inefficient and costly operation of water-using appliances. The Rural Water District #1 water now used has a hardness of 21 grains per gallon. In March 2009, the city of Hanover forfeited its water rights (Water Appropriation Program 2009).

The Washington County RWD #1 currently maintains three well fields consisting of 10 wells: Lanham (4 wells), Washington (2 wells), and Marysville (4 wells). The Hanover community receives its water supply primarily from the Lanham well field. The RWD #1, however, can transfer water from one well field to the other if a capacity problem occurs at any of the three well fields. The recent KDHE annual RWD sampling data indicate that carbon tetrachloride was detected at concentrations of 0.86 μg/L to 1.4 μg/L (below the maximum containment level [MCL] of 5 μg/L) in annual sampling events in 2005, 2007, 2008, and 2009 (KDHE 2009f). All of the groundwater samples were collected from a single point of entry at the Lanham Pump House 1, which connects four wells (2, 3, 11, and 12) in the Lanham well field.

At the request of the KDHE, the CCC/USDA conducted a review of historical aerial photos and interviewed the Washington County FSA. A records search indicated that no former grain storage facilities operated by the CCC/USDA were located at or near the Lanham well field. The historical aerial photos show that other commercial or private grain storage facilities were present in the past at and near the Lanham well field. It is anticipated that the KDHE will determine whether further investigation is warranted for the former commercial/private grain storage facilities at and near the Lanham well field.

In response to the initial detection of trace levels of carbon tetrachloride in private lawn and garden wells at Hanover in early 1998, the KDHE and the CCC/USDA conducted the following investigations and studies:

- Pre-CERCLIS site reconnaissance and evaluation (SRE) in July 1998 (KDHE 1998)

- Private well sampling in April 2006, as a part of statewide USDA private well sampling program (KDHE 2007a)

- Near-surface soil sampling at the former CCC/USDA grain storage facility in April 2007 (Argonne 2008a)

- Indoor air sampling at nine residences on or adjacent to the former CCC/USDA grain storage facility in July 2007 (Argonne 2008a)

- Review of site historical data and the former grain storage facilities (Argonne 2008a)

The main findings of the previous investigations are summarized as follows:

- The CCC/USDA operated a grain storage facility from 1950 to the early 1970s on approximately 6.5 acres in the northeastern part of the city. The facility reached a maximum operational scale in the late 1960s with 223 grain bins and 1 storage building. Another major private grain storage facility is currently operated by the Farmers Cooperative Association (the Co-op), located approximately 2,000 ft west of the former CCC/USDA property (Figure 1.2).

- In 1973, the CCC/USDA grain bins were sold at auction to local farmers. In 1974, the parcel was formally surveyed as the Warren Addition, and in 1974-1975 the first of nine homes now present on or immediately adjacent to the former CCC/USDA property were constructed. The parcel was significantly sloped prior to residential development. Leveling of the entire area displaced much of the original surface soil. Further changes in the area's surface

resulted from excavation to remove bins, installation of roadways, and residential landscaping.

- Two other facilities in the area are associated with petroleum contamination leaking from aboveground storage tanks and underground storage tanks, respectively. Both were operated by Bill's Service Center (Figure 1.2).

- In 1998, five private wells were sampled as part of the USDA private well sampling program and the subsequent KDHE (1998) SRE investigation. Carbon tetrachloride was found in groundwater from one private lawn and garden well (Meyn) at a concentration (5.9 μg/L) near the MCL. The well is located approximately 1,000 ft west of the former CCC/USDA facility. Trace (approximately 1 μg/L) to no contamination was detected in groundwater samples collected from four other private wells surrounding the former CCC/USDA facility (Figure 1.3).

- In July 1998, the KDHE collected 11 soil samples above the bedrock (9 samples at 10.5-11.5 ft BGL [below ground level] and 2 samples at 19.5 ft BGL) in a pre-CERCLIS SRE investigation. All soil samples showed trace or no carbon tetrachloride contamination, except for one collected at the west edge of the former CCC/USDA facility. A low level of carbon tetrachloride (3.9 μg/kg in on-site analysis and 7.1 μg/kg [well below the state's cleanup level of 200 μg/kg] in off-site laboratory analysis) was detected at 11.5 ft BGL at this location (SP-9) (Figure 1.4).

- In April 2006, the KDHE resampled two private wells where low contamination had been detected in the previous sampling event. Low-level carbon tetrachloride (4.3 μg/L, below Kansas standards) was confirmed at the lawn and garden well (Meyn), but no contamination was found at the other well (Bruna) (Figure 1.3).

- In April 2007, Argonne collected near-surface soil samples at 1.8-2 ft BGL at 61 locations across the former CCC/USDA facility. Analysis of soil samples by the heated-headspace method (a screening tool) indicated four areas with trace-level carbon tetrachloride (Figure 1.5), where further investigation of

underlying subsurface soils was warranted. No contamination was found in confirmation analysis of the samples by the rigorous gas chromatograph-mass spectrometer (GC-MS) analytical method (the purge-and-trap method).

- In July 2007, indoor air samples were collected from the basement areas of nine residences on or adjacent to the former CCC/USDA property.[1] Carbon tetrachloride was detected in the air samples from four residences at concentrations ranging from 1.4 to 4.8 $\mu g/m^3$ (Figure 1.6). On the basis of these results, on March 26, 2008, the KDHE (2008a) asked the CCC/USDA to prepare a work plan for a vapor intrusion investigation. The *Supplemental VI Work Plan* (Argonne 2008b) was submitted on July 9, 2008, and approved by the KDHE (2008b) on July 17, 2008.

- In August 2008, discussions between the KDHE and the CCC/USDA led to an agreement to delay implementation of the *Supplemental VI Work Plan* until winter and to conduct site characterization in the interim (KDHE 2008c). A work plan for site characterization (Argonne 2008a) was submitted on August 15, 2008, and approved by the KDHE on November 18, 2008 (KDHE 2008d).

1.2 Objectives of the 2009-2010 Investigations

The 2009-2010 CCC/USDA-Argonne investigations were conducted at the request and with the concurrence of the KDHE (2008a-d). The primary goals of these investigations were to characterize soil and groundwater contamination that may be associated with the past use of carbon tetrachloride-based grain fumigants at the former CCC/USDA facility and to identify potential intrusion of contaminant vapor (to indoor air) due to possible soil and groundwater contamination. Investigation of other potential contaminant sources was outside the scope of the CCC/USDA work.

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[1] The KDHE standard for carbon tetrachloride in residential indoor air at this time was 1.6 $\mu g/m^3$. In April 2010, the KDHE changed the standard to 4.055 $\mu g/m^3$, as a result of the release by the U.S. Environmental Protection Agency of new data related to human health risk associated with inhalation of carbon tetrachloride. A more detailed discussion is in Section 2.6.3.

The results of the CCC/USDA studies are being used to determine whether response actions are warranted and in what form. To meet the goals, the detailed technical objectives of the investigations were as follows:

- Identify contaminant sources and the extent of soil contamination beneath the former CCC/USDA facility.
- Characterize the groundwater-bearing system.
- Delineate the vertical and lateral extent of the groundwater contamination.
- Determine groundwater flow patterns.
- Evaluate the hydraulic properties of the groundwater-bearing system.
- Determine potential VI attributable to subsurface contamination.

The 2009-2010 investigations were designed to generate specific information required to address these technical objectives. The *Final Work Plan* (Argonne 2008a) for the overall investigation and the *Supplemental VI Work Plan* (Argonne 2008b) were approved by the KDHE (2008b,d). Subsequently, smaller work plans to guide specific activities were developed during the investigations and incorporated into the *Final Work Plan* and the *Supplemental VI Work Plan* as addenda, with the approval of the KDHE (2008e, 2009a-d, 2009h, 2010a,c). The investigations were carried out in accordance with KDHE (2005a,b) guidance and with KDHE oversight. The *Final Work Plan* (Argonne 2008a) is reproduced as Supplement 1 on the compact disc (CD) inside the back cover of Volume 1. The *Supplemental VI Work Plan* (Argonne 2008b) is reproduced as Supplement 2 (also on CD).

1.3 Summary and Timeline of Field Investigation Activities

The 2009-2010 investigations were conducted in five phases, as outlined in the *Final Work Plan* (Argonne 2008a) and the *Supplemental VI Work Plan* (Argonne 2008b). The five implementation phases, as planned, were as follows:

- *Phase 1.* Identify potential contaminant sources, and determine the vertical and lateral distributions of potential soil contamination beneath the former CCC/USDA facility.

- *Phase 2.* Determine the potential vertical and lateral extents of groundwater contamination beneath the former CCC/USDA facility, and obtain data to accurately characterize the site lithology, hydrostratigraphy, and groundwater flow.

- *Phase 3.* Delineate the off-site vertical and lateral extents of contamination in groundwater emanating from any potential source areas identified on the former CCC/USDA facility, and develop a monitoring system to evaluate groundwater flow patterns.

- *Phase 4.* Install additional monitoring wells to augment data collected during Phases 1-3 and to establish a long-term monitoring network. Conduct hydrogeologic testing to evaluate aquifer properties.

- *Phase 5.* Conduct a VI investigation.

The investigations in Phases 1-4 focused on the characterization of soil and groundwater, with work guided by the *Final Work Plan* (Argonne 2008a). The Phase 5 activities were implemented to identify potential VI. These activities were in accord with the *Supplemental VI Work Plan* (Argonne 2008b).

Data collected in each phase were evaluated to determine whether further activities in that phase and/or subsequent phases were necessary. During the 2009-2010 investigations, several addenda to the *Final Work Plan* (Argonne 2008a) and the *Supplemental VI Work Plan* (Argonne 2008b) were developed as results accumulated and understanding of the site improved. These addenda provide the scope, approaches, and plans that guided detailed activities that had not been anticipated or specified in the *Final Work Plan* and the *Supplemental VI Work Plan*. All addenda were approved by the KDHE (2008c, 2009a-d, 2009g, 2010a,c) prior to implementation.

The 2009-2010 studies at Hanover were conducted in accord with the *Final Work Plan* (including addenda; Argonne 2008a), the *Supplemental VI Work Plan* (including addenda; Argonne 2008b), and the *Master Work Plan* (Argonne 2002). These investigations included the following major field activities:

- *January 13-February 10, 2009.* Characterization of soil and groundwater systems and associated contamination, at and near the former CCC/USDA facility (Phases 1-2).

- *February 2-4, 2009.* Investigation of upward VI in residences, with collection of vapor/air samples from sub-slab, basement, and first-floor spaces for analyses of volatile organic compounds (VOCs) and a tracer (radon). Three residences were investigated at and near the former CCC/USDA facility, where relatively higher levels of carbon tetrachloride had been detected in the July 2007 sampling (Phase 5).

- *February 23-March 6, 2009.* Characterization of the contamination in groundwater emanating from the former CCC/USDA facility (beyond the limits of the former facility), in the uppermost water-bearing unit of the hydrogeologic sequence (Zone 1). The work in Phases 1-3 resulted in the identification of the four water-bearing zones illustrated schematically in Figure 1.7.

- *March 12-13, 2009.* Wintertime indoor air sampling in six additional residences, on the basis of the results of the February 2-4, 2009, sampling at three residences at and near the former CCC/USDA facility (Phase 5 extension). In previous (July 2007) summertime sampling, these six additional residences had exhibited no carbon tetrachloride or low levels.

- *March 24-April 3, 2009.* Completion of characterization of groundwater-bearing Zone 1, with extension of the groundwater investigation to deeper water-bearing Zones 2-4 (Phases 3-4).

- *March 23-April 9, 2009.* On-site screening for residential VI through collection of vapor/air from soil, sub-slab, basement, and first- or second-floor

spaces of all accessible residences in the area where groundwater contamination had been identified in Zone 1 (Phase 5 extension).

- *June 22, 2009.* Groundwater sampling for four additional private wells identified during the community meeting on May 29, 2009 (Phases 3-4).

- *August 10-14, 2009.* Slug testing to evaluate the hydraulic properties of groundwater-bearing Zone 1 (Phase 4).

- *August 11-13, 2009.* Indoor air sampling for summertime monitoring of 17 selected residences associated with groundwater contamination in Zone 1, as indicated by the results of on-site screening on March 23-April 9, 2009 (Phase 5).

- *September 21-October 16, 2009.* Characterization of the deep groundwater system (water-bearing Zones 2-4) and associated contamination (Phases 3-4).

- *November 23-25, 2009.* Step-drawdown testing of water-bearing Zone 1 at three wells selected on the basis of the results of the slug testing on August 10-14, 2009, to determine the sustainable pumping potential at these locations (Phase 4).

- *January 25-26, 2010.* Indoor air sampling for wintertime monitoring of 17 residences selected on the basis of results of the on-site screening related to water-bearing Zones 1 and 2 on March 23-April 9, 2009 (Phase 5).

- *January 26-27, 2010.* Slug testing to evaluate the hydraulic properties of groundwater-bearing Zone 2 (Phase 4).

- *February 22-23, 2010.* Constant-rate pump testing of Zone 1 well MW05, to determine the long-term sustainable pumping rate at this location. Well MW05 was selected on the basis of the results of the step-drawdown testing on November 23-25, 2009 (Phase 4).

- *February 22-25, 2010.* Investigation of potential VI for two schools at Hanover, at the residents' request, as well as collection of indoor air samples at nine residences associated with contamination in groundwater Zone 2 (Phase 5).

- *March 17-20, 2010.* Constant-rate pump testing (24-hr) of Zone 2 well MW44, to determine the long-term sustainable pumping rate at this location. Well MW44Z2 was selected on the basis of the results of the slug testing on January 26-27, 2010 (Phase 4).

- *April 12, 2010.* Inspection of creek bottoms and ditches to search for seeps, from the former CCC/USDA facility and westward to the creek (east of Denver Avenue).

- *June 17, 2010*. Sampling of selected monitoring wells for nitrate analysis.

More detailed information for all of the activities during the 2009-2010 investigations is listed chronologically in Table 1.1.

1.4 Organization of This Report

This report documents all the data acquired during the 2009-2010 investigations, presents integrated analyses and interpretation of the results to address the objectives stated in Section 1.2, and proposes preliminary response action objectives and potential corrective action technologies for the investigation area. Section 1 provides brief background information, summarizes previous investigations of the site, identifies specific technical objectives of the 2009-2010 investigations, and summarizes the major investigation events in a time sequence. Section 2 describes the investigative methods used during the 2009-2010 studies. Section 3 presents the results of all investigative activities. Section 4 discusses and interprets the results in the context of the specific technical objectives outlined in Section 1.2. Section 5 summarizes the findings of the investigations. Response action objectives and potential corrective action technologies for the site are proposed in Section 6.

The appendixes in Volume 2 contain lithology logs, well construction and registration information, sample descriptions, hand-measured water level data, survey data, and brief summaries of aquifer testing results. The CD inside the back cover of Volume 1 contains complete results of aquifer testing, automatic water level monitoring, waste characterization, vapor intrusion monitoring, and quality control activities, along with reports for specific investigation and vapor mitigation tasks performed during the 2009-2010 investigation and the work plans that guided the investigation.

TABLE 1.1 Summary of investigation activities and response actions at Hanover, 1998-2010.

Date	Activity	Objective	Methodology
Prior investigation by the KDHE to evaluate potential carbon tetrachloride contamination			
February 17, 1998	Private well sampling by the KDHE under the joint KDHE-CCC/USDA private well sampling program.	Determine whether carbon tetrachloride is present in groundwater as a result of former CCC/USDA grain storage operations.	Sample collection from 3 private wells located within 1 mi of the former CCC/USDA grain storage facility.
July 1998	KDHE completion of SRE report for the former CCC/USDA grain storage facility.	Identify site contamination and potentially responsible party.	Subsurface soil sampling with Geoprobe; private well sampling.
April 26, 2006	KDHE private well sampling.	Update the previously identified groundwater contamination.	Sample collection from Bruna and Meyn private wells (also sampled in 1998).
Investigation by the CCC/USDA to address residents' concerns regarding former grain storage operations			
April 18, 2007	Near-surface soil sampling in response to resident concerns regarding potential carbon tetrachloride contamination due to former CCC/USDA grain storage operations.	Evaluate the potential for subsurface soil contamination and for human exposure.	Near-surface soil sampling at 61 locations across the former CCC/USDA property, with preservation on dry ice and analysis for VOCs at the AGEM Laboratory.
July 10-11, 2007	Indoor air sampling in the basements of 9 residences on the former CCC/USDA property, in response to resident concerns.	Conduct an initial evaluation of indoor air contamination.	Air collection over 24 hr in Summa canisters; analysis by TestAmerica, Burlington, Vermont, by EPA Method TO-15.
October 11, 2007	Submittal to the KDHE of results of near-surface soil sampling (April 2007) and indoor air sampling (July 2007).	–	–
October 18, 2007	Submittal to the KDHE of an evaluation of indoor air carbon tetrachloride concentrations measured in July 2007.	Evaluate potential risk.	Although no immediate health risk was evident, investigation was recommended to determine whether the detected concentrations were due to VI from contaminated subsurface soil or groundwater.
December 5, 2007	Issuance of KDHE response regarding evaluation of indoor air results and request for VI work plan.	–	Additional sampling or installation of mitigation systems requested.

TABLE 1.1 (Cont.)

Date	Activity	Objective	Methodology
Investigation by the CCC/USDA to characterize the nature and extent of site contamination and potential response actions			
March 26, 2008	Issuance of KDHE request to develop a VI work plan.	Evaluate the potential for VI.	Investigation under the KDHE-CCC/USDA Inter-Governmental Agreement.
July 9, 2008	Submittal to the KDHE of the draft VI investigation work plan.	Evaluate the potential for VI by comparison of sub-slab and indoor air concentrations.	Phased investigation in conjunction with the site characterization investigation.
July 17, 2008	Issuance of KDHE approval for the VI work plan.	–	–
August 15, 2008	Submittal to the KDHE of the draft site characterization work plan.	Characterize soil and groundwater contamination associated with past use of carbon tetrachloride-based grain fumigants at the former CCC/USDA facility.	Phased investigation of the nature and extent of carbon tetrachloride contamination in soil and groundwater on and adjacent to the former CCC/USDA property.
September 9, 2008	Issuance of KDHE comments on the draft site characterization work plan.	–	–
October 13, 2008	Submittal to the KDHE of the revised site characterization work plan and a response to KDHE comments.	–	–
November 18, 2008	Issuance of KDHE approval for the site characterization work plan.	–	–
December 15, 2008	Submittal to the KDHE of a plan for indoor air and ambient air sampling.	Evaluate the potential for VI in 4 homes on the former CCC/USDA facility.	Sub-slab and indoor air sampling for carbon tetrachloride, chloroform, and radon (as a tracer).
December 23, 2008	Issuance of KDHE comments on the indoor air sampling plan.	–	–
January 13-15, 2009	Implementation of Phase 1 of the site characterization work plan, on the former CCC/USDA property.	Identify potential soil sources and determine the vertical and lateral distribution of carbon tetrachloride contamination in soil.	Subsurface soil sampling to bedrock based on 2007 surface soil results; sampling at 25 locations (TI01-TI25), approximately every 4 ft; preservation on dry ice and analysis for VOCs at the AGEM Laboratory.

TABLE 1.1 (Cont.)

Date	Activity	Objective	Methodology
Investigation by the CCC/USDA to characterize the nature and extent of site contamination and potential response actions (cont.)			
January 28- February 10, 2009	Implementation of Phase 2 of the site characterization work plan, on the former CCC/USDA property.	Determine the vertical and lateral extent of groundwater contamination, and obtain data to characterize the site lithology, hydrostratigraphy, and groundwater flow.	Additional subsurface soil sampling and installation of 12 monitoring wells (MW01, MW02, MW04-MW13) on and adjacent to the former CCC/USDA facility.
February 2-4, 2009	Investigation of upward VI in 3 residences on the former CCC/USDA property where carbon tetrachloride was detected in July 2007.	Evaluate indoor air contamination during optimal winter sampling period when homes are most closed to outside air.	Collection of vapor/air samples from sub-slab, basement, and first-floor spaces for analysis of VOCs and tracer radon.
February 18, 2009	KDHE-CCC/USDA teleconference.	Present results of site investigation to date.	–
February 23- March 6, 2009	Implementation of Phase 3 of the site characterization work plan, outside the former CCC/USDA property.	Characterize water-bearing Zone 1; delineate associated contamination; develop a monitoring system to evaluate groundwater flow patterns.	Installation and sampling of 28 additional monitoring wells (MW14-MW41); sampling of existing private wells.
March 12-13, 2009	Investigation of upward VI in the remaining 6 residences on the former CCC/USDA property, where carbon tetrachloride was not detected in July 2007.	Evaluate indoor air contamination during the optimal winter sampling period when homes are most closed to outside air.	Collection of basement and first-floor indoor air samples for analysis by TestAmerica with EPA Method TO-15.
March 25-27, 2009	VI evaluation at residences outside the former CCC/USDA property (completed April 7-10, 2009).	Screen all residences in the identified groundwater contaminant distribution area for potential vapor intrusion.	Collection of vapor/air samples from sub-slab, basement, and first-floor spaces for on-site analysis, with submittal of selected samples for off-site verification analysis.
March 24- April 3, 2009	Continuation of groundwater investigation; confirmation of multiple-zone model.	Complete characterization of groundwater-bearing Zone 1; extend the investigation to deeper Zones 2-4.	Installation of 10 additional monitoring wells: MW42, MW43, MW44S, MW44M, MW44D, MW45S, MW45M, MW45D, MW46, and MW47.
April 1, 2009	KDHE-CCC teleconference.	Present results for indoor air sampling at 9 homes in February-March.	–
April 7-10, 2009	Continuation of the VI evaluation at residences outside the former CCC/USDA property.	Screen all residences in the identified groundwater contamination area for potential VI.	Collection of vapor/air samples from sub-slab, basement, and first-floor spaces for on-site analysis, with submittal of selected samples for off-site verification analysis.

TABLE 1.1 (Cont.)

Date	Activity	Objective	Methodology
Investigation by the CCC/USDA to characterize the nature and extent of site contamination and potential response actions (cont.)			
May 7, 2009	KDHE-CCC teleconference.	Discuss VI investigation results and proposed mitigation.	–
May 29, 2009	Public availability session in Hanover.	Present the results of site investigation to date to Hanover residents.	Community meeting led by the KDHE.
June 16, 2009	Submittal to the KDHE of a plan for indoor air sampling in 16 homes (subsequently expanded to 17 homes).	Monitor indoor air contamination at homes where the potential for VI had been identified.	Indoor air and ambient air sampling with analysis by TestAmerica.
June 22, 2009	Sampling of 4 additional private wells identified during community meeting.	Determine potential carbon tetrachloride contamination in active private wells; verify use of wells.	Sample collection for analysis by the AGEM Laboratory.
July 7, 2009	Issuance of KDHE approval of the plan for indoor air sampling at 17 homes.	–	–
July 15, 2009	Submittal to the KDHE of two addenda to the site characterization work plan, for hydrogeologic testing under Phase 4 of the site characterization work plan.	Evaluate aquifer properties and determine the pumping capacity of the identified contaminated water-bearing zones.	Addendum 1: Slug testing for groundwater Zone 1; Addendum 2: Further investigation for groundwater Zone 2.
July 15, 2009	Issuance of KDHE approval for vegetation sampling, with request for location map.	–	–
July 17, 2009	Submittal to the KDHE of a plan for vegetation sampling.	Determine the potential for phytoremediation as a response technology.	Collection of branch and leaf samples from existing mature trees across the investigation area, with analysis at the AGEM Laboratory.
July 22, 2009	Issuance of KDHE approval for the plan for groundwater Zone 1 slug testing.	–	–
July 23-24, 2009	Vegetation sampling of mature trees across the investigation area.	Determine whether carbon tetrachloride uptake in vegetation is occurring, to evaluate the potential for phytoremediation of the identified groundwater contamination.	Branch and leaf sampling at 171 locations across the investigation area; preservation on dry ice, with analysis at the AGEM Laboratory for carbon tetrachloride and chloroform by modified EPA Method 3810.

TABLE 1.1 (Cont.)

Date	Activity	Objective	Methodology
Investigation by the CCC/USDA to characterize the nature and extent of site contamination and potential response actions (cont.)			
August 5, 2009	Submittal to the KDHE of a plan for vapor mitigation of 3 homes.	Reduce identified carbon tetrachloride contamination in indoor air.	Installation of sub-slab depressurization systems.
August 10, 2009	Issuance of KDHE approval of plan for vapor mitigation of 3 homes.	–	–
August 12-13, 2009	Monitoring of 17 residences where carbon tetrachloride was identified in prior indoor air sampling.	Conduct summertime monitoring of indoor air.	Collection of basement and first-floor indoor air samples for analysis by TestAmerica with EPA Method TO-15.
August 10-14, 2009	Slug testing of wells in groundwater-bearing Zone 1.	Evaluate hydraulic properties and identify critical factors that govern groundwater flow and contaminant migration in the Zone 1 unit.	Slug testing in 20 Zone 1 monitoring wells: MW01, MW02, MW04-MW07, MW09-MW13, MW16, MW18, MW20, MW21, MW28, MW29, MW34, MW37, and MW38.
August 25-27, 2009	Completion of vapor mitigation of 3 homes.	Reduce identified carbon tetrachloride contamination in indoor air.	–
August 28, 2009	Issuance of KDHE approval for plan for investigation of groundwater Zones 2-4.	–	–
September 15, 2009	Issuance of KDHE electronic mail message outlining expectations for future monitoring and remediation.	–	–
September 28, 2009	Retesting of indoor air in 3 homes after installation of sub-slab vapor intrusion mitigation systems in August.	Verify elimination of identified carbon tetrachloride contamination in indoor air.	Indoor air sampling.
September 21-October 16, 2009	Zone 2-4 groundwater investigation.	Characterize the deep groundwater system in water-bearing Zones 2-4.	Installation and sampling of 12 monitoring wells: MW48Z2, MW48Z3, MW48Z4, MW49Z2, MW49Z3, MW49Z4, MW50Z2, MW50Z3, MW50Z4, MW51Z2, MW51Z3, and MW52Z4.
October 13, 2009	Meeting of CCC/USDA and KDHE in Topeka.	Present results of investigation to date.	–
October 28, 2009	Submittal to the KDHE of results of August 2009 Zone 1 slug testing.	–	–

TABLE 1.1 (Cont.)

Date	Activity	Objective	Methodology
Investigation by the CCC/USDA to characterize the nature and extent of site contamination and potential response actions (cont.)			
November 18, 2009	Submittal to the KDHE of Addendum 3 to the site characterization work plan, for performance testing of selected Zone 1 monitoring wells.	Assess the technical and logistic feasibility of groundwater pumping from groundwater Zone 1 as a potential corrective action technology.	Step-drawdown testing at Zone 1 monitoring wells MW05, MW09, and MW10.
November 23-25, 2009	Single-well step-drawdown testing at 3 wells selected per the August 2009 slug test responses.	Determine the specific capacity and radius of influence of selected Zone 1 wells.	Step pumping testing at water-bearing Zone 1 wells MW05, MW09, and MW10.
January 25-26, 2010	Monitoring of 17 residences where carbon tetrachloride was identified in prior indoor air sampling.	Conduct wintertime monitoring of indoor air contamination.	Collection of basement and first-floor indoor air samples for analysis at TestAmerica with EPA Method TO-15.
January 26-27, 2010	Slug testing of wells in groundwater-bearing Zone 2.	Evaluate the hydraulic properties of Zone 2 and the potential effectiveness of localized groundwater extraction as a corrective action technology.	Slug testing in 6 Zone 2 monitoring wells: MW44Z2, MW45Z2, MW48Z2, MW49Z2, MW50Z2, and MW51Z2.
January 29, 2010	Submittal to the KDHE of results of the November 2009 Zone 1 pumping test.	Evaluate the potential effectiveness of localized groundwater extraction from groundwater Zone 1 as a corrective action technology.	Step pumping testing at water-bearing Zone 1 wells MW05, MW09, and MW10.
February 22-24, 2010	Constant-rate pumping test at Zone 1 well MW05, selected per the November 2009 step-drawdown test results.	Determine the long-term sustainable pumping rate for water-bearing Zone 1 well MW05, to evaluate the potential effectiveness of localized groundwater extraction as a corrective action technology.	Measurement of water level response and recovery during sustained pumping of water-bearing Zone 1 monitoring well MW05.
February 22-25, 2010	Indoor air sampling at Hanover public school and St. John's School, at the request of residents; sampling of 9 residences potentially at risk for VI from groundwater Zone 2.	Determine the potential for upward VI of carbon tetrachloride, chloroform, and radon contamination from the subsurface to indoor air.	Indoor air sampling with on-site analysis in accessible rooms in the schools, with follow-up sampling and quantitative analysis for rooms selected per the screening results; quantitative VOCs analysis by TestAmerica with EPA Method TO-15.

TABLE 1.1 (Cont.)

Date	Activity	Objective	Methodology
Investigation by the CCC/USDA to characterize the nature and extent of site contamination and potential response actions (cont.)			
March 17-20, 2010	Constant-rate pumping test at Zone 2 well MW44, selected per the January 2010 slug test results.	Determine the long-term sustainable pumping rate for water-bearing Zone 2.	Measurement of water level response and recovery during sustained pumping of water-bearing Zone 2 monitoring well MW44.
April 26, 2010	Submittal to the KDHE of results of the January 2010 Zone 2 slug testing.	Evaluate the potential effectiveness of localized groundwater extraction from groundwater Zone 2 as a corrective action technology.	–
April 27, 2010	Submittal to the KDHE of a plan for vapor mitigation of 2 homes.	Reduce identified carbon tetrachloride contamination in indoor air.	Installation of sub-slab depressurization systems.
April 30, 2010	Submittal to the KDHE of results of the February 2010 constant-rate pumping test for Zone 1 monitoring well MW05 submitted to the KDHE.	Evaluate the potential effectiveness of localized groundwater extraction from groundwater Zone 1 as a corrective action technology.	–
May 4, 2010	Issuance of KDHE approval of plan for vapor mitigation of 2 homes.	–	–
May 12-13, 2010	Completion of vapor mitigation of 2 homes.	Reduce identified carbon tetrachloride contamination in indoor air.	–
June 17, 2010	Retesting of indoor air in 2 homes after installation of sub-slab vapor intrusion mitigation systems in May 2010.	Verify elimination of identified carbon tetrachloride contamination in indoor air.	Indoor air sampling.
June 17, 2010	Sampling of selected monitoring wells for nitrate analysis.	Indicate subsurface infiltration to water-bearing zones.	Groundwater sampling.
July 29, 2010	Submittal to the KDHE of results of the March 2010 constant-rate pumping test for Zone 2 monitoring well MW44Z2.	Evaluate the potential effectiveness of localized groundwater extraction from groundwater Zone 2 as a corrective action technology.	–

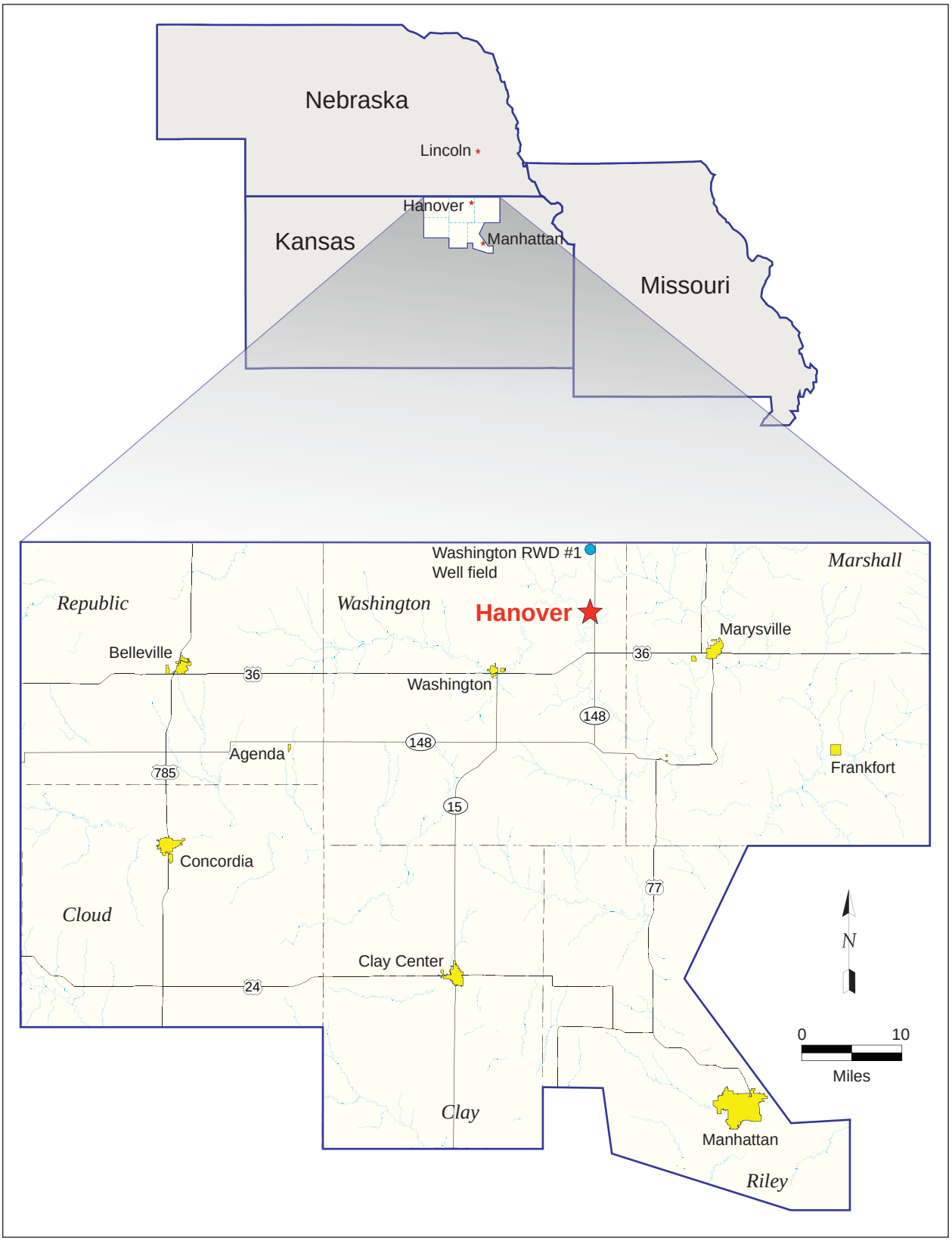

FIGURE 1.1 Location of Hanover, Kansas, and the public water well field of Washington County RWD#1 for the Hanover public water supply.

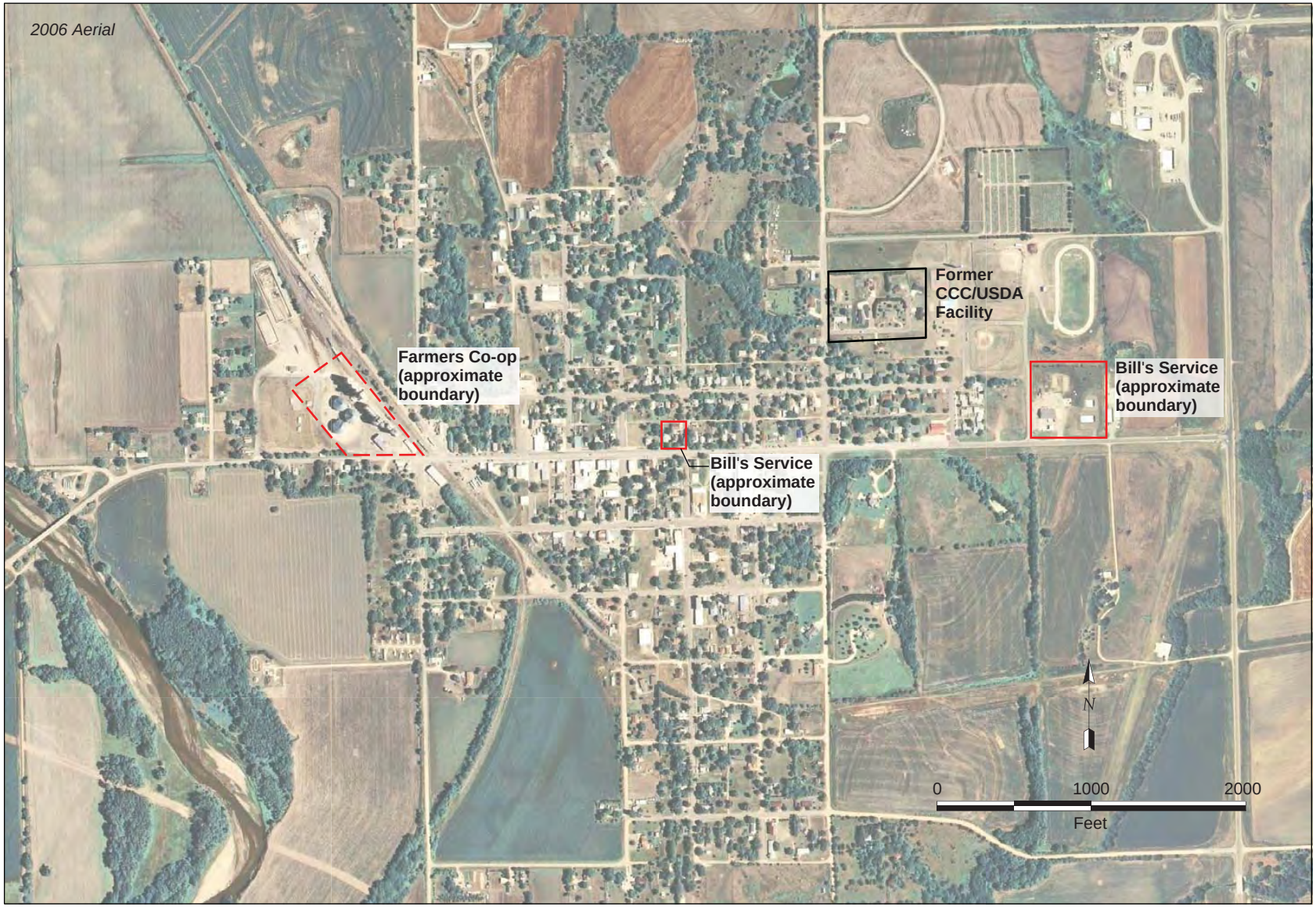

FIGURE 1.2 Location of the former CCC/USDA facility, the Farmers Co-op Association, and petroleum-contaminated sites. Source of photograph: NAIP (2006).

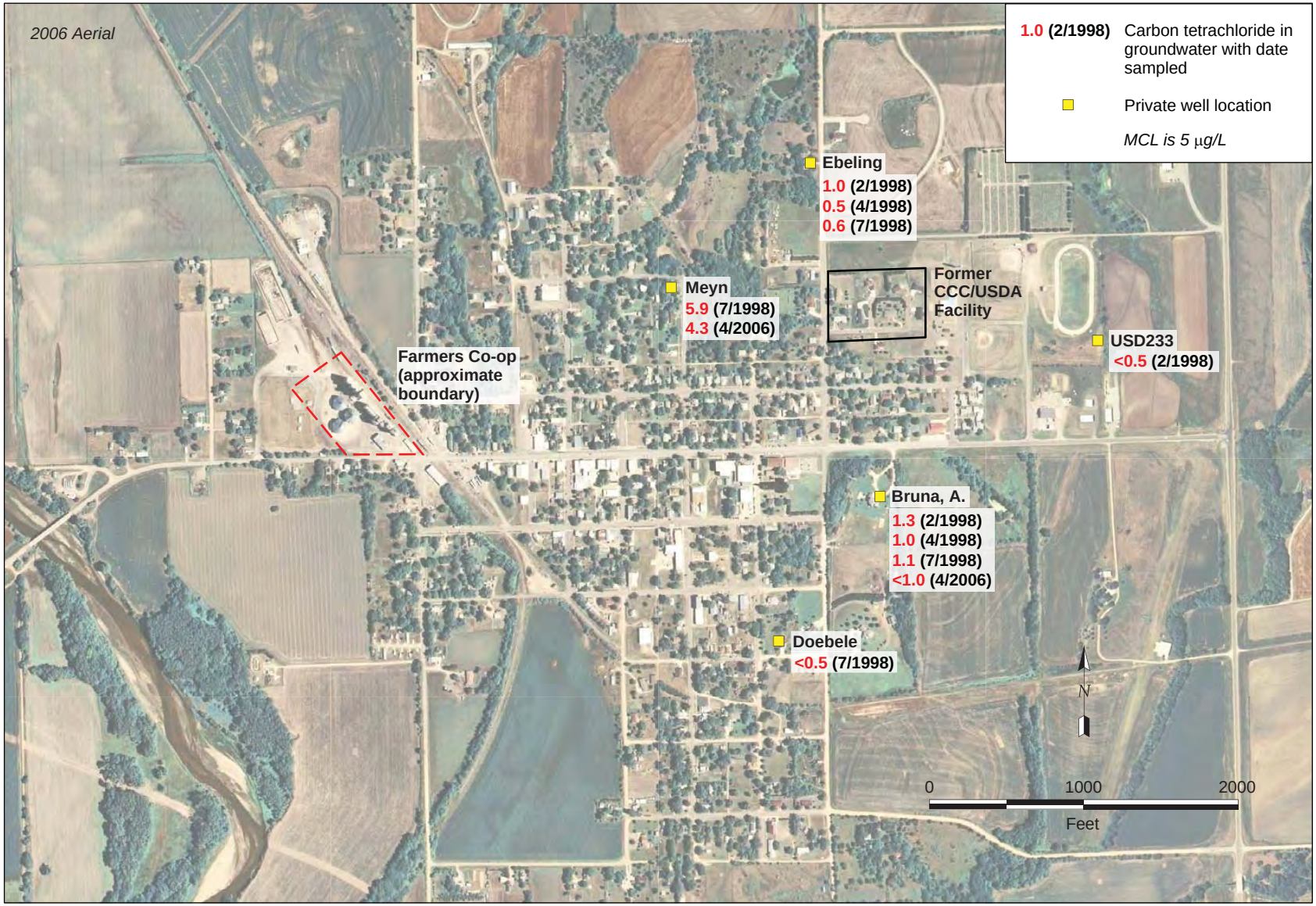

FIGURE 1.3 Historical results of carbon tetrachloride analyses on groundwater samples collected by the KDHE in 1998-2006 from private wells in and near Hanover. Source of photograph: NAIP (2006).

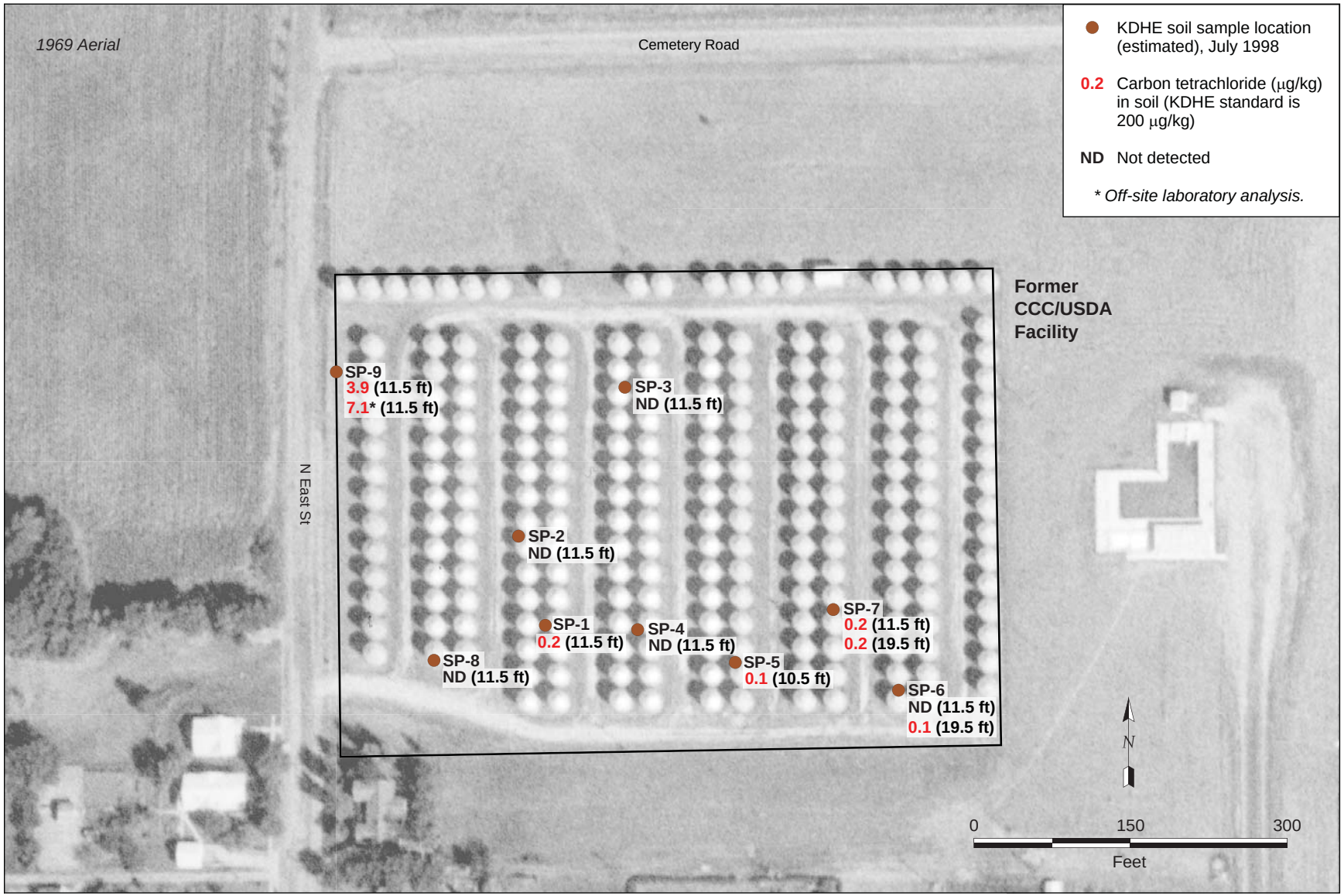

FIGURE 1.4 Field laboratory analytical results for soil samples collected by the KDHE in 1998 at the former CCC/USDA facility. Source of photograph: USDA (1969).

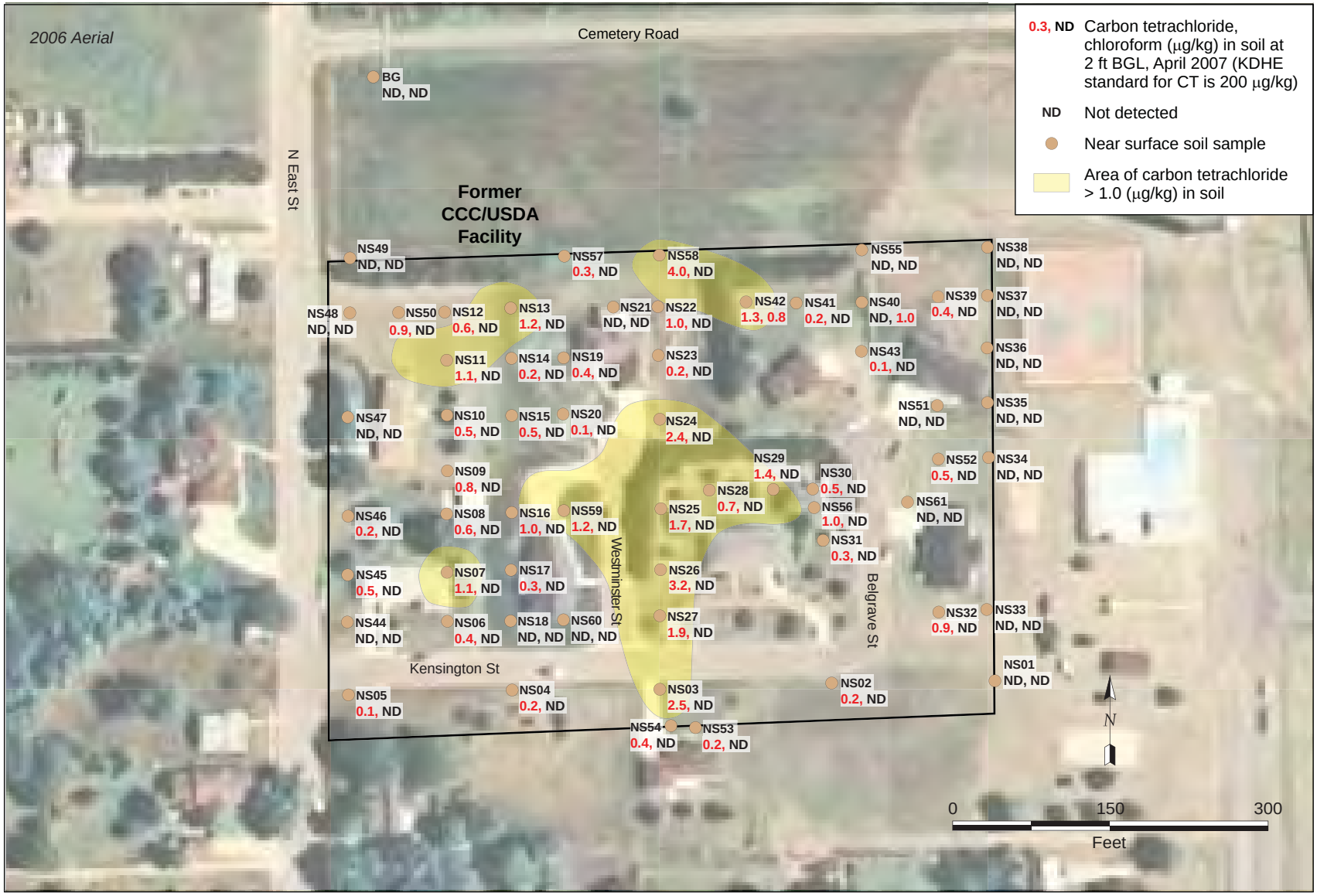

FIGURE 1.5 Results of headspace screening analyses for carbon tetrachloride in near-surface soil samples collected in 2007 at the former CCC/USDA facility. Source of photograph: NAIP (2006).

FIGURE 1.6 Results of analyses for carbon tetrachloride and chloroform in indoor air samples collected in 2007 at and near the former CCC/USDA facility. Source of photograph: NAIP (2006).

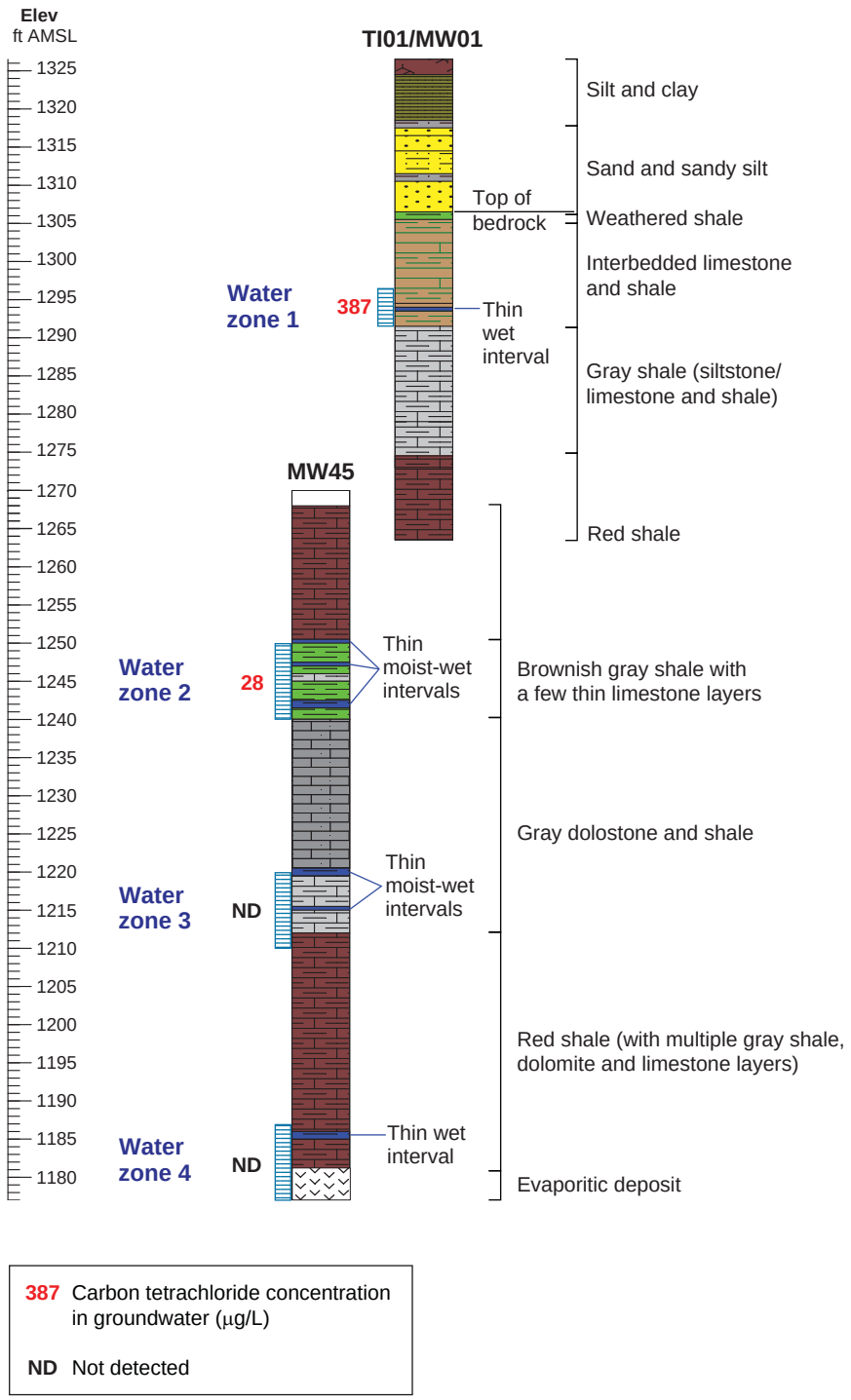

FIGURE 1.7 General stratigraphic section in the investigation area at Hanover.

2 Investigative Methods

This section discusses the methods used to implement the 2009-2010 investigations and to achieve the specific technical objectives stated in Section 1.2. Individual activities were performed as specified in the *Final Work Plan* (including addenda; Argonne 2008a), the *Supplemental VI Work Plan* (including addenda; Argonne 2008b), and the *Master Work Plan* (Argonne 2002). Detailed procedures are not repeated here.

Throughout the field program, a comprehensive quality assurance/quality control (QA/QC) program was implemented to confirm the reliability of all information as it was accumulated. The results of implementation of the QA/QC program are discussed in Section 3.11.

2.1 Methods to Identify Contaminant Sources and the Extent of Soil Contamination

The investigation activities described here focused on identification of soil contamination on and near the former CCC/USDA property, which is currently a residential subdivision. To ensure that all soil sources and soil-to-groundwater pathways were identified with minimum interference to the residents, the following approaches were implemented:

- Continuous vertical soil profiling with sampling for VOCs analyses was conducted through the vadose zone and to the depth of the first water-bearing unit identified beneath the former CCC/USDA facility. The analytical results were evaluated to determine whether carbon tetrachloride was present in soil as a potential contaminant source.

- Vertical soil profiling was performed in two steps:

  - *Step 1.* Use of a portable Geoprobe to collect subsurface soil samples in the unconsolidated interval above bedrock, over most of the residential area.

  - *Step 2.* Use of a minisonic drilling rig to collect bedrock samples to the depth of the first water-bearing zone, at selected locations.

- In the initial step (Geoprobe sampling), access was permitted for a total of 25 subsurface soil sampling locations (TI01-TI25; Figure 2.1). Locations for this sampling were selected to target the following areas:

  - Four potentially contaminated areas identified from the results of headspace analyses of near-surface soil sampling in 2007 (highlighted areas in Figure 2.1).

  - Areas near the homes in which carbon tetrachloride had been detected in indoor air.

- The subsequent bedrock sampling was conducted at locations selected on the basis of results of the initial Geoprobe sampling. Seven locations within the former CCC/USDA facility were chosen to represent areas associated with any contamination identified in the Geoprobe sampling and/or with potential VI as indicated for the sampled homes. Five additional locations were selected for bedrock soil sampling at the edge of the former CCC/USDA facility. Figure 2.2 shows the bedrock soil sampling locations on and near the former CCC/USDA property.

2.2 Methods to Characterize Groundwater Contamination

2.2.1 Methods to Identify the Groundwater-Bearing System

Characterization of the groundwater-bearing system was conducted in two steps addressing groundwater-bearing Zone 1 and Zones 2-4, respectively.

Groundwater-bearing Zone 1 is shallow, and its occurrence is limited to the area of the bedrock high where the former CCC/USDA facility was located. To fully delineate the hydrostratigraphy, contaminant distribution, and potential VI pathways associated with the Zone 1 interval, 48 locations (Figure 2.3) were investigated.

The investigation program for deeper groundwater-bearing Zones 2-4 was developed within the context of the findings from the initial studies (primarily related to water-bearing

Zone 1). Plans for this program are documented in Addendum 2 to the *Final Work Plan* (Argonne 2008a). Factors considered in selecting locations for the Zones 2-4 investigation included the following:

1. The results for water samples from private wells inferred to intersect Zones 2-4 (see below).

2. The extent of the contamination in Zone 1.

3. The apparent pattern of groundwater flow in Zone 1.

Figure 2.4 shows the locations (MW44-MW45, MW48-MW51) investigated in Zones 2-4.

At each boring location, multiple lines of evidence obtained from visual and laboratory analyses of continuous cores, observed relationships to previously identified water-bearing zones in nearby borings, and the elevation ranges of water-bearing zones in existing private wells were used to determine the locations, lithologic characteristics, and lateral continuity of the water-bearing intervals.

To assist in characterizing multiple water-bearing zones, groundwater samples from four identified zones were collected for tritium analysis. Tritium is a short-lived isotope of hydrogen with a half-life of 12.32 yr (Lucas and Unterweger 2000). As a result of radioactive decay, tritium in soil water and groundwater derived from precipitation that fell before 1953 would have contained no more than approximately 0.5 TU in 2000. From 1953 to 1969, a series of atmospheric hydrogen bomb tests resulted in the addition of a large amount of tritium to the atmosphere, for a peak concentration of nearly 10,000 TU in 1963 (Drever 1988). In the post-bomb period, tritium levels in precipitation were monitored at the International Atomic Energy Agency (IAEA) monitoring station in Lincoln, Nebraska (74 mi north of Hanover), until 1986 (IAEA 1992). At that time, the atmospheric tritium level was approximately 14 TU. Therefore, this tritium concentration is commonly used to separate pre-bomb and post-bomb waters (McMahon et al. 2006). The results of tritium analysis may help to qualitatively differentiate the age of waters in various water-bearing zones and to infer possible hydraulic connections and/or water mixing.

2.2.2 Methods to Delineate the Extent of Groundwater Contamination

The initial results of the hydrostratigraphic characterization efforts described in Section 2.2.1 demonstrated that the groundwater flow system in the bedrock sequence at Hanover is poorly developed. Very slow or no initial water accumulation was observed in the borings at most locations. If no immediate water entry was identified during the drilling process, an optimal depth interval spanning the potential water-bearing zone was identified on the basis of the criteria outlined above. At almost all locations, a monitoring well was installed at the selected depth. A water sample was collected for VOCs analysis from every well in which sufficient groundwater accumulation occurred after development.

At each deep-zone investigation point, monitoring wells were installed separately to screen Zones 2, 3, and 4, respectively. Groundwater samples collected from each well for VOCs analyses provided information on contaminant levels for the corresponding zones at that location.

To assist in the delineation of contamination in the deep water-bearing zones, groundwater samples were also collected for VOCs analyses from accessible private wells, most of which penetrate groundwater-bearing Zones 2-4 (as determined on the basis of depths for these wells — ranging from 41 ft to 82 ft BGL). Figure 2.5 shows the locations of the 24 private wells sampled during these investigations. Well BSMW13, also shown in Figure 2.5, was not sampled because of the presence of petroleum free product.

In this study, nitrate concentrations in groundwater were used as an indicator of subsurface infiltration to water-bearing zones. High concentrations of nitrate are commonly associated with agriculture activities on the ground surface. The measurement of nitrate levels in water-bearing Zone 1 and Zone 2 could provide indirect evidence suggesting or confirming the potential presence of contaminant migration pathways in the subsurface. Figure 2.6 shows the locations of groundwater samples collected in Zone 1 and Zone 2 and selected for nitrate analysis.

2.3 Methods to Determine and Monitor Groundwater Flow Patterns

Accurate determination of groundwater flow patterns was accomplished through a systematic process: (1) identification of all possible groundwater-bearing zones in the upper

portion of the bedrock formation potentially used by local residents, (2) installation of monitoring wells to identify complex flow patterns, (3) measurement of water levels for each identified groundwater-bearing zone, and (4) analysis of data to determine flow patterns in each zone.

The methods discussed in Section 2.2 were used to identify all groundwater-bearing zones. Monitoring wells were installed at most of the investigative locations because of slow water accumulation from the bedrock formation in the area. Groundwater levels were periodically determined manually in the entire network of observation wells for each water-bearing zone. Water level fluctuations were also monitored continuously at selected locations through the use of automatic water level sensors and data loggers. Groundwater flow patterns were determined from stabilized water levels in wells that showed minimal, if any, interference from local events. Determination of flow patterns was not attempted for water-bearing Zones 3 and 4, in which apparent stabilization of the water levels did not occur within the time frame of the 2009-2010 studies.

To determine the groundwater flow pattern for water-bearing Zone 1, water level data were generated for 41 monitoring wells (MW01, MW02, MW04-MW40, MW46-MW47; Figure 2.7). The networks for deep groundwater-bearing Zones 2-4 consisted of 18 individual monitoring wells (one well screened in each of these three deeper zones, at six locations [MW44-MW45 and MW48-MW51]; Figure 2.8).

Four additional private monitoring wells were installed with the GeoCore on behalf of Bill's Service Center during a previous investigation of aboveground storage tanks (see Section 2.2.5 of the *Final Work Plan*; Argonne 2008a). These wells are screened exclusively in Zone 2 and were included in the Zone 2 water level monitoring network for the purpose of determining flow direction (Figure 2.8). Sampling of private wells for VOCs analyses is discussed in Section 2.2.2.

2.4 Methods to Evaluate the Hydraulic Properties of the Groundwater-Bearing System

The hydraulic properties of the groundwater-bearing system are important parameters that govern contaminant transport and the effectiveness of potential corrective action technologies. The results of the Phase 1-3 investigations demonstrated that Zone 1 (Figure 1.7) is

a critical water-bearing unit with the potential to provide a contaminant migration pathway for both upward VI and downward leakage to underlying groundwater Zone 2. Results also suggest that Zone 2 is a significant unit in which migration of contaminants leaked from Zone 1 occurs. However, no evidence indicates that deep water-bearing Zones 3 and 4 are providing contaminant migration pathways. This section discusses methods to investigate the hydraulic properties of groundwater-bearing Zones 1 and 2.

During the time period of the investigation, groundwater in Zone 3 and Zone 4 wells continued to recover without reaching equilibrium. No tests of hydraulic properties were attempted in these zones because of the non-static condition of the water-bearing units and the absence of contaminants.

2.4.1 Methods for Groundwater-Bearing Zone 1

To facilitate evaluation of the hydraulic properties in groundwater-bearing Zone 1, the following hydraulic characteristics of this interval were investigated:

- *Hydraulic conductivity*. The ability of a porous medium (formation or soil) to transmit water; a measure of the ease or difficulty with which fluid flows through the formation (soil) matrix system.

- *Specific capacity*. The yield of a water well per unit of drawdown (usually expressed as gallons per minute per foot); the amount of water that a well can produce under a unit drop of water level from the water-bearing formation or soil.

- *Radius of influence*. The radial distance from the center of a pumping well to the point where there is no lowering of the water table or potentiometric surface (the edge of the cone of depression — the area affected by the pumping well, beyond which there is no measurable or observed effect).

Quantitative data on these properties in the Zone 1 unit were acquired through the following activities:

- Single-well response ("slug") testing of 20 monitoring wells to generate data on the range and distribution of the hydraulic conductivity values in water-bearing Zone 1 across the area, including the apparent contaminant migration pathways (Figure 2.9). This activity was guided by Addendum 1 to the *Final Work Plan* (Argonne 2008a).

- Step-drawdown testing to determine the specific capacity and potential radius of influence (ROI) of Zone 1 monitoring wells MW05, MW09, and MW10. These three wells were selected for step testing on the basis of relatively higher hydraulic conductivity values identified at their locations by slug testing. Eleven monitoring wells surrounding the three (individually pumped) wells were used as observation points throughout the testing (Figure 2.10). The testing was implemented as specified in Addendum 3 to the *Final Work Plan* (Argonne 2008a).

- Constant-rate pump testing of water Zone 1 to determine the long-term sustainable pumping rate from this interval at the MW05 well location. Well MW05 was selected for constant-rate testing because it exhibited the highest specific capacity, as estimated from the step-drawdown pumping. Two attempts were made in February 2010 to pump MW05 for an extended period; 11 nearby Zone 1 monitoring wells were used as observation wells for these tests (Figure 2.11).

2.4.2 Methods for Groundwater-Bearing Zone 2

The hydraulic properties of groundwater-bearing Zone 2 were evaluated, because Zone 2 also hosts a saturated unit that provides a pathway for contaminant transport. All monitoring wells installed in Zone 2 (Figure 2.9) were subjected to slug testing in January 2010 to generate data on the range and distribution of hydraulic conductivity values. A long-term, constant-rate pumping test was conducted at Well MW44Z2 in March 2010. Five monitoring wells (MW45Z2, MW48Z2. MW49Z2, MW50Z2, and MW51Z2) installed in Zone 2 were used as observation wells during the testing (Figure 2.12).

2.5 Methods to Determine Potential Vapor Intrusion Attributable to Subsurface Contamination

This section briefly describes the methods and approaches applied at the Hanover site in the 2009-2010 evaluation of potential VI. The procedures guiding specific techniques are outlined in the *Supplemental VI Work Plan* and its four addenda (Argonne 2008b) and are not repeated here.

2.5.1 Vapor Intrusion Pathway

To assess potential VI, the following three components of a complete VI pathway are the key elements that must be considered:

- *Sources* of vapors in the form of residual contamination in subsurface soil and groundwater.
- *Migration routes* for contaminant vapors, by diffusion and advection processes, from sources and through soil and structures.
- *Receptors* occupying residences or commercial/public buildings within a distance reachable by a contaminant vapor migrating upward from soil.

The activities in the VI investigation were designed to generate data needed for quantifying the conditions of some or all of the components in the pathway and for determining whether potential VI may be attributable to subsurface contamination associated with the former CCC/USDA facility.

2.5.2 Characterization Methods for Soil, Groundwater, Soil Gas, Sub-Slab Vapor, and Indoor Air

The methods to identify soil and groundwater contamination as the potential source(s) of vapors in indoor air are discussed in Sections 2.1 and 2.2. The acquired data were used to determine source parameters such as distance to receptors, contaminant concentrations, and the presence of potential barriers or preferential conduits that might affect vapor movement.

Several attempts were made to identify migration routes and to demonstrate the presence of upward VI due to subsurface contamination. The methods applied or attempted were as follows:

- A soil gas survey adjacent to the foundations of homes to determine the presence and distribution of contaminant vapors outside the residential structures.

- Coupled sub-slab soil vapor and indoor air sampling for VOCs analyses to identify potential upward migration routes for VI through a structure's foundation.

- Coupled sub-slab soil vapor and indoor air sampling, with radon as a tracer, to confirm an upward migration route that supports VI into the structure. This method was applied at selected homes for confirmation.

- Indoor air sampling for VOCs analyses to determine contaminant vapor conditions surrounding residents as potential receptors in homes and as a direct indicator of health risks for receptors.

During the 2009-2010 investigation, prior to the KDHE's update of the indoor air standard for carbon tetrachloride (April of 2010), the VI investigation faced a significant challenge because of the similarity of the KDHE standard and background concentrations of carbon tetrachloride. To confirm the presence of upward VI processes, multiple investigation techniques were applied in this investigation. Radon, as a secondary probe in addition to VOCs, was also analyzed in selected sub-slab soil vapor and indoor air samples to determine the ratio of indoor air concentration to sub-slab soil vapor concentration. The radon results could qualitatively determine the presence of upward VI migration and might also provide quantitative information on the attenuation factor, which indicates how the properties of soil and/or a building can limit the intrusion of contaminant vapor as it migrates into the structure.

Radon is a naturally occurring radioactive gas produced from the natural decay of uranium, which commonly exists in minerals of rock and soil. Radon gas can follow the same upward VI process as VOCs migrating into the structure. In most cases, samples for radon analysis were collected over intervals of 3-4 days by using test kits with activated charcoal.

Radon adsorbed onto the charcoal was analyzed by scintillation counting to detect the gamma rays produced by the breakdown products ("daughters") of radon. In a few cases, the radon samples were collected in canisters.

2.5.3 Evaluation Methods and Investigation Processes

The general investigation process applied at Hanover began with the identification of vapor sources (soil and groundwater contamination) and proceeded with a phased approach to ultimately pinpoint VI-affected structures. In the investigation process, three screening criteria were used, as approved by the KDHE project manager. These evaluation criteria are as follows:

- *To determine the investigation area for potential VI.* On the basis of the distance criteria specified in KDHE (2007b) guidance, areas within a lateral distance of 100 ft or a vertical distance of 40 ft from groundwater contamination (above 5.0 µg/L for carbon tetrachloride) were designated for VI investigation.

- *To identify potentially VI-affected homes or buildings.* The KDHE standard of 1.6 µg/m^3 for carbon tetrachloride in indoor air and an attenuation factor of 0.01 for sub-slab vapor were used in these investigations.[2] As noted in Section 2.6.3, the KDHE changed its risk-based standard to 4.055 µg/m^3 in April 2010 (KDHE 2010f). Any tested structure with a carbon tetrachloride concentration higher than 1.6 µg/m^3 in indoor air and/or 160 µg/m^3 in sub-slab vapor (as determined by on-site analysis), was selected for 24-hr indoor air sampling.

- *To select potentially VI-affected homes or buildings for monitoring in summer and/or winter seasons.* If the results of 24-hr indoor air sampling suggested a concentration above the KDHE's indoor air standard, the affected structures were monitored during the summer and/or winter seasons.

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[2] The attenuation factor of 0.01 is based on an assumption (KDHE 2007b) that upward flow of the contaminant through the building materials is impeded enough to decrease the concentration in indoor air to 1% of the concentration in the sub-slab vapor.

The following investigation processes and evaluation methods were employed in four geographic areas:

1. The residential subdivision (including nine homes) within and near the footprint of the former CCC/USDA property (Figure 2.13).

   - *Step 1a.* To confirm the presence of upward VI, three accessible residences were selected with relatively high carbon tetrachloride concentrations in indoor air on the basis of the results of sampling in 2007.

   - *Step 1b.* To generate data on upward VI, coupled sub-slab vapor and indoor air sampling was conducted at the three selected residences for analyses for VOCs and radon (as a tracer). This activity was guided by the *Supplemental VI Work Plan* (Argonne 2008b) and its Addendum 1.

   - *Step 1c.* Monitoring for VI was expanded to six additional residences in the winter season, after the results from Step 1b demonstrated upward VI. This activity was also guided by Addendum 1 to the *Supplemental VI Work Plan* (Argonne 2008b).

   - *Step 1d.* Indoor air sampling (24-hr) was performed at three residences selected according to the criteria above, for summertime and wintertime monitoring. This activity was guided by Addenda 2 and 3 to the *Supplemental VI Work Plan* (Argonne 2008b).

2. Residences overlying the identified groundwater contamination in Zone 1 but outside the former CCC/USDA property.

   - *Step 2a.* The KDHE distance and depth criteria discussed above were used relative to the groundwater contamination in Zone 1 to identify an area outside the former CCC/USDA property for VI investigation.

   - *Step 2b.* A soil gas survey and coupled sub-slab vapor and indoor air sampling were conducted, with on-site analysis. The activities were guided by the *Supplemental VI Work Plan* (Argonne 2008b). Locations for

the soil gas survey are shown in Figure 2.14, and residences tested by sampling of sub-slab vapor and indoor air are shown in Figure 2.15. Some residences received only the sub-slab and indoor air sampling, after soil gas results had shown little correlation with corresponding sub-slab and indoor air values.

- *Step 2c.* The Step 2b results were used to identify homes or buildings potentially affected by VI. The evaluation criteria for sub-slab vapor and indoor air were as discussed above.

- *Step 2d.* Summertime and/or wintertime 24-hr indoor air samples were collected at 14 residences selected in Step 2c. This activity was guided by Addenda 2 and 3 to the *Supplemental VI Work Plan* (Argonne 2008b). The locations of the 14 residences potentially affected by the Zone 1 contamination are included in Figure 2.16.

3. Residences overlying the groundwater contamination in Zone 2 but outside the former CCC/USDA property.

- *Step 3a.* The KDHE distance criteria discussed above were used relative to the groundwater contamination in Zone 2 to identify an area outside the former CCC/USDA property for VI investigation.

- *Step 3b.* A soil gas survey and coupled sub-slab vapor and indoor air sampling were conducted, with on-site analysis. The activities were guided by the *Supplemental VI Work Plan* (Argonne 2008b). Locations for the soil gas survey are shown in Figure 2.14, and residences tested by sampling of sub-slab vapor and indoor air are shown in Figure 2.15. Some residences received only the sub-slab and indoor air sampling, after soil gas results had shown little correlation with corresponding sub-slab and indoor air values.

- *Step 3c.* Conduct 24-hr indoor air sampling at nine residences potentially affected by the Zone 2 contamination. This activity was guided by Addendum 3 to the *Supplemental VI Work Plan* (Argonne 2008b). The

locations of the nine residences potentially affected by Zone 2 contamination are included in Figure 2.16.

4. School buildings beyond the limits of the groundwater contamination in Zones 1 and 2.

   - *Step 4a.* Indoor air sampling with on-site analysis was performed for all accessible rooms within the school buildings. The activities were guided by the *Supplemental VI Work Plan* (Argonne 2008b) and its Addendum 4.

   - *Step 4b.* Overnight and daytime indoor air sampling was conducted in the school buildings at locations selected on the basis of the Step 4a results. The activities were guided by the *Supplemental VI Work Plan* (Argonne 2008b) and its Addendum 4.

The VI investigation for the school buildings was requested by local residents, even though the buildings are outside the identified area of groundwater contamination in Zones 1-2. Activities were designed to generate data to address the residents' concerns. The locations of the school buildings are shown in Figure 2.17.

2.6 Methods to Evaluate Human Health and Environmental Risks

An initial screening evaluation for human health and environmental risks was performed for the chemicals of primary interest, carbon tetrachloride and chloroform, which might be associated with the past use of fumigants at the former CCC/USDA grain storage facility. Contamination in three media were evaluated by using the methods discussed below.

In addition to the two chemicals of primary interest, radon was also evaluated for human health risk because of its prevalence and the high concentrations identified in many indoor air samples in this investigation. Radon is a naturally occurring, radioactive gas. Its assessment focused only on its level in indoor air in comparison with available standards.

2.6.1 Soil

The KDHE (2010f) Tier 2 risk-based standards for contaminated soil were used for screening as specified. In deriving the Tier 2 standards based on risk to human health, the KDHE evaluated two exposure pathways: (1) direct exposure, including ingestion of contaminated soil, inhalation of chemical volatilizing from contaminated soil, inhalation of airborne contaminated particulates, and direct dermal contact, and (2) indirect exposure via the soil-to-groundwater pathway. The risk-based standards for direct exposure to soil are provided for two land use settings: residential and nonresidential. The Tier 2 risk-based standards for soil contaminated with carbon tetrachloride and chloroform are listed in Table 2.1.

2.6.2 Groundwater

The two potential pathways for exposure to contaminated groundwater evaluated in this study are (1) direct exposure of humans and (2) exposure of aquatic life via discharge to the nearest creeks. The KDHE (2010f) Tier 2 risk-based standards for contaminated groundwater were used as screening criteria for human risk, and the KDHE surface water quality standards (KDHE 2004) were used for evaluating environmental risk to aquatic life. The standards for carbon tetrachloride and chloroform are listed in Table 2.1. The MCL values used in the federal Safe Drinking Water Act are adopted in the KDHE (2010f) Tier 2 risk-based standards for carbon tetrachloride and chloroform.

2.6.3 Indoor Air

Contamination in indoor air was evaluated during the investigations reported here by using the KDHE Tier 2 risk-based standard in force at the time. The KDHE uses carcinogenic risk to calculate its Tier 2 standard, rather than the less stringent non-carcinogenic risk. The KDHE calculates the carcinogenic risk-based indoor air concentration for carbon tetrachloride by using Equation 8 in the *RSK Manual* (KDHE 2010f) for human exposure to contaminated air for 24 hr per day, 350 days per year, over a period of 30 yr. The standard for carbon tetrachloride in residential indoor air is intended to prevent human exposure that could result in occurrence of cancer at a rate greater than 1 in 100,000 individuals. It is the threshold for KDHE action.

A key parameter associated with toxicity data and used in Equation 8 is the *inhalation slope factor* (SF_i), which can be derived from the toxicity parameter *inhalation unit risk*. The operative SF_i value for carbon tetrachloride during these investigations, 5.25×10^{-2} (kg-day/mg)$^{-1}$, was derived from a value of inhalation unit risk, 1.5×10^{-5} (µg/m^3)$^{-1}$. This value was posted on the U.S. Environmental Protection Agency (EPA) Integrated Risk Information System (IRIS) database in 1987. Use of this 1987 SF_i value resulted in a calculated KDHE Tier 2 standard of 1.6 µg/m^3 for carbon tetrachloride.

On March 31, 2010, in response to more recent research, the EPA posted an updated value for inhalation unit risk, 6×10^{-2} (µg/m^3)$^{-1}$, in the IRIS database. The corresponding updated SF_i value is 2.10×10^{-2} (kg-day/mg)$^{-1}$. With these values, the KDHE has now used Equation 8 in the *RSK Manual* (KDHE 2010f) to calculate an updated risk-based concentration of 4.055 µg/m^3 for carbon tetrachloride.

The EPA is conducting a similar review of research related to chloroform; an updated value of inhalation unit risk for that compound is expected when the review is complete.

The current KDHE Tier 2 risk-based standards for carbon tetrachloride and chloroform are listed in Table 2.1.

The evaluations for radon were based on the EPA action level (4.0 pCi/L; Table 2.1). At this level, the estimated carcinogenic risk due to exposure (for a non-smoker; Table 2.2) is about 7 in 1,000 individuals (EPA 2009). For comparison, the estimated carcinogenic risk for exposure to carbon tetrachloride at the KDHE screening level of 4.055 µg/m^3 is 1 in 100,000 (KDHE 2010f).

TABLE 2.1 Regulatory standards for initial evaluation of human health and environmental risks.

Scenario	Pathway	Standard[a] (units indicated below for soil, groundwater, and indoor air)		
		Carbon Tetrachloride	Chloroform	Radon
Soil Pathways (μg/kg for carbon tetrachloride and chloroform)				
Residential	Direct exposure	2,500	3,900	–
	Soil to groundwater	200	960	–
Non-residential	Direct exposure	7,000	6,000	–
	Soil to groundwater	200	960	–
Groundwater Pathways (μg/L for carbon tetrachloride and chloroform)				
Residential	Direct exposure	5	80	–
Non-residential	Direct exposure	5	80	–
Aquatic life	Groundwater seepage to surface water			
	Acute exposure	35,200	28,900	–
	Chronic exposure	Not available	1,240	–
Indoor Air (μg/m^3 for carbon tetrachloride and chloroform; pCi/L for radon)				
Residential	Direct exposure	4.055[b]	1.05[c]	4.0 pCi/L[d]

[a] Source of values for carbon tetrachloride and chloroform in soil and groundwater and for chloroform in indoor air: KDHE (2004, 2010f).

[b] The value of 4.055 μg/m^3 for carbon tetrachloride was calculated by using the KDHE (2010f) Equation 8 (for indoor air carcinogens) with the updated inhalation slope factor (SF_i) of 2.10×10^{-2} (kg-day/mg)$^{-1}$ derived from the new EPA IRIS value of inhalation unit risk, 6×10^{-2} (μg/m^3)$^{-1}$. This new value was posted on the IRIS database (http://www.epa.gov/iris/subst/0020.htm#inhalrfc) on March 31, 2010. The previous SF_i value for carbon tetrachloride, 5.25×10^{-2} (kg-day/mg)$^{-1}$, was derived from the IRIS value of inhalation unit risk, 1.5×10^{-5} (μg/m^3)$^{-1}$, posted on the IRIS database in 1987. This previous SF_i value was used in calculation of the KDHE value of 1.6 μg/m^3 that was operative during the investigations reported here.

[c] The KDHE value of 1.05 μg/m^3 for chloroform is based on the carcinogenic scenario and an SF_i value of 8.05×10^{-2} (kg-day/mg)$^{-1}$, (equal to the KDHE [2010f] toxicity factor). The currently posted IRIS summary provides an inhalation unit risk of 2.3×10^{-5} per (μg/m^3), which is converted to the SF_i value used by the KDHE to calculate the risk-based concentration. In IRIS, a note immediately above the posted inhalation risk factor reads, "Note: The following evaluation of cancer risk from chloroform inhalation was developed in 1987 and does not incorporate newer data or the 1996 or 1999 draft cancer assessment guidelines." The EPA is currently working to revise the assessment for inhalation exposure. Regarding the potential for chloroform to cause cancer, the toxicity summary in IRIS states, "Under the Proposed Guidelines for Carcinogen Risk Assessment . . . chloroform is *likely to be carcinogenic to humans by all routes of exposure* under high-dose conditions that lead to cytotoxicity and regenerative hyperplasia in susceptible tissues. . . . Chloroform is *not likely to be carcinogenic to humans by any routes of exposure* at a dose level that does not cause cytotoxicity and cell regeneration." The EPA's current reassessment for chloroform will seek to update values for toxicity via inhalation.

[d] Source: EPA action level (http://www.ksradon.com/files/basic_radon_facts_english.pdf).

TABLE 2.2 Risks of cancer for individuals exposed to radon or carbon tetrachloride in their homes for a lifetime.[a]

Concentration	Expected Lifetime Incidence
Radon: Risks of lung cancer for smokers exposed to radon in their homes for a lifetime[b]	
10 pCi/L	150 out of 1,000
4 pCi/L[c]	62 out of 1,000
Radon: Risks of lung cancer for non-smokers exposed to radon in their homes for a lifetime[b]	
10 pCi/L	18 out of 1,000
4 pCi/L[c]	7 out of 1,000
Carbon tetrachloride: Risk of all cancers for smokers or non-smokers exposed to carbon tetrachloride in their homes for a lifetime	
4.055 $\mu g/m^3$ [d]	1 out of 100,000 (equal to 0.01 out of 1,000)

[a] Sources of information: EPA 2009; KDHE 2010f.

[b] Risks for former smokers might be lower than the risks for smokers but higher than the risks for non-smokers.

[c] EPA action level for radon in residential indoor air.

[d] KDHE screening level for carbon tetrachloride in residential indoor air.

FIGURE 2.1 Locations of subsurface soil sampling with the Geoprobe in the unconsolidated interval at and near the former CCC/USDA facility in the 2009-2010 investigations. Source of photograph: NAIP (2008).

FIGURE 2.2 Locations of bedrock soil sampling with a minisonic drilling rig at and near the former CCC/USDA facility in the 2009-2010 investigations. Source of photograph: NAIP (2008).

FIGURE 2.3 Locations of groundwater sampling for groundwater-bearing Zone 1 (including attempted sampling points) from boreholes and from temporary and long-term monitoring wells installed during the 2009-2010 investigations. Source of photograph: NAIP (2008).

FIGURE 2.4 Locations of groundwater sampling for groundwater-bearing Zones 2-4 from temporary and long-term monitoring wells installed during the 2009-2010 investigations. Source of photograph: NAIP (2008).

FIGURE 2.5 Locations of the 24 private wells sampled during the 2009-2010 investigations and 1 private well (BSMW13) that was not sampled. Source of photograph: NAIP (2008).

FIGURE 2.6 Locations of groundwater samples from Zone 1 and Zone 2 analyzed for nitrate. Source of photograph: NAIP.

FIGURE 2.7 Locations of the network of observation points used for measurement of water levels in groundwater-bearing Zone 1 during the 2009-2010 investigations. Source of photograph: NAIP (2008).

FIGURE 2.8 Locations of the network of observation points used for measurement of water levels in groundwater-bearing Zones 2-4 during the 2009-2010 investigations. Source of photograph: NAIP (2008).

FIGURE 2.9 Locations of monitoring wells used for slug testing during the 2009-2010 investigations. Source of photograph: NAIP (2008).

FIGURE 2.10 Locations of the pumping wells (MW09, MW10, and MW05) and observation wells used for the step-drawdown pumping tests in Zone 1 during the 2009-2010 investigations. Source of photograph: NAIP (2008).

FIGURE 2.11 Locations of the pumping well (MW05) and observation wells (MW01, MW02, MW04-MW13) for constant-rate pumping tests in Zone 1 during the 2009-2010 investigations. Source of photograph: NAIP (2008).

FIGURE 2.12 Locations of the pumping well (MW44Z2) and observation wells (MW45Z2, MW48Z2-MW51Z2) for the constant-rate pumping test in Zone 2 during the 2009-2010 investigations. Source of photograph: NAIP (2008).

FIGURE 2.13 Locations of the homes in the residential subdivision on and near the former CCC/USDA property.

FIGURE 2.14 Locations of soil gas survey (with on-site analysis) in the area potentially affected by groundwater contamination in water-bearing Zone 1. Source of photograph: NAIP (2008).

FIGURE 2.15 Locations of residential structures tested during the on-site screening in the 2009-2010 investigations. Source of photograph: NAIP (2008).

FIGURE 2.16 Locations of selected homes monitored during the winter and/or summer seasons for VI testing in the 2009-2010 investigations. Source of photograph: NAIP (2008).

FIGURE 2.17 Locations of the Hanover schools.

3 Field and Laboratory Data

The data generated by the 2009-2010 investigations are presented in this section by the type of test performed or the medium analyzed. The methodologies for data collection are discussed in Section 2. Detailed procedures for the 2009-2010 investigation were described in the *Final Work Plan* (including addenda; Argonne 2008a), the *Supplemental VI Work Plan* (including addenda; Argonne 2008b), and the *Master Work Plan* (Argonne 2002). The timeline of activities is summarized in Table 1.1.

3.1 Geologic Coring Data

At all drilling locations, continuous cores were collected and evaluated to generate geologic logs. The lithologic descriptions for all logs are in Appendix A (in Volume 2). The lithologic data were analyzed to identify the local stratigraphic and hydrostratigraphic units (Section 4.2).

3.2 Soil Sampling Data

Subsurface soil samples were collected for VOCs analyses to generate soil contamination data. Sampling was conducted primarily in vertical profiles through the vadose zone across two distinct intervals: (1) the unconsolidated soils above bedrock and (2) the underlying bedrock to the depth of the first water-bearing zone.

At borings TI01-TI25 on the former CCC/USDA property (Figure 2.1), the Geoprobe was used to collect subsurface soil samples from unconsolidated material at 4-ft intervals, from 2 ft to approximately 25 ft BGL. Bedrock samples were recovered with the minisonic drilling rig at 4-ft intervals at locations MW01-MW05, MW12, and TI26 on the former facility, as well as at borings MW07, TI28, and MW34 near the former facility (Figure 2.2). In addition, continuous soil sampling was conducted with the minisonic drilling rig at 4-ft intervals in both the unconsolidated soils and bedrock at locations TI30, MW08, and MW45 outside the former facility (Figures 2.2 and 2.4). At two locations (TI30/MW09 and MW01), confirmatory soil samples were collected in the bedrock formation below water-bearing Zone 1.

All soil samples were analyzed for VOCs at the Applied Geosciences and Environmental Management (AGEM) Laboratory at Argonne according to a modification of EPA Method 8260B (purge-and-trap method), as referenced in SW-846 (EPA 1998), to achieve a quantitation limit of 10 µg/kg. This method involves methanol extraction and analysis with a GC-MS system. The results are in Table 3.1. Seven soil samples from selected intervals in the bedrock formation at locations MW44, MW45, and MW47 were analyzed for grain density and porosity by National Petrographic Service, Inc., Houston, Texas. The results are in Appendix B. Descriptions of all soil samples are in Appendix C, Table C.1. Replicate soil samples collected for verification analysis are discussed in Section 3.11. The results for the replicate samples are reported in the supplementary material on CD, as discussed in Section 3.11.

3.3 Groundwater Sampling Data

Groundwater samples were collected for VOCs analyses from all of the water-bearing zones identified in the 2009-2010 investigations. Four groundwater-bearing zones were identified in the bedrock formation (Figure 1.7). These zones have limited thicknesses (< 10 ft) and exhibit very poor production in most of the study area. Because of generally slow rates of groundwater accumulation during drilling, monitoring wells were installed at most of the borehole locations for use in groundwater sampling. Groundwater samples were collected from Zone 1 at 38 wells (MW01-MW02, MW04-MW24, MW27-MW38, MW40, and MW46-MW47) and at one borehole location, MW48, which was completed as a well in Zones 2-4 but not in Zone 1 (Figure 2.3). Unsuccessful attempts were made to collect water samples from Zone 1 in the days after well installation in February-April 2009, at locations MW03 and TI27 (plugged wells) and at wells MW25-MW26, MW39, and MW41-MW43 (permanent wells) (Figure 2.3). Subsequently, wells MW25, MW26, MW39, and MW43 eventually produced small amounts of water, as noted when water levels were measured in all monitoring wells in July 2009. For groundwater-bearing Zones 2-4, water samples were collected at 6 locations (MW44-MW45 and MW48-MW51; Figure 2.4). Descriptions of the groundwater samples are in Appendix C, Table C.1.

Groundwater samples were also collected from all accessible private wells surrounding the former CCC/USDA facility (Figure 2.5). The 24 sampled private wells included 12 for lawn and garden use, 1 for use at the school athletic field (USD 223), 2 for irrigation (D. Bruna), 1 for domestic purposes (J. Kruse) outside Hanover, 3 currently not in use (K. Prell, R. Schlabach [E], and Farmers Co-op), and 5 for monitoring at the Bill's Service Center site (Table 3.2). One of the

6 existing wells at the Bill's Service Center site (BSMW13) was not sampled because of the presence of petroleum hydrocarbons. Descriptions of water samples taken from the private wells are in Appendix C, Table C.1.

All groundwater samples were analyzed for VOCs at the AGEM Laboratory, according to a modification of EPA Method 524.2 (EPA 1995). Replicate groundwater samples collected for verification analysis with the EPA's Contract Laboratory Program (CLP) methodology are discussed in Section 3.11. The analytical results for groundwater samples are in Table 3.2.

In addition to VOCs analysis, groundwater samples were also collected at selected locations to extract isotope and geochemical information that might indicate potential contaminant migration and preferential pathways. Eight groundwater samples were collected for tritium analysis from monitoring wells MW05 and MW46 (Zone 1), MW44Z2 and MW45Z2 (Zone 2), MW45Z3 (Zone 3), and MW44Z4 and MW45Z4 (Zone 4). All eight samples were analyzed by the Tritium Laboratory at the University of Miami in Miami, Florida. The results of these analyses are in Table 3.3. Tritium concentrations ranging from 0.12 TU to 5.70 TU were identified.

A total of 12 groundwater samples were collected for nitrate analysis. Of these, 7 samples were from monitoring wells (MW05, MW09-MW11, MW13, MW28-MW29) in groundwater Zone 1, and 5 were from wells (MW44Z2-MW45Z2, MW48Z2-MW49Z2, MW51Z2) in groundwater Zone 2. All samples collected for nitrate analysis were sent to TestAmerica Laboratory. The analytical results are in Table 3.4.

3.4 Installation of Temporary and Permanent Monitoring Wells

Sixty-two monitoring wells (44 in water-bearing Zone 1 and 6 in each of water-bearing Zones 2-4) were installed to facilitate groundwater sampling and the monitoring of groundwater levels. At each location (Figures 2.3 and 2.4), the targeted groundwater-bearing zone was identified by evaluating continuous cores and analyzing their lithology, water content, and stratigraphic relationships.

All monitoring wells were installed by Boart Longyear through use of a sonic rig. With KDHE approval, all of the wells were completed at the surface as flush mounts. Well

construction data are in Table 3.3; construction diagrams and well registration forms are in Appendix D.

3.5 Groundwater Level Data

Groundwater levels were measured both manually and automatically during the 2009-2010 investigations. The networks of observation points for water level measurements are shown in Figure 2.7 (for water-bearing Zone 1) and Figure 2.8 (for water-bearing Zone 2). Water levels were periodically measured manually in all wells. Continuous water level monitoring was conducted at selected locations in each of the four water-bearing zones, to identify possible water level trends.

Manual measurements were taken by reading the depth to water in each well to the nearest 0.01 ft with an electronic water level sensor, from a surveyed reference mark at the top of the well casing. The hand-measured water level data for groundwater-bearing Zones 1-2 are in Appendix E. Water levels were determined automatically in selected wells by installing self-contained water level sensors and data loggers (Instrumentation Northwest, Inc., Model PT2X^{TM}) programmed to collect measurements once every 4 hr. The complete data logger records are in Supplement 3, on CD.

The gaps in the data for the Zone 1 wells (Table S3.1 in Supplement 3) occurred when the recorders were reprogrammed for slug tests (August 2009) or for step tests (November-December 2009). The gap for Zone 2 well MW51Z2 in Table S3.2 (November 2009) was due to slow recovery after slug testing. In Table S3.3, the data gaps for Zone 3 wells MW44Z3 and MW45Z3 (September-October 2009) occurred during recovery after slug testing. The later gaps for well MW45Z3 (October 2009-June 2010) were caused by an electronic problem that resulted in depletion of the batteries; no spare recorder was available as a replacement. The short periodic gaps for Zone 4 well MW44Z4 (Table S3.4) reflect a fault in the recorder's clock that interrupted data collection periodically at fixed intervals, for a fixed duration, before normal recording resumed. Comparison with hand-measured water levels verified that this problem with the well MW44Z4 recorder did not affect the accuracy of the automatic measurements.

The water levels determined manually were used, for those wells in which the observed levels reached ambient static conditions, to construct estimates of the local potentiometric

surfaces for water-bearing Zones 1 and 2. For Zones 3 and 4, monitoring data indicated that the groundwater levels in most monitoring wells were in recovery mode and did not appear to reach equilibrium during the 2009-2010 investigation period. To avoid generating potentially distorted flow patterns by using non-static water level data, no attempts were made to construct potentiometric surfaces for these two zones. The characteristics of slow recovery in Zones 3 and 4 are evaluated in Section 4.6.

3.6 Slug Testing Data for Zone 1 (August 2009) and Zone 2 (January 2010)

Slug tests were performed to investigate the range and distribution of hydraulic conductivity values for groundwater-bearing Zones 1 and 2. The testing was conducted at 20 monitoring wells lying along the identified contaminant migration pathways in Zone 1 and at the 6 monitoring wells installed in Zone 2 (Figure 2.9). Slug testing was not conducted for Zones 3 and 4, because no contamination was detected and no apparent equilibrium was reached in these zones.

The slug tests in all wells were performed by quickly lowering or withdrawing a physical slug into the casing to perturb the static water column. For this purpose, the physical slugs used consisted of 1.0-in.-diameter, sealed, sand-filled PVC (polyvinyl chloride) pipes, either 5 ft long or 3 ft long. The slugs were used either individually or in pairs to achieve the desired water level offset in each well. The slug configuration used for the testing of each well is indicated in Table 3.6.

The slug test response times for the wells in Zone 1 varied significantly, from a few minutes to several days. In keeping with the recommendations in Addendum 1 to the *Final Work Plan* (Argonne 2008a), the number of slug test data sets collected at each well was determined on the basis of the observed water level response. For wells having a water level recovery period of less than 1 hr, four sets of slug test data were collected, representing two complete insertion-and-withdrawal cycles of the physical slug. For wells having recovery periods longer than 1 hr, the following data collection scheme was employed:

Length of Recovery Period	Number of Data Sets
1 hr to 3 hr	3
3 hr to 1 day	2
> 1 day	1

With one exception, the water level responses for all Zone 1 tests were recorded by using self-contained, downhole pressure sensor and data logging units (Instrumentation Northwest, Inc., Model PT2X™). Data for the tests conducted at well MW34 were recorded by using a downhole pressure transducer connected to an external data logger (In-Situ, Inc., Hermit™ 1000C). The number of data sets collected at each well tested is in Table 3.6.

Groundwater recoveries generally occurred more quickly in the Zone 2 monitoring wells than in the Zone 1 wells. The tests in all Zone 2 monitoring wells were therefore conducted by using a downhole pressure transducer (In-Situ, Inc., Model PTX-161) linked to an aboveground data-logging unit (In-Situ, Inc., Hermit™ 1000C) capable of obtaining water level measurements at an initial rate of five readings per second. Four sets of slug test data were collected for each Zone 2 well, representing two complete insertion-and-withdrawal cycles of the physical slug. The slug configurations used for testing of the Zone 2 wells are summarized in Table 3.6.

Complete slug test data for the Zone 1 tests are in the report presented as Supplement 4 (on CD), and complete data for the Zone 2 tests are in Supplement 5. Interpretive curve fits for each test data set are in Appendix F (Zone 1 tests) and Appendix G (Zone 2 tests). The hydraulic conductivity estimates for water-bearing Zones 1 and 2, derived from interpretation of the slug test data sets, are discussed in Section 4.6.

3.7 Step Pumping Test Data for Zone 1, November 2009

On the basis of the Zone 1 slug testing results, additional hydraulic testing of this interval was requested by the KDHE in October 2009 (KDHE 2009e). Addendum 3 to the *Final Work Plan* (Argonne 2008a) outlines a program of investigation, consisting of step-drawdown and constant-rate pumping tests, to determine the specific capacity, long-term pumping capability, and potential ROI of selected existing wells at the site. With the approval of the KDHE (2009h), step pumping tests were performed on November 23-25, 2009, at monitoring wells MW05, MW09, and MW10. The configuration of pumping (MW09, MW05, or MW10) and observation wells employed for each test is summarized in Table 3.7 and Figure 2.10.

The step tests were performed by using a Geotech Environmental Equipment, Inc., Geosub™ pump with precise control for flow rates from < 0.1 gpm (gallons per minute) to approximately 1.25 gpm. In each well, the pump was installed so that the pump inlet was

approximately 0.3 ft above the measured bottom of the well. The pump is 1.0 ft in length. As proposed in Addendum 3, the specific pumping rates employed for the step testing at each targeted well were selected in the field. The pumping rates were measured by using a stop watch to periodically determine the time required to fill a calibrated 0.5-gal or 1-gal container placed at the discharge outfall. Each test was started at a target initial flow rate of approximately 0.1 gpm. The flow rate for each subsequent step was selected on the basis of the water level responses observed during the preceding step of the test.

The three Zone 1 step tests were performed as follows:

- *Step test at MW09*. The Geosub™ pump and downhole transducer were installed in well MW09 on November 23 at approximately 17:00, and the well was allowed to reequilibrate overnight. The step testing of MW09 began at 9:25 on November 24, and the pumping was terminated at 12:20. The pumping rates for the individual steps in this test ranged from approximately 0.08 gpm to 1.8 gpm. The residual drawdown in MW09 was subsequently monitored until approximately 90% recovery had been achieved. The pump was then removed and decontaminated.

- *Step test at MW05*. After installation of the pump and transducer at MW05, manual measurements indicated that the groundwater level in the well returned to within 0.01 ft of the static water level within 20 min. The test pumping of MW05 began at 14:40 on November 24 and was concluded at 18:11. The test was performed at flow rates that ranged from approximately 0.1 gpm to 1.1 gpm. The residual drawdown in well MW05 was monitored until approximately 80% recovery was observed. The pump was then removed and decontaminated.

- *Step test at MW10*. The pump and downhole transducer were installed in well MW10 at approximately 19:20 on November 24, and the well was allowed to reequilibrate overnight. Test pumping of MW10 began on November 25 at 8:25 and ended at 11:39. The test was conducted at flow rates ranging from 0.1 gpm to 0.3 gpm. The residual drawdown in MW10 was monitored until approximately 98% recovery had been achieved. The pump was then removed and decontaminated.

The groundwater level in each pumped well was monitored (1) manually, by periodically measuring the depth to water from the top of the well casing with the aid of an electronic water level meter, and (2) by using a downhole pressure transducer and data logger (Instrumentation Northwest, Inc., Model PT2X^{TM}). The downhole loggers were programmed to record readings at 10-sec intervals in wells MW09 and MW10 and at 15-sec intervals in well MW05. In each well, the automatic water level readings were recorded as the height of groundwater in the well above the pressure sensor. In well MW09, the pressure sensor was installed approximately 1.4 ft above the pump intake. In wells MW05 and MW10, the pressure sensors were installed approximately 1.2 ft above the pump intakes. The results are summarized in Appendix H, Figures H.1 and H.2 (for pumping of well MW09), Figures H.3 and H.4 (for pumping of well MW05), and Figures H.5 and H.6 (for pumping of well MW10).

Downhole pressure sensors and data loggers (Instrumentation Northwest, Inc., Model PT2X^{TM}) were also employed at all observation wells adjacent to the pumping well to identify potential drawdown responses. Water level readings started approximately 18 hr prior to the beginning of pumping, at 5-min intervals, and were continued throughout the step testing program. The distances of the observation wells from the corresponding pumping well are in Table 3.7.

To facilitate interpretation of the monitoring well data, a barometric pressure sensor-data logger was placed at the site (near well MW09) on November 23. This data logger was programmed to collect measurements of the local atmospheric pressure, at 15-min intervals, throughout the testing program.

The continuously measured water levels at observation wells and the barometric pressure measurements are illustrated in Appendix H, Figures H.7 and H.8. The detailed report of step pumping test results is in Supplement 6 (on CD).

3.8 Constant-Rate Pumping Test Data

Constant-rate pumping tests were conducted to obtain quantitative estimates of (1) aquifer hydraulic parameters (transmissivity and hydraulic conductivity), (2) sustainable groundwater extraction rates, and (3) the potential ROI associated with pumping at selected well

locations in groundwater-bearing Zones 1 and 2. These data were generated to facilitate evaluation of potential corrective action technologies for the restoration of Zone 1 or Zone 2.

3.8.1 Constant-Rate Pumping Test at Zone 1 Well MW05, February 2010

The pumping capacity of Zone 1 well MW05 could not be fully explored during the step pumping test conducted on November 23-25, 2009, because of the physical configuration of the pumping equipment employed at that time. The potential for greater groundwater (and contaminant) capture in Zone 1 in response to longer-term pumping of well MW05 at a higher rate remained uncertain. A constant-rate pumping test was, therefore, recommended for well MW05 by Argonne and approved by the KDHE (2010b).

The Zone 1 constant-rate pumping test was performed on February 22-24, 2010, with well MW02 representing the closest observation point to pumping well MW05 (Table 3.8, Figure 2.11). Testing was carried out in accordance with the procedures in Addendum 3 to the *Final Work Plan* (Argonne 2008a) and in the *Master Work Plan* (Argonne 2002), except that two short-term pumping events (instead of a single 24-hr test) were conducted because of rapid groundwater drawdown at MW05. The revised testing program was discussed with the KDHE project manager (C. Carey) at the Hanover site on February 23, 2010, and was conducted with the KDHE's verbal approval. The testing activities were as follows:

- *Pre-test pumping*. On February 22, 2010, the pump in well MW05 was briefly operated (less than 1 hr) to establish initial settings for the electronic pump controller and flow metering valve being used for the proposed constant-rate testing of this well. The pumping was started at a rate of 1.71-1.75 gpm, as estimated on the basis of the previous step pumping test, but was reduced to 1.57 gpm and then 1.43 gpm in response to the levels of drawdown observed in well MW05 at each rate. The pre-test pumping was completed after 55 min, and the well was allowed to recover overnight. The results suggested a target flow rate of approximately 1.3-1.4 gpm for the constant-rate pumping test. Data collected in this pumping episode are summarized in Appendix I, Table I.1 and Figure I.1.

- *Pumping test 1.* The first pumping test began at 10:01 on February 23 at a target flow rate of 1.3-1.4 gpm. The actual time-weighted average rate achieved during the test was 1.37 gpm. A relatively steady decline in the water level was observed for the first 70 min, from approximately 1 ft to 2.4 ft of drawdown. At that point, rapid drawdown was encountered, and the water level quickly reached the maximum recordable drawdown (3.76 ft) after 86 min (Appendix I, Table I.2 and Figure I.2). The test had to be terminated after 91 min. The maximum drawdown recorded at observation well MW02 was less than 0.1 ft (Appendix I, Figure I.3). Water level recovery after the termination of pumping was monitored continuously in wells MW05 and MW02. By 208 min after termination (at 15:00), the observed water level had recovered to within approximately 0.1 ft of the initial static position in MW05 and had recovered by approximately 0.03 ft in well MW02 (Appendix I, Figures I.4 and I.5).

- *Pumping test 2.* An additional attempt at constant-rate pumping of well MW05 began at 15:03 on February 23, at the lower rate of approximately 1.2 gpm, with the verbal approval of the KDHE. As observed in Test 1, a relatively steady drawdown (1-2 ft) was maintained through 169 min of pumping. Rapid drawdown then occurred again, and the limit was quickly reached (drawdown of 3.76 ft) after 187 min (Appendix I, Table I.3, Figure I.6). The pumping was terminated after 189 min. A maximum corresponding drawdown of approximately 0.13 ft was observed in MW02 (Appendix I, Figure I.7). Recoveries in both MW02 and MW05 were monitored for 14 hr and 20 min after the end of pumping. The results of this pumping episode and the subsequent recovery for wells MW05 and MW02 are in Appendix I (Figures I.8 and I.9).

The detailed report of the MW05 constant-rate pumping experiments is presented in Supplement 7 (on CD). Included are the complete test data sets for wells MW05 and MW02.

Groundwater level variations in the network of existing Zone 1 monitoring wells near MW05 (MW01, MW04, MW06-MW13) were also monitored continuously throughout the MW05 pumping events by using self-contained pressure sensors and data loggers (Instrumentation Northwest, Inc., Model PT2X^{TM}). The distance from each observation well to

the pumping well is listed in Table 3.8. All of the water level data recorded in the pumping events are in Supplement 7 (on CD).

The results of the preceding step pumping tests (Section 3.7) strongly suggested that many of the Zone 1 monitoring wells show groundwater level responses related to fluctuations in the local barometric pressure, commonly termed *barometric efficiency* (BE). To provide a basis for quantitative evaluation of potential BE responses in the Zone 1 monitoring well network, coincident measurements of the local atmospheric pressure and ambient groundwater levels in monitoring wells MW01, MW02, and MW04-MW13 (Figure 2.11) were collected, at 1-hr intervals, during the 6-day period preceding the MW05 pumping (from February 16 to February 22). Barometric pressure readings were obtained by using an absolute-pressure sensor-data logger placed at the site near MW09. The data from this monitoring (in the detailed report in Supplement 7) were used as a basis for correction of the water level variations observed in these wells during the MW05 constant-rate pumping events.

3.8.2 Constant-Rate Pumping Test at Zone 2 Well MW44, March 2010

The results of slug testing at six monitoring wells installed in groundwater-bearing Zone 2 (Section 3.6) suggested that Zone 2 might exhibit higher hydraulic conductivity values than the overlying Zone 1. To evaluate quantitatively the potential groundwater-producing capacity of Zone 2, a 24-hr constant-rate pumping test in this unit was recommended by the CCC/USDA and approved by the KDHE (2010d).

Well MW44Z2 is located at a relatively central position along the water-bearing Zone 2 migration pathway, as the pathway is currently defined. Well MW44Z2 appeared to offer the best opportunity for evaluation of the potential for groundwater extraction from Zone 2 as a means to (1) establish hydraulic control preventing groundwater contaminants from migrating downgradient and (2) possibly capture the existing contamination in Zone 2. In addition, pumping at location of well MW44Z2 could facilitate monitoring for the possible influence of induced drawdown effects in Zone 2, in both the upgradient and downgradient directions.

Well MW44Z2 was therefore selected as the producing well for this constant-rate pumping test. All monitoring wells installed in Zone 2 were used as observation wells

(Figure 2.12). The testing was conducted on March 17-20, 2010. Activities during this period included a brief step-drawdown test, followed by a 24-hr constant-rate pumping test.

3.8.2.1 Pre-Test Pumping

On March 17, 2010, the pump in well MW44Z2 was operated for approximately 3 hr to (1) test the functioning of the pumping equipment and installed sensors, (2) provide initial data on the pumping capacity of the well, and (3) determine target settings for the electronic pump controller and flow metering valve to be used for the planned constant-rate test. This pumping took the form of a step-drawdown test. Pumping began at a rate of 0.53 gpm and then increased progressively to 2.13 gpm in five steps at 30-min intervals. The pre-test pumping was completed after 179 min, and the well was allowed to recover overnight. The maximum drawdown achieved at the rate of 2.13 gpm was approximately 4.0 ft. A target flow rate of 2 gpm was suggested for the constant-rate pumping test, through combined consideration of the pumping capacity and the sizes of the pumping well and the pump. The testing results are summarized in Appendix J, Table J.1 and Figures J.1-J.2.

A detailed report of the MW44Z2 constant-rate pumping test, including the complete test data sets for pumping well MW44Z2 and the nearest observation well (MW45Z2), is presented in Supplement 8 (on CD).

3.8.2.2 24-Hour Pumping Test

The 24-hr pumping test began at 10:15 on March 18, 2010, at a target flow rate of 2 gpm, with a variation of 1.95-2.02 gpm (Appendix J, Table J.2 and Figure J.3). A relatively rapid decline in the water level was observed in the pumping well (MW44Z2) for the first 60 min, reaching approximately 3.5 ft of drawdown. During the last 8 hr of the test, the increase in drawdown at MW44Z2 was minimal (< 0.1 ft), suggesting an approximately steady-state condition (Appendix J, Figure J.3). The 24-hr pumping test was completed at 10:15 on March 19. By that time, the maximum drawdown was approximately 4.0 ft in pumping well MW44Z2.

After termination of pumping, water level recovery was monitored continuously. The water level in MW44Z2 recovered to within approximately 0.1 ft of the initial static position in

6 hr after termination (Appendix J, Figure J.4). In response to the pumping at MW44Z2, the water level in MW45Z2 (the nearest observation well to MW44Z2, at a distance of 263 ft) increased slightly (by 0.13 ft) in the first 8 hr and then declined steadily to 0.05 ft below the initial water level over the remaining 16 hr (Appendix J, Table J.2 and Figure J.5). A small but distinct drawdown response (approximately 0.13 ft) was identified, however, at well MW45Z2 after correction of the field observations for the effects of barometric pressure variations during the pumping period (see below). The complete data logger records for MW44Z2 and MW45Z2 for this pumping event are included in Supplement 8 (on CD).

In addition to the nearest observation well (MW45Z2), the groundwater levels in the other four monitoring wells installed in Zone 2 (MW48Z2-MW51Z2) were also monitored continuously during the MW44Z2 constant-rate pumping and recovery periods, through use of self-contained pressure sensor-data loggers (Instrumentation Northwest, Inc., Model PT2X^{TM}). The distances of these observation wells from the pumping well are listed in Table 3.9. The data loggers in these wells were programmed to take measurements at intervals that varied with elapsed time during the well MW44Z2 pumping period, for efficient documentation of water level variations throughout the testing. The details are in Supplement 8 (on CD).

To facilitate the evaluation of potential BE responses in the Zone 2 monitoring wells, measurements of the local atmospheric pressure were collected, at 10-min intervals, throughout the MW44Z2 constant-rate pumping and recovery periods. The barometric readings were obtained by using an absolute-pressure sensor-data logger placed at the site near well MW09. All readings are in Supplement 8 (on CD).

To identify any potential local background trends in groundwater level, the ambient water levels were monitored at MW44Z2, MW45Z2, and MW48Z2-MW51Z2 from March 1 to March 13 (at 4-hr intervals), and the levels in these wells and the local barometric pressure were recorded from March 13 to March 17 (immediately prior to the pumping test) at 1-hr intervals. The ambient background water levels and barometric pressure measurements are shown in Appendix J, Figures J.6-J.7. The records collected on March 13-17 are in Supplement 8 (on CD).

3.9 Soil Vapor and Indoor Air Sampling Data

A number of sampling events for VI investigation were implemented according to the VI investigation processes and methods presented in Section 2. The analytical results for all soil vapor and indoor air samples are summarized chronologically by location in Appendix K, Table K.1. Complete data are in Supplement 9 (on CD). The sections below provide details for each major sampling event.

3.9.1 Initial Sampling Data for Nine Residences at and near the Former CCC/USDA Property, February and March 2009

The initial upward VI investigation started at the residential area (nine residences) near and on the former CCC/USDA property. On the basis of the 2007 indoor air results for homes in the area, three residences (413 E. Kensington St., 400 E. Kensington St., and 400 N. East St.; Figure 1.6) were selected for sampling in winter 2009. Soil vapor or air samples for VOCs and radon analyses were collected from sub-slab, basement, and first-floor spaces on February 2-4, 2009. After a potential for upward VI was demonstrated, indoor air sampling was conducted in six additional residences on March 12-13, 2009. All sampling activities were conducted in accordance with procedures specified in *Supplemental VI Work Plan* (Argonne 2008b) and its Addendum 1 and in compliance with Kansas guidance (KDHE 2007b). This initial VI evaluation was under the direction of a nationally recognized VI specialist, Dr. Blayne Hartman (Hartman Environmental Geoscience, Solana Beach, California).

The detailed sampling procedure for each residence in this initial sampling (February 2-4, and March 12-13, 2009) was as follows:

- *Residence survey before sampling.* Approximately two days prior to sample collection, each home was surveyed to identify any products known to potentially contain carbon tetrachloride or chloroform. The identified products were then removed if permitted. Records/forms documenting the survey are in Supplement 9 (on CD).

- *Air sampling.* Indoor air samples were collected in Summa canisters, individually certified clean, for a period of 24 hr. Canisters were placed on the first floor and in the basement of each residence, in a location of common

occupancy (as allowed by the residents) but away from heating system registers. To determine ambient air quality at the site, one ambient outdoor air sample was collected for each sampling event in an upwind location, away from obvious sources of VOCs and over the same collection period as the indoor air samples. Meteorological conditions were noted and recorded. These records are also in Supplement 9 (on CD).

- *Sub-slab soil vapor sampling*. Sub-slab vapor sampling was conducted after completion of the indoor air sampling in February and March 2009 to eliminate potential interference from soil vapor. To install a sampling probe, a small-diameter hole (< 1 in.) was drilled through the slab to allow insertion of a small-diameter tube filled with 1 in. of sand to cover the tip. The hole was then sealed to the surface with bentonite, and the tubing was purged to remove residual air. A soil vapor sample was withdrawn through the probe with a syringe. The sample was transferred to a small-volume canister (approximately 400 cm^3). After sampling was complete, the sub-slab sampling probe was covered with a container filled with carbon dioxide, and soil vapor from the tubing was tested to verify that no leakage had occurred through the sampling probe. No leakage was identified for any sub-slab sample. Sampling records are in Supplement 9 (on CD).

Indoor air samples were analyzed for VOCs by Calscience Environmental Laboratories, Inc., Garden Grove, California, according to EPA method TO-15, with a detection limit of 1.5 $\mu g/m^3$. Sub-slab soil vapor samples were shipped to H&P Mobile Geochemistry, Inc., Carlsbad, California, and analyzed for carbon tetrachloride and chloroform by EPA Method TO-15, with a detection level of 5.0 $\mu g/m^3$. This value is below the most stringent risk-based standard for these compounds in sub-slab samples. Analytical results are in Table 3.10.

To generate multiple lines of evidence of VI to indoor air, samples were also collected and analyzed for radon as a potential natural tracer of upward soil gas emissions and a surrogate for determining a foundation-specific attenuation factor for each residence. Separate sub-slab soil vapor and basement air samples, collected according to a procedure similar to that discussed above, were stored in small-volume canisters and used for this purpose. All samples were analyzed for radon by scintillation counting at the University of Southern California, Los Angeles, California. Results are in Table 3.10.

3.9.2 On-Site Screening Data, March-April 2009

On-site screening for soil gas, sub-slab vapor, and indoor air was conducted on March 23-April 9, 2009, in areas where off-site groundwater contamination had been identified in Zone 1 and Zone 2 (Figures 2.14-2.15). The on-site screening began with the soil gas survey. Soil gas samples were collected at the following locations if access was permitted (Figure 2.14):

1. North, west, and south sides of homes on the north side of E. Elm Street.

2. North and west sides of homes on the south side of E. Elm Street.

3. East, north, and south sides of homes near Hanover Street.

4. Additional locations on the south side of the Kloppenberg Senior Center and at the northeastern corner of the intersection of E. North Street and Highland Street.

Sampling probes for the soil gas survey were installed by using a Geoprobe unit to push a 1.25-in.-diameter rod to the targeted sampling depth, typically at an average depth of 8 ft BGL (equivalent to the foundation depths of the structures). Teflon tubing was inserted and attached with an adaptor to the bottom probe rod. After purging of the gas probe, a soil gas sample was collected with a syringe and transferred via a three-way valve to a Tedlar bag for on-site analysis in the field laboratory. A leakage test was also conducted by using carbon dioxide as described for sub-slab sampling (Section 3.9.1). All soil gas samples were analyzed on-site for carbon tetrachloride by modified EPA Method 8021 (on a gas chromatograph with electron capture detection [GC-ECD]), at a reporting limit of 6 $\mu g/m^3$. The analytical results are in Table 3.11.

Only sub-slab soil vapor sampling and indoor air grab sampling were performed after the soil gas survey was terminated, because soil gas results earlier in the sampling event had shown little correlation with corresponding sub-slab and indoor air values. All sub-slab and indoor air samples were collected according to a procedure similar to that discussed in Section 3.9.1, except that these samples were stored in Tedlar bags for direct analysis in the field laboratory. Access was allowed for sampling in 49 residences within or near the edge of identified groundwater contamination in Zone 1 and Zone 2 (Figure 2.15). All sub-slab vapor and indoor air samples were analyzed on-site for carbon tetrachloride by modified EPA method 8021 (GC-ECD). For

confirmation, a few samples were transferred to canisters and analyzed by an off-site laboratory, H&P Mobile Geochemistry, with EPA Method TO-15. All results are in Table 3.12.

3.9.3 Sampling Data for Monitoring during the Summer and Winter Seasons, August 2009 and January 2010

On the basis of the results from (1) on-site screening of 49 homes in the areas of identified Zone 1 and Zone 2 contamination (Section 3.9.2) and (2) vapor/air sampling at 9 residences on and near the former CCC/USDA property (Section 3.9.1), 16 homes were selected for further summertime monitoring. In addition, one residence that had previously been inaccessible was also sampled. Indoor air sampling at these 17 homes was conducted on August 12-13, 2009, in accordance with Addendum 2 to the *Supplemental VI Work Plan* (Argonne 2008b). Air samples were collected for a period of 24 hr in the basement and on the first floor of each home by using certified-clean Summa canisters. All samples were analyzed for carbon tetrachloride and chloroform by TestAmerica Laboratories, Inc., South Burlington, Vermont, with EPA Method TO-15. Results are in Table 3.13.

At the KDHE's request, wintertime indoor air samples were also collected at 15 of the 17 homes in this group on January 25-26, 2010. Two of the homes were inaccessible during the January sampling. The VOCs sampling was performed according to Addendum 3 to the *Supplemental VI Work Plan* (Argonne 2008b) and followed the procedure used for the August 12-13, 2009, sampling at these locations (paragraph above). These samples were analyzed for carbon tetrachloride and chloroform by TestAmerica with EPA Method TO-15. The analytical results are in Table 3.14.

In view of the historically elevated radon values in this portion of Washington County, the CCC/USDA offered radon testing to residents whose homes were being tested for carbon tetrachloride in January 2010. Radon test kits obtained from the Washington County offices were placed in the basements of participating homes. The kits were retrieved after 3-4 days and sent to Air Chek, Inc., Mills River North Carolina (http://www.radon.com/) for analysis through National Radon Program Services at Kansas State University, Manhattan, Kansas. The results of the radon testing were reported to the residents along with the results of the indoor air sampling for carbon tetrachloride, in letters from the KDHE Bureau of Environmental Remediation. The results are included in Table 3.14.

The extent of groundwater contamination in Zone 2, delineated on the basis of results obtained from the Zones 2-4 investigation in October 2009, suggested that nine residences lie within an area that is less than 100 ft laterally and 40 ft vertically from the Zone 2 contamination (Figure 2.16). Indoor air sampling at these nine homes was conducted in accordance with Addendum 3 on February 24-25, 2010. The samples were collected and analyzed for both VOCs and radon, as in the January event. Results are in Table 3.15.

3.9.4 Sampling Data for the Hanover Public School and St. John's School, February 2010

To address residents' concerns, indoor air sampling was performed on February 22-25, 2010, at the Hanover public school and St. John's School facilities in accordance with Addendum 4 to the *Supplemental VI Work Plan* (Argonne 2008b) and as approved by the KDHE (2010c). Screening indoor air samples were collected initially in 49 classrooms, cafeterias, bathrooms, gyms, locker rooms, shops, and offices in the public school facility and in 26 comparable locations in the adjacent St. John's School. On-site screening was conducted by a nationally recognized VI specialist, Dr. Blayne Hartman (Hartman Environmental Geoscience, Solana Beach, California) by modified EPA Method 8021 (a GC-ECD method) at a reporting limit of 1.5 $\mu g/m^3$. The results are in Table 3.16.

The on-site screening process allowed selection of specific locations within the schools for further testing. On the basis of the results of the screening analyses, two sets of certified-clean Summa canisters were deployed in each school. One canister was used to collect an air sample through the evening of February 22 in the kindergarten/day care classroom at each facility. After these evening canisters had been retrieved, another set of canisters was set to collect air samples representative of indoor air conditions through the 8-hr school day. An air sample canister was set outside each school to measure background values of carbon tetrachloride and chloroform that might be present in the ambient outdoor air. All Summa canister samples were analyzed for carbon tetrachloride and chloroform by the independent TestAmerica Laboratories with EPA Method TO-15 at detection limits of 1.3 $\mu g/m^3$ for carbon tetrachloride and 0.98 $\mu g/m^3$ for chloroform. The KDHE project manager (C. Carey) was present during the sampling event; he placed duplicate Summa canisters in each school for independent verification of the sample results. Analytical results are in Table 3.16.

Radon kits acquired from the Washington County offices, Washington, Kansas, were placed in each classroom, office, library, cafeteria, gym, etc. in each school and associated public

school outbuildings housing classrooms and shops. Although radon sampling was not required by the KDHE, the CCC/USDA offered this testing and analysis to the schools because of the previous detections in Hanover, at levels exceeding EPA and KDHE action levels, and because of the sample population (i.e., children). The radon kits were analyzed through National Radon Program Services at Kansas State University, Manhattan, Kansas. Analytical results are in Table 3.16.

3.9.5 Sampling Data for Five Residences with Mitigation Systems

After initial evaluation of the on-site screening and indoor air sampling results generated in early 2009, mitigation was recommended by the CCC/USDA for three residences (Figure 3.1) and was implemented with KDHE (2009g) approval. On behalf of the CCC/USDA, EnviroGroup Limited, Lawrence, Kansas, installed a VI mitigation system for each home on August 25-27, 2009, as described in Supplement 10. The mitigation systems were tested after 30 days to ensure that the systems were performing as designed. To further assess the performance of the mitigation systems, indoor air samples were collected in the basements and first-floor spaces of these homes during the sampling event of January 25-26, 2010, as discussed in Section 3.9.3 and in Addendum 3 to the *Supplemental VI Work Plan* (Argonne 2008b). Samples were analyzed for carbon tetrachloride, chloroform, and radon. Results are in Table 3.17.

Two additional homes were identified for mitigation in April 2010, on the basis of results from a series of sampling events (the most recent being in winter 2010). With the approval of the KDHE (2010e), EnviroGroup, Limited, installed a VI mitigation system for each home on May 12-13, 2010, as described in Supplement 11. The mitigation systems were tested after 30 days to ensure that the systems were performing as designed. In conjunction with a second performance assessment, indoor air samples will be collected in the basements and first-floor spaces of these homes in January-February 2011.

3.10 Land Survey Data

The exact locations of field activities are required to provide horizontal and vertical control for stratigraphic correlation, water level measurement, hydrogeologic mapping, and contaminant delineation in soil and groundwater. All investigative boring locations, all existing

monitoring points, and most of the private wells were surveyed by licensed professional surveyors of Schwab-Eaton, P.A., Manhattan, Kansas. The results are in Appendix L, Table L.1.

3.11 Results of Quality Control Activities

The QA/QC procedures for sample collection, handling, and analysis are described in detail in the *Master Work Plan* (Argonne 2002), the *Final Work Plan* (Argonne 2008a), and the *Supplemental VI Work Plan* (Argonne 2008b). Evaluation of the organic analytical data was consistent with EPA (1994) guidelines.

A detailed report of quality control activities supporting the analytical data generated during the site characterization and vapor intrusion investigations is on CD in Supplement 12. Significant findings are discussed below.

3.11.1 Quality Control for Organic Analyses of Soil and Groundwater Samples

Sample collection and handling activities were monitored by the documentation of samples as they were collected and the use of chain-of-custody forms and custody seals to ensure sample integrity during the handling and shipment of samples for analysis. The QA/QC samples collected included field blanks, equipment rinsates, and trip blanks. Field replicate samples were collected, and samples were selected for duplicate analysis as a measure of analytical precision.

- Field blanks were collected to represent waters from the Hanover public water supply that were used during equipment decontamination. Carbon tetrachloride was not detected in the field blanks. Chloroform, a by-product of water chlorination, was detected at a trace concentration (1.1 µg/L).

- An equipment rinsate collected to monitor decontamination procedures for reusable sampling equipment contained neither carbon tetrachloride or chloroform, indicating that cross-contamination of groundwater samples did not occur during sample collection.

- Trip blanks were prepared and included in shipments of soil or water samples for organic analysis as an indicator of cross-contamination during shipment. The trip blanks did not contain carbon tetrachloride or chloroform.

- As an indicator of the consistency of the sampling methodology followed and to provide a measure of analytical precision, replicate soil and groundwater samples were collected. In addition, samples were selected by the AGEM Laboratory for duplicate organic analysis. Selected samples were submitted for verification organic analysis at a secondary laboratory.

- During the field investigations to characterize the extent of groundwater contamination, numerous groundwater samples were collected as field evaluation samples, including some collected prior to completion of monitoring wells or prior to development of monitoring wells. Such samples are considered non-representative of site conditions. These samples were collected and submitted for overnight analysis to aid in evaluation of site contamination during the field effort. Following well completion and development, each well was later sampled to provide quantitative data for determination of contaminant distribution.

Vertical-profile subsurface soil sampling was conducted at 39 locations, from which 206 soil samples (and 24 additional field replicate samples) were collected. Soil samples were quick-frozen on dry ice as they were collected. The subsurface soils were analyzed at the AGEM Laboratory for VOCs, including carbon tetrachloride and chloroform, by using a modification of EPA Method 8260B (a purge-and-trap method), as referenced in SW-846 (EPA 1998), to achieve a quantitation limit of 10 µg/kg. At the laboratory, the VOCs present in each soil sample were extracted with methanol from the sample matrix. For the purge-and-trap soil analyses, an aliquot of the methanol extract was purged, and the volatile species were transferred to a sorbent tube. After purging, the sorbent tube was heated and backflushed with an inert gas to desorb the components into the GC-MS system.

Groundwater sampling was conducted at 70 locations, including 19 private wells, 5 monitoring wells installed during an investigation of an unrelated contaminated site (Bill's Service Station), and 54 of the monitoring wells established during the current investigation. In total, 110 groundwater samples (and 7 additional field replicate samples) were collected for

organic analysis at the AGEM Laboratory by EPA Method 524.2 (EPA 1995) to achieve a quantitation limit of 1.0 µg/L. Water samples shipped to the AGEM Laboratory were analyzed by the purge-and-trap method with a GC-MS system. For these analyses, VOCs present in the groundwater sample were extracted (purged) from the sample matrix by bubbling an inert gas through the sample. The purged components were trapped in a sorbent tube. After the purging, the sorbent tube was heated and backflushed with an inert gas to desorb the components into the GC-MS system.

Samples submitted to the AGEM Laboratory for organic analysis were analyzed in 59 sample delivery groups. For both the soil and water analyses, the compounds eluting from the GC column were identified by retention time and by comparison with reference library spectra. The concentration of each component was calculated by comparison of the MS response for the quantitation ion to corresponding calibration curves, the responses for internal standards, or both. The QA/QC procedures followed included analysis of instrument calibration check standards, the analysis of laboratory blanks, monitoring of surrogate spike recovery, and duplicate laboratory analyses. Significant results include the following:

- Samples shipped to the AGEM Laboratory were received with custody seals intact and at the appropriate temperature. All samples were analyzed within required holding times.

- Carbon tetrachloride and chloroform, contaminants of concern in the investigation, were not detected in laboratory method blanks analyzed with the samples.

- For each sample delivery group, analytical instrument calibration was monitored by the analysis of calibration check standards. The concentrations of calibration check standards measured in all groups were within the acceptable range of ±20%.

- Surrogate standard determinations were performed on samples and blanks by using surrogate spike compounds fluorobenzene, 1,4-dichlorobenzene-d_4, and bromofluorobenzene. The surrogate recoveries were within the specified range of 80-120% for all samples in either the initial analysis or a successful reanalysis.

- Dual analysis of soil and groundwater samples at the AGEM Laboratory was conducted as a measure of consistency in the sampling and analytical methodologies. This was accomplished through the analysis of replicate samples submitted to the laboratory or duplicate analysis of samples selected by the laboratory.

The soil and groundwater analytical data from the AGEM Laboratory are acceptable for quantitative determination of contaminant distribution.

3.11.2 Quality Control for Organic Analyses of Sub-Slab and Air Samples

During the VI investigation, a total of 333 sub-slab, indoor air, and ambient air samples were collected first to identify the investigation area at risk for vapor intrusion, then to test specific residences in the area identified as being at risk, and subsequently to monitor residences where carbon tetrachloride or chloroform (the fumigant compound of interest and its primary degradation product, respectively) were known to be present. Analyses were conducted as follows:

- For grab samples of indoor air collected in glass syringes and sub-slab grab samples collected in Tedlar bags, on-site analysis for carbon tetrachloride was conducted by using Method 8021, with reporting limits of 1.5 $\mu g/m^3$ for indoor air samples and 6 $\mu g/m^3$ for sub-slab samples. On-site analysis and subsequent data review were performed by Dr. Blayne Hartman.

- For 24-hr indoor air samples, off-site laboratory analysis for carbon tetrachloride and chloroform was conducted by Calscience Environmental Laboratories, Inc., Garden Grove, California, by EPA Method TO-15 on a GC-MS system in the selected ion monitoring (SIM) acquisition mode, with a reporting limit of 1.5 $\mu g/m^3$.

- For indoor air samples, off-site laboratory analysis for carbon tetrachloride and chloroform was conducted by H&P Mobile Geochemistry, Inc., Carlsbad, California, by EPA Method TO-15 on a GC-MS system, with a reporting limit of 1.5 $\mu g/m^3$.

- For sub-slab-samples, off-site laboratory analysis for carbon tetrachloride and chloroform was conducted by H&P by EPA Method TO-15 on a GC-MS system, with a reporting limit of 5 µg/m^3.

- For spilt samples collected by the KDHE, off-site laboratory analysis for carbon tetrachloride and chloroform was conducted by Pace Analytical Services, Inc., Lenexa, Kansas, by Method TO-15, with reporting limits of 1.7 µg/m^3 for carbon tetrachloride and 1.5 µg/m^3 for chloroform.

- Most of the samples were analyzed at TestAmerica Laboratories, Inc., South Burlington, Vermont, by EPA Method TO-15, to provide quantitative measures of contaminant concentrations at method detection limits of 1.3 µg/m^3 for carbon tetrachloride and 0.98 µg/m^3 for chloroform.

For each sample delivery group, the responses for target analytes in initial calibration standards and subsequent calibration checks met the 30% relative standard deviation criterion. Acceptable recoveries of target analytes were met for analyses of laboratory control samples. Method blanks and ambient air samples were free of carbon tetrachloride and chloroform contamination.

3.11.3 Quality Control for Organic Analyses of Vegetation Samples

Vegetation sampling was conducted during the 2009-2010 investigation to provide data supporting an evaluation of phytoremediation as a potential corrective action technology.

A total of 342 vegetation samples (branch and leaf tissues from 171 existing mature trees and bushes across the investigation area) were analyzed for carbon tetrachloride and chloroform at the AGEM Laboratory by a modification of the protocol in EPA Method 5021 (headspace analysis on a GC-ECD system) to achieve the low detection limits required. Typical detection limits achieved were 0.3 µg/kg for carbon tetrachloride and 0.75 µg/kg for chloroform. A limitation for the chloroform analysis is the presence of chloroform (at very low concentrations) in the methanol solvent used in standard preparation. An 11-point calibration of the GC system was established on the basis of the mass of known quantities of carbon tetrachloride and

chloroform in the range 0.125-4.000 ng. The analytical data are acceptable for qualitative determination of contaminant distribution.

3.11.4 Quality Control for Tritium Analyses of Groundwater Samples

Selected groundwater samples were analyzed for tritium at the University of Miami Tritium Laboratory in Miami, Florida. Tritium concentrations reported were based on the U.S. National Institute of Science and Technology tritium water standard #4926, as measured on September 3, 1961, and again on September 3, 1978, with a half-life of 12.43 yr. Concentrations were reported in tritium units (TU), equivalent to 3.193 picocuries per kilogram of water. Because counting efficiency and background concentration are different for each instrument, the reported concentrations were corrected for cosmic intensity and gas pressure. Typical efficiencies are equivalent to 1 count per minute (cpm) per TU. Background is about 0.3 cpm, known to ±0.02 cpm. Relative percent difference values for duplicate analyses are typically < 5%.

3.11.5 Quality Control for Radon Analyses of Indoor Air Samples

Vapor intrusion samples were initially analyzed for radon as a tracer compound for evaluation of an attenuation factor in migration of contaminants from the subsurface to indoor air. Because of the inherent serious health risks associated with radon levels detected above the EPA action level of 4.0 pCi/L, 84 samples collected across the investigation area were subsequently analyzed for radon. Included were 79 indoor air samples, 2 samples collected in crawl spaces, and 3 sub-slab samples.

Of the indoor air samples, 78 were analyzed for radon by Air Chek, Inc., Naples, North Carolina, and 6 were analyzed at the University of Southern California. Radon is measured by scintillation counting of the gamma rays produced by the daughters of radon, through use of sodium iodide detectors. Sodium iodide detectors, which are very efficient for the detection of gamma rays, have a very high background from naturally occurring radiation. The difference between the average background and total sample counts is the net or actual sample count. Since the background is a statistically varying number, the average is only an estimate of the background at any one time. Air Chek uses heavily shielded detectors to minimize the average background and its variation and thereby maximize accuracy.

3.12 Waste Characterization, Handling, and Disposal

In accordance with the procedures defined in the *Master Work Plan* (Argonne 2002) for handling and disposal of potentially contaminated investigation-derived waste, waste soil and water generated during the 2009-2010 investigations were containerized on-site, sampled, and subsequently transported off-site for disposal.

Samples of waste soil generated during drilling of monitoring wells were analyzed for VOCs by the KDHE-certified laboratory Pace Analytical Services, Lenexa, Kansas, by EPA Method 8260. Carbon tetrachloride and chloroform, contaminants of concern in the investigations, were not detected. With KDHE approval, the waste soil was subsequently taken to the Rolling Meadows Landfill, Topeka, Kansas, for disposal.

Samples of wastewater generated during development and sampling of monitoring wells and during subsequent pump tests were analyzed by Pace Analytical Services for VOCs with EPA Method 5030B/8260 and for nitrate/nitrite nitrogen with EPA Method 353.2. The maximum concentrations of carbon tetrachloride and chloroform detected in periodic sampling of accumulated wastewaters during the multiple phases of investigation were 32.7 µg/L and 7.8 µg/L, respectively. The maximum concentration of nitrate/nitrite nitrogen detected was 6.9 mg/L. With KDHE approval, the wastewaters were taken to the Sabetha publicly owned treatment works, Sabetha, Kansas, for disposal.

Documentation for handling and disposal of investigation-derived waste during the 2009-2010 investigations is in Supplement 13.

TABLE 3.1 Analytical results from the AGEM Laboratory for vertical-profile soil samples collected during the 2009-2010 investigation at Hanover.

				Concentration (µg/kg)	
Location	Sample	Sample Date	Depth (ft)	Carbon Tetrachloride	Chloroform
TI01	HATI01-S-27920	1/13/09	2	ND[a]	ND
	HATI01-S-27921	1/13/09	6	ND	ND
	HATI01-S-27922	1/13/09	10	ND	ND
	HATI01-S-27923	1/13/09	14	ND	ND
	HATI01-S-27924	1/13/09	18	3.0 J[b]	ND
	HATI01-S-27925	1/13/09	21	30	ND
TI02	HATI02-S-27926	1/13/09	2	ND	ND
	HATI02-S-27927	1/13/09	6	ND	ND
	HATI02-S-27928	1/13/09	10	ND	ND
	HATI02-S-27929	1/13/09	14	ND	ND
TI03	HATI03-S-27930	1/13/09	2	ND	ND
	HATI03-S-27931	1/13/09	6	ND	ND
	HATI03-S-27932	1/13/09	10	ND	ND
TI04	HATI04-S-27933	1/13/09	2	ND	ND
	HATI04-S-27934	1/13/09	6	ND	ND
	HATI04-S-27935	1/13/09	10	ND	ND
TI05	HATI05-S-27950	1/13/09	2	ND	ND
	HATI05-S-27951	1/13/09	6	ND	ND
	HATI05-S-27952	1/13/09	10	ND	ND
	HATI05-S-27953	1/13/09	14	ND	ND
	HATI05-S-27954	1/13/09	18	ND	ND
	HATI05-S-28059	1/15/09	20.5	6.9 J	ND
TI06	HATI06-S-27936	1/13/09	2	ND	ND
	HATI06-S-27937	1/13/09	6	ND	ND
	HATI06-S-27938	1/13/09	10	ND	ND
	HATI06-S-27939	1/13/09	14	ND	ND
TI07	HATI07-S-27940	1/13/09	2	ND	ND
	HATI07-S-27941	1/13/09	6	ND	ND
	HATI07-S-27942	1/13/09	10	ND	ND
TI08	HATI08-S-27943	1/13/09	2	ND	ND
	HATI08-S-27944	1/13/09	6	ND	ND
	HATI08-S-27945	1/13/09	10	ND	ND
	HATI08-S-27946	1/13/09	14	ND	ND
	HATI08-S-27947	1/13/09	18	ND	ND
	HATI08-S-27948	1/13/09	22	ND	ND
TI09	HATI09-S-27956	1/13/09	2	ND	ND
	HATI09-S-27957	1/13/09	6	ND	ND
	HATI09-S-28058	1/15/09	9	ND	ND
TI10	HATI10-S-27997	1/14/09	2	ND	ND
	HATI10-S-27998	1/14/09	6	ND	ND
	HATI10-S-28000	1/14/09	10	ND	ND

TABLE 3.1 (Cont.)

				Concentration (µg/kg)	
Location	Sample	Sample Date	Depth (ft)	Carbon Tetrachloride	Chloroform
TI11	HATI11-S-27970	1/13/09	2	ND	ND
	HATI11-S-27971	1/13/09	6	ND	ND
	HATI11-S-27973	1/13/09	10	ND	ND
	HATI11-S-27974	1/13/09	14	ND	ND
TI12	HATI12-S-27976	1/14/09	2	ND	ND
	HATI12-S-27977	1/14/09	6	ND	ND
	HATI12-S-27979	1/14/09	10	ND	ND
TI13	HATI13-S-27980	1/14/09	2	ND	ND
	HATI13-S-27982	1/14/09	6	ND	ND
	HATI13-S-27983	1/14/09	10	ND	ND
	HATI13-S-27985	1/14/09	14	ND	ND
TI14	HATI14-S-27958	1/14/09	2	ND	ND
	HATI14-S-27959	1/14/09	6	ND	ND
	HATI14-S-27960	1/14/09	10	ND	ND
TI15	HATI15-S-27986	1/14/09	2	ND	ND
	HATI15-S-27988	1/14/09	6	ND	ND
	HATI15-S-27989	1/14/09	10	ND	ND
	HATI15-S-27990	1/14/09	13	ND	ND
TI16	HATI16-S-27991	1/14/09	2	ND	ND
	HATI16-S-27992	1/14/09	6	ND	ND
	HATI16-S-27994	1/14/09	10	ND	ND
	HATI16-S-27995	1/14/09	14	ND	ND
TI17	HATI17-S-28031	1/14/09	2	ND	ND
	HATI17-S-28032	1/14/09	6	ND	ND
	HATI17-S-28033	1/14/09	10	ND	ND
TI18	HATI18-S-28013	1/14/09	2	ND	ND
	HATI18-S-28014	1/14/09	6	ND	ND
	HATI18-S-28016	1/14/09	10	ND	ND
	HATI18-S-28017	1/14/09	14	ND	ND
TI19	HATI19-S-28001	1/14/09	2	ND	ND
	HATI19-S-28002	1/14/09	6	ND	ND
	HATI19-S-28003	1/14/09	10	ND	ND
	HATI19-S-28005	1/14/09	14	ND	ND
TI20	HATI20-S-28006	1/14/09	2	ND	ND
	HATI20-S-28007	1/14/09	6	ND	ND
	HATI20-S-28009	1/14/09	10	ND	ND
	HATI20-S-28010	1/14/09	14	ND	ND
	HATI20-S-28011	1/14/09	18	ND	ND
	HATI20-S-28012	1/14/09	22	ND	ND
TI21	HATI21-S-28018	1/14/09	2	ND	ND
	HATI21-S-28019	1/14/09	6	ND	ND
	HATI21-S-28020	1/14/09	10	ND	ND
	HATI21-S-28021	1/14/09	14	ND	ND

TABLE 3.1 (Cont.)

Location	Sample	Sample Date	Depth (ft)	Concentration (µg/kg) Carbon Tetrachloride	Chloroform
TI21	HATI21-S-28022	1/14/09	18	ND	ND
	HATI21-S-28024	1/14/09	21	ND	ND
TI22	HATI22-S-27961	1/14/09	2	ND	ND
	HATI22-S-27962	1/14/09	6	ND	ND
	HATI22-S-27963	1/14/09	10	ND	ND
	HATI22-S-27964	1/14/09	14	ND	ND
	HATI22-S-27965	1/14/09	18	ND	ND
	HATI22-S-27966	1/14/09	21	ND	ND
TI23	HATI23-S-28025	1/14/09	2	ND	ND
	HATI23-S-28026	1/14/09	6	ND	ND
	HATI23-S-28027	1/14/09	10	ND	ND
	HATI23-S-28028	1/14/09	14	ND	ND
	HATI23-S-28029	1/14/09	18	ND	ND
TI23	HATI23-S-28030	1/14/09	22	ND	ND
TI24	HATI24-S-27967	1/14/09	2	ND	ND
	HATI24-S-27968	1/14/09	6	ND	ND
	HATI24-S-27969	1/14/09	10	ND	ND
	HATI24-S-28050	1/14/09	14	ND	ND
	HATI24-S-28051	1/14/09	18	ND	ND
	HATI24-S-28052	1/14/09	22	ND	ND
	HATI24-S-28054	1/14/09	25	ND	ND
TI25	HATI25-S-28035	1/14/09	2	ND	ND
	HATI25-S-28036	1/14/09	6	ND	ND
	HATI25-S-28038	1/14/09	10	ND	ND
TI26	HATI26-S-28045	1/31/09	14	ND	ND
	HATI26-S-28046	1/31/09	18	8.3 J	ND
	HATI26-S-28047	1/31/09	22	14	ND
	HATI26-S-28048	1/31/09	26	ND	ND
	HATI26-S-28049	1/31/09	30	ND	ND
	HATI26-S-28130	1/31/09	34	ND	ND
TI28	HATI28-S-28160	2/4/09	12	ND	ND
	HATI28-S-28161	2/4/09	16	ND	ND
	HATI28-S-28162	2/4/09	20	ND	ND
TI30[c]	HATI30-S-28230	2/28/09	2	ND	ND
	HATI30-S-28231	2/28/09	6	ND	ND
	HATI30-S-28232	2/28/09	10	ND	ND
	HATI30-S-28233	2/28/09	14	4.6 J	ND
	HATI30-S-28234	2/28/09	18	15	ND
	HATI30-S-28235	2/28/09	21	17	3.9 J
	HATI30-S-28236	2/28/09	26	ND	ND
	HATI30-S-28238	2/28/09	30	ND	ND
	HATI30-S-28239	2/28/09	34	ND	ND
	HATI30-S-28240	2/28/09	38	ND	ND
	HATI30-S-28241	2/28/09	42	ND	ND
	HATI30-S-28242	2/28/09	46	ND	ND
	HATI30-S-28243	2/28/09	50	ND	ND

TABLE 3.1 (Cont.)

Location	Sample	Sample Date	Depth (ft)	Concentration (µg/kg) Carbon Tetrachloride	Chloroform
TI30	HATI30-S-28244	2/28/09	54	ND	ND
	HATI30-S-28245	2/28/09	58	ND	ND
	HATI30-S-28246	2/28/09	62	ND	ND
	HATI30-S-28248	2/28/09	66	ND	ND
MW01	HAMW01-S-28061	1/28/09	22	2.5 J	ND
	HAMW01-S-28062	1/28/09	27	7.9 J	ND
	HAMW01-S-28063	1/28/09	32	ND	ND
	HAMW01-S-28064	1/28/09	36	ND	ND
	HAMW01-S-28066	1/28/09	40	ND	ND
	HAMW01-S-28067	1/28/09	44	ND	ND
	HAMW01-S-28068	1/28/09	48	ND	ND
	HAMW01-S-28069	1/28/09	53	ND	ND
	HAMW01-S-28070	1/28/09	58	ND	ND
	HAMW01-S-28071	1/28/09	63	ND	ND
MW02	HAMW02-S-28080	1/29/09	25	ND	ND
	HAMW02-S-28081	1/29/09	29	35	ND
	HAMW02-S-28082	1/29/09	33	27	44
MW03	HAMW03-S-28090	1/29/09	18	ND	ND
	HAMW03-S-28091	1/29/09	22	ND	ND
	HAMW03-S-28092	1/29/09	26	19	ND
	HAMW03-S-28093	1/29/09	30	ND	ND
	HAMW03-S-28094	1/30/09	34	ND	ND
	HAMW03-S-28095	1/30/09	38	ND	ND
	HAMW03-S-28096	1/30/09	42	ND	ND
	HAMW03-S-28098	1/30/09	46	ND	ND
	HAMW03-S-28099	1/30/09	50	ND	ND
	HAMW03-S-28100	1/30/09	54	ND	ND
	HAMW03-S-28101	1/30/09	58	ND	ND
	HAMW03-S-28102	1/30/09	62	ND	ND
	HAMW03-S-28103	1/30/09	66	ND	ND
	HAMW03-S-28104	1/30/09	70	ND	ND
	HAMW03-S-28105	1/30/09	74	ND	ND
	HAMW03-S-28106	1/30/09	78	ND	ND
	HAMW03-S-28107	1/30/09	82	ND	ND
	HAMW03-S-28108	1/30/09	86	ND	ND
	HAMW03-S-28109	1/30/09	90	ND	ND
	HAMW03-S-28110	1/30/09	94	ND	ND
	HAMW03-S-28111	1/30/09	98	ND	ND
MW04	HAMW04-S-28126	1/31/09	25	ND	ND
	HAMW04-S-28127	1/31/09	29	ND	ND
	HAMW04-S-28128	1/31/09	33	ND	ND
MW05	HAMW05-S-28073	1/31/09	14	ND	ND
	HAMW05-S-28074	1/31/09	18	ND	ND
	HAMW05-S-28075	1/31/09	22	14	ND
	HAMW05-S-28076	1/31/09	26	17	ND
MW07	HAMW07-S-28135	2/2/09	19	ND	ND
	HAMW07-S-28136	2/2/09	23	ND	ND

TABLE 3.1 (Cont.)

Location	Sample	Sample Date	Depth (ft)	Concentration (µg/kg) Carbon Tetrachloride	Chloroform
MW07	HAMW07-S-28137	2/2/09	27	ND	ND
	HAMW07-S-28138	2/2/09	31	ND	ND
MW08	HAMW08-S-28139	2/2/09	4	ND	ND
	HAMW08-S-28140	2/2/09	8	ND	ND
	HAMW08-S-28141	2/2/09	12	ND	ND
	HAMW08-S-28142	2/2/09	16	3.0 J	ND
	HAMW08-S-28143	2/2/09	20	ND	ND
	HAMW08-S-28144	2/2/09	24	ND	ND
	HAMW08-S-28145	2/2/09	28	ND	ND
	HAMW08-S-28147	2/2/09	32	ND	ND
MW09[c]	HAMW09-S-28155	2/2/09	19.5	18	ND
MW12	HAMW12-S-28163	2/4/09	16	ND	ND
	HAMW12-S-28164	2/4/09	20	4.6 J	ND
	HAMW12-S-28165	2/4/09	24	7.3 J	ND
	HAMW12-S-28166	2/4/09	30	ND	ND
	HAMW12-S-28167	2/4/09	34	ND	ND
MW34	HAMW34-S-28249	3/3/09	14	ND	ND
	HAMW34-S-28220	3/3/09	18	ND	ND
	HAMW34-S-28221	3/3/09	21	ND	ND
	HAMW34-S-28223	3/3/09	26	ND	ND
	HAMW34-S-28224	3/3/09	29	ND	ND
MW45	HAMW45-S-28228	3/27/09	2	ND	ND
	HAMW45-S-28229	3/27/09	6	ND	ND
	HAMW45-S-28291	3/27/09	10	ND	ND
	HAMW45-S-28292	3/27/09	14	ND	ND
	HAMW45-S-28293	3/27/09	18	ND	ND
	HAMW45-S-28294	3/27/09	22	ND	ND
	HAMW45-S-28295	3/27/09	26	ND	ND
	HAMW45-S-28296	3/27/09	30	ND	ND

[a] ND, not detected at an instrument detection limit of 1.0 µg/kg.

[b] Qualifier J indicates an estimated concentration below the purge-and-trap quantitation limit of 10 µg/kg.

[c] Locations T130 and MW09 are adjacent.

TABLE 3.2 Analytical results from the AGEM Laboratory for groundwater samples collected during the 2009-2010 investigations at Hanover.

					Concentration (µg/L)		
Location	Type[a]	Sample	Sample Date	Depth (ft)	Carbon Tetrachloride	Chloroform	Methylene Chloride
Private wells							
A. Bruna	LG	HABRUNA-W-28201	2/24/09	40-60	ND[b]	ND	ND
B. Bruna	LG	HABBRUNA-W-28264	2/28/09	–	5.1	1.1	ND
Ted Bruna	LG	HATEBRUNA-W-28255	2/26/09	65-75	ND	ND	ND
Tony Bruna	LG	HATOBRUNA-W-28256	2/26/09	62-82	ND	ND	ND
Farmers Co-op	NU	HAFACOOP-W-28199	2/24/09	20-40	ND	ND	ND
T. Koss	LG	HATKOSS-W-28212	2/25/09	34-54	ND	ND	ND
J. Kruse	D	HAJKRUSE-W-28211	2/25/09	48-58	ND	ND	ND
D. Martin	LG	HADMARTIN-W-28265	2/28/09	28-48	7.8	1.0	ND
D. Minge[c]	LG	HADMINGE-W-28191	2/23/09	32-52	ND	9.0	ND
K. Prell	NU	HAKPRELL-W-28203	2/24/09	42-52	ND	ND	ND
R. Schlabach (E)[d]	NU	HARSCHLA(E)-W-28208	2/25/09	41	ND	ND	ND
R. Schlabach (W)	LG	HARSCHLA(W)-W-28207	2/25/09	75-80	1.5	ND	ND
J. Schmidt	LG	HAJSCHMIDT-W-28202	2/24/09	42-52	ND	ND	ND
R. Warren[e]	LG	HARWARREN-W-28257	2/26/09	40-60	ND	ND	ND
USD223	SAF	HAUSD223-W-28200	2/24/09	55-75	ND	ND	ND
J. Meier	LG	HAJOEMEIER-W-28841	6/22/09	50[f]	ND	ND	ND
K. Jueneman	LG	HAJUENEMAN-W-28842	6/22/09	–	3.6	ND	ND
D. Bruna (home)	IRR	HADBRUNAHOME-W-28843	6/22/09	45[f]	ND	3.2	ND
D. Bruna (irrigation)	IRR	HADBRUNAIRR-W-28844	6/22/09	45[f]	ND	ND	ND
Bill's Service Center monitoring wells							
BSMW09	MW	HABSMW9-W-28158	2/23/09	35-45	ND	ND	ND
BSMW10	MW	HABSMW10-W-28159	2/23/09	30-50	ND	1.3	ND
BSMW12	MW	HABSMW12-W-28179	2/23/09	35-50	ND	ND	ND
BSMW14	MW	HABSMW14-W-28182	2/23/09	35-50	ND	8.6	ND
BSMW15	MW	HABSMW15-W-28183	2/23/09	30-45	ND	ND	ND

TABLE 3.2 (Cont.)

Location	Type[a]	Sample	Sample Date	Depth (ft)	Concentration (µg/L) Carbon Tetrachloride	Chloroform	Methylene Chloride
CCC/USDA monitoring wells							
MW01	MW	HAMW01-W-28184	2/23/09	30-35	387	7.6	ND
MW02	MW	HAMW02-W-28185	2/23/09	31-36	548	11	ND
MW03	MW	Dry			–	–	–
MW04	MW	HAMW04-W-28186	2/23/09	30-35	10	6.4	ND
MW05	MW	HAMW05-W-28187	2/23/09	24-29	488	6.1	ND
MW06	MW	HAMW06-W-28188	2/24/09	24-29	99	11	ND
MW07	MW	HAMW07-W-28189	2/24/09	30-35	92	6.7	ND
MW08	MW	HAMW08-W-28192	2/24/09	30-35	4.2	ND	ND
MW09	MW	HAMW09-W-28193	2/23/09	18-23	395	2.9	ND
MW10	MW	HAMW10-W-28194	2/23/09	26-31	31	3.9	ND
MW11	MW	HAMW11-W-28195	2/23/09	15-20	617	13	ND
MW12	MW	HAMW12-W-28196	2/24/09	25-35	111	18	ND
MW13	MW	HAMW13-W-28197	2/23/09	15-20	376	8.7	ND
MW14	MW	HAMW14-W-28252	2/26/09	14-19	45	7.1	ND
MW15	MW	HAMW15-W-28209	2/25/09	14-19	ND	ND	ND
MW16	MW	HAMW16-W-28251	2/26/09	15-25	5.8	2.1	ND
MW17	MW	HAMW17-W-28271	3/2/09	13-23	11	3.3	ND
MW18	MW	HAMW18-W-28268	3/2/09	15-25	3.4	4.2	ND
MW19	MW	HAMW19-W-28305	3/12/09	16-26	21	2.9	ND
MW20	MW	HAMW20-W-28275	3/2/09	18-28	17	3.0	ND
MW21	MW	HAMW21-W-28304	3/12/09	15-25	112	8.4	ND
MW22	MW	HAMW22-W-28302	3/12/09	18-28	ND	5.5	ND
MW23	MW	HAMW23-W-28261	2/28/09	19-29	3.4	ND	ND
MW24	MW	HAMW24-W-28274	3/2/09	13-18	ND	9.5	ND
MW25	MW	Dry	–	15-25	–	–	–
MW26	MW	Dry	–	10-25	–	–	–
MW27	MW	HAMW27-W-28269	3/2/09	20-30	1.0	15	ND
MW28	MW	HAMW28-W-28285	3/4/09	19-29	173	8.8	ND
MW29	MW	HAMW29-W-28286	3/4/09	19-29	179	10	ND
MW30	MW	HAMW30-W-28303	3/12/09	9-19	4.2	2.7	ND
MW31	MW	HAMW31-W-28276	3/3/09	10-20	ND	1.0	ND
MW32	MW	HAMW32-W-28847	8/13/09	10-25	64	2.8	ND
MW33	MW	HAMW33-W-28848	8/13/09	11-26	127	5.7	ND
MW34	MW	HAMW34-W-28284	3/4/09	17-27	1.3	ND	ND

TABLE 3.2 (Cont.)

Location	Type[a]	Sample	Sample Date	Depth (ft)	Concentration (µg/L) Carbon Tetrachloride	Chloroform	Methylene Chloride
CCC/USDA monitoring wells (cont.)							
MW35	MW	HAMW35-W-28287	3/4/09	15-25	ND	11	ND
MW36	MW	HAMW36-W-28282	3/4/09	14-24	ND	ND	ND
MW37	MW	HAMW37-W-28307	3/19/09	15-30	19	2.5	ND
MW38	MW	HAMW38-W-28300	3/6/09	18-28	37	6.7	ND
MW39	MW	Dry	–	12-22	–	–	–
MW40	MW	HAMW40-W-28301	3/6/09	20-30	130	14	ND
MW41	MW	Dry	–	6-26	–	–	–
MW42	MW	Dry	–	8-28	–	–	–
MW43	MW	Dry	–	11-26	–	–	–
MW44Z2	MW	HAMW44-W-28821	3/28/09	30-40	11	1.0	ND
MW44Z3	MW	HAMW44Z3-W-28319	10/16/09	55-75	ND	ND	ND
MW44Z4	MW	HAMW44Z4-W-28320	10/16/09	97-107	ND	5.7	ND
MW45Z2	MW	HAMW45S-W-28824	3/29/09	20-30	28	3.0	ND
MW45Z3	MW	HAMW45Z3-W-28321	10/16/09	50-60	ND	ND	ND
MW45Z4	MW	HAMW45Z4-W-28322	10/16/09	83-93	ND	ND	ND
MW46	MW	HAMW46-W-28828	3/30/09	20-30	ND	ND	ND
MW47	MW	HAMW47-W-28829	4/1/09	15-30	ND	2.0	ND
MW48	BH	HAMW48-W-30322	10/5/09	28-29	ND	ND	ND
MW48Z2	MW	HAMW48Z2-W-28311	10/8/09	49-59	ND	ND	ND
MW48Z3	MW	HAMW48Z3-W-28312	10/8/09	83-93	ND	ND	ND
MW48Z4	MW	HAMW48Z4-W-28313	10/8/09	111-121	ND	ND	ND
MW49Z2	MW	HAMW49Z2-W-30324	10/10/09	55-65	35	4.4	ND
MW49Z3	MW	HAMW49Z3-W-30325	10/10/09	105-115	ND	1.1	ND
MW49Z4	MW	HAMW49Z4-W-30326	10/10/09	132-142	ND	1.0	ND
MW50Z2	MW	HAMW50Z2-W-30328	10/13/09	55-65	9.7	1.4	ND
MW50Z3	MW	HAMW50Z3-W-30329	10/13/09	89-99	ND	ND	ND
MW50Z4	MW	HAMW50Z4-W-30330	10/13/09	118-128	ND	ND	ND

TABLE 3.2 (Cont.)

Location	Type[a]	Sample	Sample Date	Depth (ft)	Concentration (µg/L) Carbon Tetrachloride	Chloroform	Methylene Chloride
CCC/USDA monitoring wells (cont.)							
MW51Z2	MW	HAMW51Z2-W-28315	10/16/09	56-66	ND	ND	ND
MW51Z3	MW	HAMW51Z3-W-28316	10/16/09	104-114	ND	ND	ND
MW51Z4	MW	HAMW51Z4-W-28317	10/16/09	126-136	ND	ND	ND

[a] Well types: BH, borehole; D, domestic; IRR, irrigation; LG, lawn and garden; MW, monitoring well; NU, not in use; SAF, school athletic field.

[b] ND, not detected at the purge-and-trap method quantitation limit of 1.0 µg/L.

[c] The two wells located at the Dennis Minge residence were surveyed as "primary" and "secondary." The "primary" well, used as a lawn and garden well, was sampled. The "secondary" well is capped and is not used.

[d] Open cased pit; well out of order.

[e] The two wells located at the Roger Warren residence were surveyed as "Warren" and "Warren South." The well surveyed as "Warren" is not used and was not sampled. The well surveyed as "Warren South" is used and was sampled.

[f] Approximate total depth provided by well owner.

TABLE 3.3 Analytical results for tritium samples collected at Hanover.[a]

Location	Sample	Screen Interval (ft BGL)	Concentration (TU)	Sample Date and Time	
MW05	HAMW45S-W-28837	24-29	5.70 ± 0.19	3/29/09	10:15
MW44Z2	HAMW44S-W-28838	30-40	3.68 ± 0.12	4/1/09	13:16
MW44Z4	HAMW44D-W-28835	97-107	0.12 ± 0.09	4/24/09	10:30
MW45Z2	HAMW45S-W-28826	20-30	4.42 ± 0.15	3/29/09	10:30
MW45Z3	HAMW45M-W-28831	50-60	3.05 ± 0.10	4/3/09	14:08
MW45Z3	HAMW45M-W-28839	50-60	2.72 ± 0.09	4/9/09	16:00
MW45Z4	HAMW45D-W-28827	83-93	3.60± 0.12	3/29/09	11:45
MW46	HAMW46-W-28840	19-29	4.25 ± 0.14	3/29/09	9:35

[a] Analysis at University of Miami Tritium Laboratory. Shipped to the laboratory at 13:43 on July 6, 2009, with chain-of-custody form 3085.

TABLE 3.4 Analytical results from TestAmerica Laboratories for nitrate in groundwater at Hanover.

Location	Sample	Sample Date	Depth (ft)	Nitrate as Nitrogen (mg/L)
MW05	HAMW05-W-30333	6/17/10	24-29	6.3
MW09	HAMW09-W-30334	6/17/10	18-23	3.9
MW10	HAMW10-W-30335	6/17/10	26-31	4.7
MW11	HAMW11-W-30336	6/17/10	15-20	3.7
MW13	HAMW13-W-30337	6/17/10	15-20	2.6
MW28	HAMW28-W-30338	6/17/10	19-29	3.0
MW29	HAMW29-W-30339	6/17/10	19-29	1.8
MW44Z2	HAMW44Z2-W-30340	6/17/10	30-40	2.5
MW45Z2	HAMW45Z2-W-30341	6/17/10	20-30	4.1
MW48Z2	HAMW48Z2-W-30342	6/17/10	49-59	0.5
MW49Z2	HAMW49Z2-W-30343	6/17/10	55-65	< 0.10
MW51Z2	HAMW51Z2-W-30344	6/17/10	56-66	0.3

TABLE 3.5 Construction data for monitoring wells installed during the 2009-2010 investigations at Hanover.

Well	KDHE Registration Number	Depth (ft BGL) Well Depth	Screen Interval	Filter Pack	Casing Diameter (in.)	Completion Date
Groundwater-bearing Zone 1						
MW01	424048	35	30-35	28-37	2	1/28/09
MW02	424049	36	31-36	29-36	2	1/29/09
MW03	–	–	–	–	–	–
MW04	424050	35	30-35	28-35	2	1/31/09
MW05	424051	29	24-29	22-29	2	1/31/09
MW06	424052	29	24-29	23-31	2	1/31/09
MW07	424053	35	30-35	28.5-35	2	2/2/09
MW08	424054	35	30-35	28-35	2	2/2/09
MW09	424055	23	18-23	16.5-23	2	2/2/09
MW10	424056	31	26-31	24.5-31	2	2/3/09
MW11	424057	20	15-20	13-20	2	2/3/09
MW12	424058	35	25-35	23-35	2	2/4/09
MW13	424059	20	15-20	13-20	2	2/4/09
MW14	424060	19	14-19	12.5-19	2	2/25/09
MW15	424061	19	14-19	12.5-21	2	2/25/09
MW16	424062	25	15-25	13-25	2	2/25/09
MW17	424063	23	13-23	11-23	2	2/25/09
MW18	424064	25	15-25	13-26	2	2/26/09
MW19	424065	26	16-26	14-27	2	2/26/09
MW20	424066	28	18-28	16-30	2	2/26/09
MW21	424067	25	15-25	12-26	2	2/26/09
MW22	424068	25	18-28	16-29	2	2/27/09
MW23	424069	29	19-29	17-30	2	2/27/09
MW24	424070	18	13-18	11-19	2	2/27/09
MW25	424071	25	15-25	13-25	2	3/1/09
MW26	424084	25	10-25	8-27	2	3/1/09
MW27	424085	30	20-30	18-30	2	3/1/09
MW28	424086	29	19-29	17-29	2	3/2/09
MW29	424087	29	19-29	17-30	2	3/2/09
MW30	424088	19	9-19	7-20	2	3/2/09
MW31	424089	20	10-20	8-21	2	3/2/09
MW32	424090	25	10-25	8-26	2	3/3/09
MW33	424091	26	11-26	9-27	2	3/3/09
MW34	424092	27	17-27	15-29	2	3/3/09
MW35	424093	25	15-25	13-25	2	3/3/09
MW36	424094	24	14-24	12-24	2	3/4/09
MW37	424095	30	15-30	13-33	2	3/4/09
MW38	424096	28	18-28	16-29	2	3/4/09
MW39	424097	22	12-22	10-24	2	3/4/09
MW40	424098	30	20-30	18-31	2	3/5/09
MW41	424099	26	6-26	4-27	2	3/5/09
MW42	424100	28	8-28	6-29	2	3/24/09
MW43	424101	26	11-26	9-30	2	3/24/09
MW46	424108	29	19-29	17-30	2	3/29/09
MW47	424109	30	15-30	13-30	2	3/29/09

TABLE 3.5 (Cont.)

Well	KDHE Registration Number	Depth (ft BGL) Well Depth	Screen Interval	Filter Pack	Casing Diameter (in.)	Completion Date
Groundwater-bearing Zone 2						
MW44Z2[a]	424104	40	30-40	28-40	2	3/27/09
MW45Z2[a]	424107	30	20-30	18-30	2	3/28/09
MW48Z2	430630	59	49-59	47-59	2.375	9/21/09
MW49Z2	430638	65	55-65	53-65	2.375	10/8/09
MW50Z2	430618	65	55-65	53-65	2.375	10/12/09
MW51Z2	430627	66	56-66	54-66	2.375	10/15/09
Groundwater-bearing Zone 3						
MW44Z3[a]	424103	75	55-75	53-78	1	3/26/09
MW45Z3[a]	424106	60	50-60	48-61	2	3/28/09
MW48Z3	430631	93	83-93	80-93	2.375	9/25/09
MW49Z3	430635	115	105-115	103-115	2.375	10/8/09
MW50Z3	430620	99	89-99	87-99	2.375	10/12/09
MW51Z3	430625	114	104-114	102-114	2.375	10/15/09
Groundwater-bearing Zone 4						
MW44Z4[a]	424102	107	97-107	95-108	1	3/26/09
MW45Z4[a]	424105	93	83-93	81-93	1	3/27/09
MW48Z4	430632	121	111-121	108-121	2.375	9/25/09
MW49Z4	430628	142	132-142	130-142	2.375	10/8/09
MW50Z4	430621	128	118-128	116-128	2.375	10/12/09
MW51Z4	430623	136	126-136	124-136	2.375	10/15/09

[a] Wells at locations MW44 and MW45 were registered with the names MW44S, MW44M, MW44D and MW45S, MW45M, MW45D, respectively. The names in the table are used throughout this report to indicate the water zones in which the individual wells at each location are completed.

TABLE 3.6 Summary of construction data, measured water levels, and testing parameters for monitoring wells in which slug testing was performed in August 2009 (Zone 1) and January 2010 (Zone 2).

Well	Reported Well Depth[a] (ft BGL)	Screened Interval[a] (ft BGL)	Gravel Pack Interval[a] (ft BGL)	Measured Well Depth[b] (ft TOC)	Static Water Level[c] (ft TOC)	Height of Water Column in Casing[c] (ft)	Height of Water above Screen[c] (ft)	Slug Used for Testing[d]	Number of Data Sets Collected
Groundwater-bearing Zone 1									
MW01	35	30–35	28–35	34.53	22.18	12.35	7.36	5 ft	4
MW02	36	31–36	29–36	35.59	26.81	8.78	3.78	2 x 3 ft	4
MW04	35	30–35	28–35	34.48	24.34	10.14	5.20	5 ft	4
MW05	29	24–29	22–29	28.45	23.25	5.20	0.20	3 ft	4
MW06	29	24–29	22–29	28.30	18.07	10.23	5.54	5 ft	1
MW07	35	30–35	30–35	34.60	24.25	10.35	5.53	5 ft	2
MW09	23	18–23	18–23	22.57	18.42	4.15	–0.67	3 ft	4
MW10	31	26–31	26–31	30.30	22.07	8.23	3.63	5 ft	4
MW11	20	15–20	15–20	19.60	16.61	2.99	–1.85	3 ft	4
MW12	35	25–35	25–35	34.59	20.45	14.14	4.32	5 ft	1
MW13	20	15–20	15–20	19.74	14.63	5.11	0.15	3 ft	4
MW16	25	15–25	15–25	24.45	16.96	7.55	–2.45	2 x 3 ft	2
MW18	25	15–25	15–25	24.90	16.92	7.98	–2.57	5 ft	3
MW20	28	18–28	18–28	27.64	21.49	6.15	–3.85	5 ft	1
MW21	25	15–25	15–25	24.41	16.74	7.67	–2.27	5 ft	1
MW28	29	19–29	19–29	28.40	22.91	5.49	–4.42	3 ft	4
MW29	29	19–29	19–29	28.22	24.06	4.16	–4.61	3 ft	4
MW34	27	17–27	17–27	26.66	17.08	9.58	–0.40	5 ft	3
MW37	30	15–30	15–30	29.68	19.90	9.78	–5.20	5 ft	1
MW38	28	18–28	18–28	27.83	23.82	4.01	–6.03	3 ft	1
Groundwater-bearing Zone 2									
MW44Z2	40	30-40	28-40	39.34	28.76	10.58	0.74	5 ft	4
MW45Z2	30	20-30	18-30	29.22	20.84	8.73	–1.27	5 ft	4
MW48Z2	59	49-59	47-59	58.90[e]	48.47	10.21	0.21	5 ft	4
MW49Z2	65	55-65	53-65	65.06[e]	56.65	8.20	–1.80	5 ft	4
MW50Z2	65	55-65	53-65	64.33[e]	54.92	9.08	–0.92	5 ft	4
MW51Z2	66	56-66	54-66	64.25[e]	53.23	12.35	2.35	5 ft	4

[a] Well construction parameters as reported in KDHE WWC-5 Water Well Records.

[b] Well depth from top of casing, measured on August 10-14, 2009, except as indicated otherwise.

[c] Water levels determined from measurements on August 1-14, 2009, for Zone 1 and on January 26-27, 2010, for Zone 2.

[d] Physical slugs were constructed from 1-in.-diameter, sealed, sand-filled PVC tubing. Table shows the length of slug[s] and the number used.

[e] Well depth from top of casing, measured on November 2, 2009.

TABLE 3.7 Configuration of pumping wells and associated observation wells in the step pumping tests for Zone 1, November 2009.

Pumping Well	Observation Well	Distance to Pumping Well (ft)
MW09	MW02	184
	MW05	215
	MW11	126
	MW13	216
	MW34	137
MW05	MW01	234
	MW02	107
	MW09	215
	MW11	215
	MW12	218
	MW13	272
MW10	MW01	173
	MW04	227
	MW07	165
	MW18	237
	MW19	198
	MW20	274

TABLE 3.8 Configuration of pumping well MW05 and associated observation wells in the constant-rate pumping test for Zone 1, February 2010.

Pumping Well	Observation Well	Distance to Pumping Well (ft)
MW05	MW02[a]	107
	MW01	234
	MW04	387
	MW06	379
	MW07	377
	MW08	363
	MW09	215
	MW10	382
	MW11	215
	MW12	218
	MW13	272

[a] Primary observation well.

TABLE 3.9 Configuration of pumping well MW44Z2 and associated observation wells in the constant-rate pumping test for Zone 2, March 2010.

Pumping Well	Observation Well	Distance to Pumping Well (ft)
MW44Z2	MW45Z2[a]	263
	MW48Z2	1,237
	MW49Z2	1,019
	MW50Z2	402
	MW51Z2	726

[a] Primary observation well.

TABLE 3.10 Analytical results for sub-slab and indoor air samples collected at nine residences near and on the former CCC/USDA property, February-March 2009.

Residence Address	Sample Location	Sample Date	Concentration (µg/m^3) Carbon Tetrachloride	Chloroform	Reporting Limit	Laboratory[a]	Radon[b] (pCi/L)
	First floor	2/4/09	17	ND[c]	1.5	CEL	–
400 N. East St.	Basement	2/4/09	26	ND	1.5	CEL	5.2
	Sub-slab	2/4/09	62,000	140	–	H&P	2616
	First floor	2/4/09	11	ND	1.5	CEL	–
413 E. Kensington St.	Basement	2/4/09	16	ND	1.5	CEL	9.4
	Sub-slab	2/4/09	350	ND	5.0	H&P	2500
	First floor	2/4/09	ND	ND	1.5	CEL	–
400 E. Kensington St.	Basement	2/4/09	1.8	ND	1.5	CEL	8
	Sub-slab	2/4/09	130	ND	5.0	H&P	1293
	First floor	3/13/09	ND	ND	1.5	CEL	–
300 Westminster St.	Basement	3/13/09	ND	ND	1.5	CEL	–
	First floor	3/13/09	ND	ND	1.5	CEL	–
297 Westminster St.	Basement	3/13/09	ND	ND	1.5	CEL	–
	First floor	3/13/09	ND	ND	1.5	CEL	–
300 N. Belgrave St.	Basement	3/13/09	ND	ND	1.5	CEL	–
	First floor	3/13/09	2.9	ND	1.5	CEL	–
301 N. Belgrave St.	Basement	3/13/09	4.2	ND	1.5	CEL	–
	First floor	3/13/09	ND	3.6	1.5	CEL	–
298 N. Belgrave St.	Basement	3/13/09	ND	3.4	1.5	CEL	–
	Sub-slab	4/9/09	13	ND	5.0	H&P	
	First floor	3/13/09	2.6	ND	1.5	CEL	–
414 E. Kensington St.	Basement	3/13/09	3.7	ND	1.5	CEL	–
–	Ambient	2/4/09	ND	ND	1.5	CEL	–
–	Ambient	3/13/09	ND	ND	1.5	CEL	–

[a] Laboratory:
CEL indicates analysis for carbon tetrachloride and chloroform at Calscience Environmental Laboratories, Inc., Garden Grove, California, by EPA Method TO-15 on a GC-MS system in the SIM acquisition mode.
H&P indicates analysis for carbon tetrachloride and chloroform by H&P Mobile Geochemistry, Inc., Carlsbad, California, by EPA Method TO-15 on a GC-MS system.

[b] Radon was determined by scintillation counting at the University of Southern California. Samples were collected in small canisters.

[c] ND, not detected at the indicated reporting limit for the respective laboratory.

TABLE 3.11 Results of on-site screening analysis of soil gas samples collected in areas potentially affected by contamination in groundwater Zone 1 and Zone 2, March 2009.

Sample Location	Sample Position	Depth (ft BGL)	Sample Date	Location[a]	Carbon Tetrachloride in Soil Gas (µg/m^3)
North side of East Elm Street					
400 E. Elm	North	14	3/24/09	SV15	ND[b]
	West	14	3/24/09	SV25	16
	South	8	3/24/09	SV24	114
404 E. Elm	North	8	3/25/09	SV29	ND
	West	5	3/24/09	SV16	ND
	South	5	3/24/09	SV14	ND
406 E. Elm	North	8	3/25/09	SV30	ND
	West	8	3/24/09	SV13	ND
	South	8	3/24/09	SV12	ND
408 E. Elm	North	8	3/25/09	SV28	ND
	South	8	3/24/09	SV22	22
412 E. Elm	North	8	3/25/09	SV27	ND
	West	8	3/24/09	SV21	700
	South	8	3/24/09	SV20	ND
500 E. Elm	North	8	3/25/09	SV26	ND
	West	8	3/24/09	SV11	ND
	South	8	3/24/09	SV10	17
504 E. Elm	North	8	3/23/09	SV07	ND
	West	8	3/23/09	SV08	ND
	South	8	3/23/09	SV09	9
508 E. Elm	North	8	3/23/09	SV06	ND
	West	8	3/23/09	SV05	ND
	South	8	3/23/09	SV04	10
512 E. Elm	North	8	3/23/09	SV01	ND
	West	8	3/23/09	SV02	11
	South	8	3/23/09	SV03	ND
South side of East Elm Street					
310 E. Elm	South	8	3/25/09	SV49	ND
315 E. Elm	East	8	3/25/09	SV48	ND
	East	8	3/25/09	SV48 Dup	ND
405 E. Elm	North	8	3/25/09	SV47	ND
409 E. Elm	North	8	3/25/09	SV45	ND
411 E. Elm	North	8	3/25/09	SV44	ND
415 E. Elm	North	8	3/25/09	SV41	ND
	West	8	3/25/09	SV34	ND

TABLE 3.11 (Cont.)

Sample Location	Sample Position	Depth (ft BGL)	Sample Date	Location[a]	Carbon Tetrachloride in Soil Gas (µg/m^3)
South side of East Elm Street (cont.)					
501 E. Elm	North	8	3/25/09	SV43	ND
	North	8	3/25/09	SV43 Dup	ND
	West	8	3/25/09	SV33	ND
505 E. Elm	North	8	3/25/09	SV19	ND
	West	8	3/25/09	SV32	ND
513 E. Elm	North	8	3/25/09	SV46	ND
	West	8	3/25/09	SV31	ND
Along North Street					
Highland and North	NE corner	5	3/25/09	SV17	130
Kloppenberg	South	8	3/25/09	SV18	ND
One residence at former CCC/USDA facility					
400 N. East	East	8	3/25/09	SV60	ND
	North	8	3/25/09	SV61	ND
	West	8	3/25/09	SV62	ND
	South	8	3/25/09	SV63	85
Northwest area					
308 N. Hollenberg	East	8	3/27/09	SV57	ND
	South	8	3/27/09	SV58	ND
309 N. Hanover	East	8	3/26/09	SV55	ND
	North	8	3/26/09	SV54	ND
310 N. Hanover	East	8	3/26/09	SV52	ND
	North	8	3/26/09	SV53	ND

[a] Location designated in the field for the GPS survey of the identified sampling location.

[b] ND, not detected at the method reporting limit of 6 µg/m^3.

TABLE 3.12 Results of on-site screening analyses of sub-slab vapor and indoor air samples collected at homes in areas potentially affected by contamination in groundwater Zone 1 and Zone 2, March-April 2009, with results for confirmation samples analyzed off-site.[a]

				Carbon Tetrachloride in Sub-Slab Vapor and Indoor Air (µg/m^3)		
	Sample	Analysis Date	Analysis Time	On-Site Method 8021[b]	Off-Site Method TO-15[c]	Comments
East Elm Street						
211 E. Elm	First floor	4/9/09	12:32	ND[b]		
	Basement	4/9/09	12:34	ND		
	Garage	4/9/09	12:37	ND		
	Sub-slab (in garage)	4/9/09	12:41	ND[b]		
304 E. Elm	First floor	3/26/09	18:27	ND		
	Basement	3/26/09	18:31	ND		
	Sub-slab	4/7/09	16:42	16		
307 E. Elm	Sub-slab	4/8/09	15:04	ND		
308 E. Elm	First floor	3/26/09	18:15	ND		
	Basement	3/26/09	18:18	ND		
309 E. Elm	First floor	3/26/09	11:16	ND		
	Basement	3/26/09	11:20	1.7		
	Sub-slab	3/27/09	13:10	290		
310 E. Elm	First floor	3/26/09	9:02	ND		
	Basement	3/26/09	9:09	ND		
	Basement	4/7/09	15:51	ND		
	Sub-slab	4/7/09	15:56	ND		
311 E. Elm	First floor	3/26/09	10:04	ND		
	Basement	3/26/09	10:10	1.8		
	Basement	4/8/09	18:06	ND		
	Sub-slab	4/8/09	18:15	2,200		
314 E. Elm	First floor	3/27/09	11:06	ND		
	Basement	3/27/09	11:09	ND		
315 E. Elm	First floor	3/26/09	16:57	ND		
	Basement	3/26/09	17:01	ND		Dirt floor
	Basement	4/7/09	17:09	ND		
	Sub-dirt	4/7/09	17:15	ND		
400 E. Elm	First floor	3/26/09	9:19	ND	1.7	
	Basement	3/26/09	9:23	ND		
	Sub-slab			2,800		
401 E. Elm	First floor	3/26/09	18:48	ND		
	Basement	3/26/09	18:52	ND		
	Sub-slab	4/8/09	11:31	400		
404 E. Elm	First floor	3/26/09	12:09	ND		Crawl space
	Crawl space	4/8/09	15:24	ND		

TABLE 3.12 (Cont.)

	Sample	Analysis Date	Analysis Time	Carbon Tetrachloride in Sub-Slab Vapor and Indoor Air (µg/m^3) On-Site Method 8021[b]	Off-Site Method TO-15[c]	Comments
East Elm Street (cont.)						
405 E. Elm	First floor	3/26/09	19:14	ND	2.6	High ethanol detected
	Basement	3/26/09	19:17	22		
	First floor dup	3/26/09	19:39	ND		
	Basement dup	3/26/09	19:43	19		
	Sub-slab	3/27/09	13:58	2,800		
406 E. Elm	First floor	3/26/09	12:13	ND		
	Basement	3/26/09	12:19	3.0		Partial dirt basement
	Basement	4/7/09	15:27	9.4		
	Sub-slab	4/7/09	15:24	410		
408 E. Elm	First floor	3/26/09	12:37	2.6	7[d]	
	Basement	3/26/09	12:40	2.3		
	Sub-slab	3/27/09	14:07	1,600		
	First floor	4/8/09	16:04	2.7		
	Basement	4/8/09	16:00	6.0		
	Sub-slab	4/7/09	14:49	1,900		
409 E. Elm	First floor	3/26/09	14:47	2.4[e]	1.5	
	Basement	3/26/09	14:52	6.2[e]	ND	
	First floor dup	3/26/09	16:01	ND		
	Basement dup	3/26/09	16:05	2.7		
	Sub-slab	3/27/09	14:29	2,400		
411 E. Elm	First floor	3/25/09	19:00	ND		
	Basement	3/25/09	19:03	ND		
	Basement	4/7/09	14:54	ND		
	Sub-slab	4/7/09	14:57	ND		
412 E. Elm	First floor	4/14/09	–	–	2.1	Collected 4/10/09 in canister
	Sub-slab	4/14/09	–	–	360	Collected 4/10/09 in canister
415 E. Elm	First floor	3/26/09	13:24	ND		
	Basement	3/26/09	13:21	ND		
	Sub-slab	4/7/09	14:27	ND		
500 E. Elm	Basement	4/8/09	17:40	ND		
	Sub-slab	4/8/09	17:44	ND		
501 E. Elm	First floor	3/26/09	13:28	ND		
	Basement	3/26/09	13:32	ND		
	Sub-slab	4/7/09	14:32	ND		
504 E. Elm	First floor	3/26/09	12:24	ND		
	Basement	3/26/09	12:28	ND		
	Basement	4/7/09	15:06	ND		
	Sub-slab	4/7/09	15:01	100	91	
505 E. Elm	First floor	3/26/09	12:51	ND		
	Basement	3/26/09	12:55	ND		

TABLE 3.12 (Cont.)

	Sample	Analysis Date	Analysis Time	Carbon Tetrachloride in Sub-Slab Vapor and Indoor Air (µg/m^3) On-Site Method 8021[b]	Off-Site Method TO-15[c]	Comments
East Elm Street (cont.)						
508 E. Elm	First floor	3/26/09	14:39	ND		
	Basement	3/26/09	14:43	ND		
	Basement	4/7/09	15:11	ND		
	Sub-slab	4/7/09	15:16	51		
509 E. Elm	First floor	3/27/09	11:51	ND		
	Basement	3/27/09	11:55	ND		
513 E. Elm	First floor	3/26/09	12:58	2.1	ND	
	Basement	3/26/09	13:02	ND		
	Sub-slab	3/27/09	14:14	290	260	
North East Street						
210 N. East	Basement #1	3/25/09	18:33	ND		
	Basement #2	3/25/09	18:37	ND		
	Sub-slab	4/8/09	11:36	33		
211 N. East	First floor	4/8/09	12:42	1.6		
	Basement	4/8/09	12:45	2.7		
	Sub-slab	4/7/09	17:52	940		
213 N. East	First floor	3/26/09	10:34	ND		
	Basement	3/26/09	10:38	ND		
	Basement	4/7/09	16:34	ND		
	Sub-slab	4/7/09	16:38	ND		
311 N. East	First floor	3/27/09	9:46	14		Trailer on top of basement
	Basement	3/27/09	9:50	18		
	First floor	4/7/09	16:14	4.3		
	Basement	4/7/09	16:18	9.0		
	Sub-slab	4/7/09	16:28	4500		
East North Street						
204 E. North	First floor	4/9/09	19:12	ND		
	Basement	4/9/09	19:15	ND		
	Sub-slab	4/9/09	19:19	20		
214 E. North	First floor	4/9/09	17:36	ND		
	Basement	4/9/09	17:40	ND		
	Sub-slab	4/9/09	18:32	ND		
312 E. North	First floor	3/26/09	13:55	ND		
	Basement	3/26/09	13:59	ND		
	Basement	4/7/09	18:28	ND		
	Sub-slab	4/7/09	18:32	300		
400 E. North	First floor	3/27/09	12:26	ND		
	Basement	3/27/09	12:19	ND		

TABLE 3.12 (Cont.)

Sample		Analysis Date	Analysis Time	Carbon Tetrachloride in Sub-Slab Vapor and Indoor Air (µg/m^3) On-Site Method 8021[b]	Off-Site Method TO-15[c]	Comments
East North Street (cont.)						
404 E. North	First floor	3/27/09	12:15	ND		
	Basement	3/27/09	12:29	ND		
	Sub-slab	4/8/09	11:46	180	200	
500 E. North	First floor	4/8/09	17:31	ND		
	Basement	4/8/09	17:38	ND		
500 E. North	Sub-slab	4/8/09	18:22	ND		
Kloppenberg parking N		4/8/09	13:57	ND		
Kloppenberg parking S		4/8/09	14:06	ND		
Church parking lot		4/8/09	16:07	ND		
107 Church St	First floor	4/9/09	17:28	ND		
	Basement	4/9/09	17:31	ND		
	Sub-slab	4/9/09	18:29	ND		
Northwestern Area						
309 N. Hanover	Basement	4/7/09	18:06	ND		
	Sub-slab	4/7/09	18:00	7.2		
310 N. Hanover	First floor	4/9/09	16:02	ND		
	Basement	4/9/09	16:06	ND		
	Sub-slab	4/8/09	16:37	64	68	
307 Hollenberg	First floor	4/9/09	14:38	ND		
314 N. Hollenberg	Basement	4/7/09	18:20	ND		
	Sub-slab	4/7/09	18:23	9.1		
Multi-tenant housing east of Highland St.						
Highland Haven #4	Sub-slab	4/9/09	13:55	ND		
Highland Haven #3	Sub-slab	4/9/09	14:05	ND		
Highland Haven #2 north	Sub-slab	4/9/09	14:09	ND		
Highland Haven #2 south	Sub-slab	4/9/09	14:22	ND		
Highland Haven office	Sub-slab	4/9/09	14:19	ND		
Highland Haven #11	Sub-slab	4/9/09	16:42	ND		
Highland Haven #5	Sub-slab	4/9/09	16:49	ND		
Highland Haven #4	Indoor air	4/9/09	14:12	ND		
Highland Haven office	Indoor air	4/9/09	14:15	ND		
Highland Haven #11	Indoor air	4/9/09	16:38	ND		
Highland Haven #5	Indoor air	4/9/09	16:46	ND		

TABLE 3.12 (Cont.)

[a] On-site analyses were performed by Dr. Blayne Hartman, who also reviewed the data. The QA/QC criteria specified in the *Supplemental VI Work Plan* (Argonne 2008b) were met.

[b] Indoor air grab samples from glass syringes and sub-slab samples from Tedlar bags were analyzed on-site by EPA Method 8021. For this method, ND indicates no detection at a limit of 1.5 $\mu g/m^3$ for indoor air samples or 6 $\mu g/m^3$ for sub-slab samples.

[c] Confirmation samples were transferred to canisters and analyzed off-site by Method TO-15 by H&P Mobile Geochemistry. For this method, ND indicates no detection at a limit of 1.5 $\mu g/m^3$.

[d] H&P reported a problem with the sample. Result is questionable.

[e] Possible interferences caused high bias in the results.

TABLE 3.13 Analytical results for indoor air samples collected at 17 selected homes during the summer season, August 2009.

Residence Address	Sample Location	Sample Date	Concentration in Indoor Air ($\mu g/m^3$) Carbon Tetrachloride	Chloroform
400 E. Kensington St.	First floor	8/12/09	1.5	1.2
	Basement	8/12/09	1.8	1.1
301 N. Belgrave St.	First floor	8/12/09	ND[a]	ND
	Basement	8/12/09	ND	ND
414 E. Kensington St.	First floor	8/12/09	1.4	1.7
	Basement	8/12/09	1.5	1.6
309 E. Elm	First floor	8/12/09	3.0	18
	Basement	8/12/09	ND	9.3
311 E. Elm	First floor	8/12/09	1.6	1.4
	Basement	8/12/09	2.3	ND
400 E. Elm	First floor	8/12/09	ND	ND
	Basement	8/12/09	ND	ND
401 E. Elm	First floor	8/12/09	ND	3.5
	Basement	8/12/09	1.6	4.6
405 E. Elm	First floor	8/12/09	2.3	3.3
	Basement	8/12/09	2.9	2.6
406 E. Elm	First floor	8/12/09	1.5	ND
	Basement	8/12/09	4.5	ND
408 E. Elm	First floor	8/12/09	11	ND
	Basement	8/12/09	17	ND
409 E. Elm	First floor	8/12/09	ND	ND
	Basement	8/12/09	1.4	ND
412 E. Elm	First floor	8/12/09	1.9	ND
	Basement	8/12/09	2.8	ND
513 E. Elm	First floor	8/13/09	ND	ND
	Basement	8/13/09	ND	ND
211 N. East	First floor	8/12/09	1.8	ND
	Basement	8/12/09	2.5	ND
312 E. North	First floor	8/12/09	2.0	ND
	Basement	8/12/09	3.2	ND
404 E. North	First floor	8/12/09	1.6	ND
	Basement	8/12/09	1.8	ND
303 N. East	First floor	8/12/09	1.4	3.4
	Basement	8/12/09	1.9	3.3
	Sub-slab	8/12/09	ND	19

[a] ND, not detected at the reporting limit of 1.3 $\mu g/m^3$ for carbon tetrachloride or 0.98 $\mu g/m^3$ for chloroform in analysis at TestAmerica with Method TO-15.

TABLE 3.14 Analytical results for indoor air samples collected at 17 selected homes during the winter season, January 2010.

			Concentration in Indoor Air		
Residence Address	Sample Location	Sample Date	Carbon Tetrachloride (µg/m^3)	Chloroform (µg/m^3)	Radon (pCi/L)
400 E. Kensington St.	First floor	1/26/10	ND[a]	ND	–
	Basement	1/26/10	ND	ND	7.9
301 N. Belgrave St.[b]	First floor	1/26/10	–	–	–
	Basement	1/26/10	–	–	–
					–
414 E. Kensington St.[c]	First floor	1/26/10	–	–	–
	Basement	1/26/10	–	–	–
309 E. Elm	First floor	1/26/10	2.0	1.1	–
	Basement	1/26/10	2.3	ND	16
311 E. Elm	First floor	1/26/10	2.0	1.3	–
	Basement	1/26/10	2.4	ND	7.7
400 E. Elm	First floor	1/26/10	ND	ND	–
	Basement	1/26/10	1.7	ND	4.6
401 E. Elm	First floor	1/26/10	ND	ND	–
	Basement	1/26/10	1.4	ND	9.1
405 E. Elm	First floor	1/26/10	1.9	ND	–
	Basement	1/26/10	4.7	ND	10.4
406 E. Elm	First floor	1/26/10	2.1	ND	–
	Basement	1/26/10	3.9	ND	15.3
	Basement dup	1/26/10	4.0	ND	–
408 E. Elm	First floor	1/26/10	5.9	ND	–
	Basement	1/26/10	6.9	ND	21.8
409 E. Elm	First floor	1/26/10	ND	ND	–
	Basement	1/26/10	ND	ND	3.4
412 E. Elm	First floor	1/26/10	1.6	ND	–
	Basement	1/26/10	1.3	ND	–
513 E. Elm	First floor	1/26/10	ND	ND	–
	Basement	1/26/10	ND	ND	6.8
211 N. East	First floor	1/26/10	ND	ND	–
	Basement	1/26/10	ND	ND	6.3
303 N. East	First floor	1/26/10	ND	ND	–
	Basement	1/26/10	ND	1.0	6.4
312 E. North	First floor	1/26/10	1.5	0.98	–
	Basement	1/26/10	2.1	ND	17.6
404 E. North	First floor	1/26/10	1.3	ND	–
	Basement	1/26/10	1.3	ND	21.3

TABLE 3.14 (Cont.)

[a] ND, not detected at the following analytical reporting limits:

Carbon tetrachloride, analysis by Method TO-15 at TestAmerica:	1.3 µg/m^3
Chloroform, analysis by Method TO-15 at TestAmerica:	0.98 µg/m^3
Radon, analysis through National Radon Program Services at Kansas State University, Manhattan, Kansas:	0.3 pCi/L

[b] Residence not sampled; resident out of town for the winter.

[c] Residence not sampled; illness in family.

[d] Outdoor ambient air sample.

TABLE 3.15 Analytical results for indoor air samples collected at nine homes in the area potentially affected by contamination in groundwater Zone 2, February 2010.

			Concentration in Indoor Air ($\mu g/m^3$)		
Residence Address	Sample Location	Sample Date	Carbon Tetrachloride	Chloroform	Radon (pCi/L)
211 N. Hanover	First floor	2/24/10	ND[a]	ND	–
	Crawl space	2/24/10	ND	ND	2.1
309 N. Hanover	First floor	2/24/10	ND	ND	–
	Basement	2/24/10	ND	ND	3.1
310 N. Hanover	First floor	2/24/10	ND	ND	–
	Basement	2/24/10	ND	ND	11.6
	Basement dup	2/24/10	ND	ND	–
208 N. Hollenberg	First floor	2/24/10	ND	0.98	–
	Basement	2/24/10	ND	ND	4.1
212 N. Hollenberg	First floor	2/24/10	ND	1.7	–
	Basement	2/24/10	ND	ND	9.2
300 N. Hollenberg	First floor	2/24/10	ND	ND	9.8
	Crawl space	2/24/10	ND	ND	17.5
304 N. Hollenberg	First floor	2/24/10	ND	ND	–
	Basement	2/24/10	ND	ND	13.9
308 N. Hollenberg	First floor	2/24/10	ND	ND	–
	Basement	2/24/10	ND	ND	9.8
314 N. Hollenberg	First floor	2/24/10	ND	ND	–
	Basement	2/24/10	ND	ND	27.6
Ambient		2/24/10	ND	ND	–

[a] ND, not detected at the analytical reporting limit of 1.3 $\mu g/m^3$ for carbon tetrachloride, 0.98 $\mu g/m^3$ for chloroform, or 0.3 pCi/L for radon.

TABLE 3.16 Analytical results for indoor air samples collected at the Hanover public school and St. John's School, February 2010.

			Concentration (µg/m^3)			
			On-Site Analysis	Off-Site Analysis		
School	Sample Location	Sample Date	Carbon Tetrachloride	Carbon Tetrachloride	Chloroform	Radon (pCi/L)
Hanover Public School	Kindergarten[a]	2/23/10	ND[b]	ND, ND	2.3, ND	14.2
	Weight room	2/23/10	ND	–	–	1.7
	Math room	2/23/10	ND	–	–	0.6
	Math room	2/23/10	ND	ND	1.7	2.3
	Band room	2/23/10	ND	ND	1.5	4.6
	Grades 3-4	2/23/10	ND	–	–	3.4
	Office	2/23/10	ND	–	–	<0.3
	Office	2/23/10	ND	ND	2.2	1.0
	Grades 1-2	2/23/10	ND	–	–	1.8
	Special ed room	2/23/10	ND	–	–	3.1
	Special ed room	2/23/10	ND	–	–	6.0
	Back counselor room	2/23/10	ND	–	–	5.4
	Front counselor room	2/23/10	ND	–	–	7.0
	Computer room	2/23/10	ND	–	–	2.9
	Computer room	2/23/10	ND	–	–	1.8
	Chemistry	2/23/10	ND	–	–	2.3
	Science	2/23/10	ND	–	–	3.1
	Chem lab	2/23/10	ND	–	–	2.4
	Library	2/23/10	ND	–	–	4.9
	English	2/23/10	ND	–	–	2.5
	History	2/23/10	ND	–	–	1.9
	Grades 5-6	2/23/10	ND	–	–	4.8
	Library	2/23/10	ND	–	–	5.2
	FCCLA classroom	2/23/10	ND	–	–	0.9
	Gym	2/23/10	ND	–	–	3.3
	Art room	2/23/10	ND	–	–	4.8
	Cafeteria	2/23/10	ND	–	–	1.1
	Woodshop 1	2/23/10	ND	–	–	2.1
	Woodshop 2	2/23/10	ND	–	–	2.6
	Woodshop 3	2/23/10	ND	–	–	2.8
	Woodshop 4	2/23/10	ND	–	–	2.7
	Ag shop 1	2/23/10	ND	–	–	2.8
	Ag shop 2	2/23/10	ND	–	–	2.1
	Math	2/23/10	ND	–	–	1.5
	Chemistry	2/23/10	ND	–	–	1.2
	English	2/23/10	ND	–	–	1.3
	Classroom	2/23/10	ND	–	–	0.9
	Ambient air	2/23/10	ND	ND	ND	–
St. John's School	Gym	2/23/10	ND	–	–	2.0
	All purpose room 1	2/23/10	ND	–	–	6.0
	All purpose room 2[a]	2/23/10	ND	ND, ND	ND, ND	3.7
	Kitchen	2/23/10	ND	ND	ND	–
	Northwest room	2/23/10	ND	–	–	1.2
	Northeast room	2/23/10	ND	ND	ND	1.0
	Southwest room	2/23/10	ND	–	–	2.2
	Southeast room	2/23/10	ND	ND	ND	< 0.3
	Northwest room	2/23/10	ND	–	–	0.7
	Northeast room	2/23/10	ND	–	–	1.1
	Office 1	2/23/10	ND	–	–	1.9
	Office 2	2/23/10	ND	–	–	1.1
	Workroom	2/23/10	ND	–	–	1.1
	Library	2/23/10	ND	–	–	1.0
	South room	2/23/10	ND	–	–	0.8
	Ambient air	2/23/10	ND	ND	ND	–

TABLE 3.16 (Cont.)

[a] Two canister samples (8 hr and 24 hr) were collected for VOCs analyses by EPA Method TO-15.

[b] ND, not detected at the following analytical reporting limits:
Carbon tetrachloride, on-site analysis: 1.5 $\mu g/m^3$
Carbon tetrachloride, off-site analysis: 1.3 $\mu g/m^3$
Chloroform, off-site analysis: 0.98 $\mu g/m^3$
Radon: 0.3 pCi/L

TABLE 3.17 Analytical results for indoor air samples collected to evaluate the performance of VI mitigation systems installed at three homes in August 2009 and at two homes in May 2010.

		Before Remediation			With Mitigation		
Residence Address	Sample Location	Carbon Tetrachloride ($\mu g/m^3$)	Chloroform ($\mu g/m^3$)	Radon (pCi/L)	Carbon Tetrachloride ($\mu g/m^3$)	Chloroform ($\mu g/m^3$)	Radon (pCi/L)
311 N. East St.	First floor	14[a]	–	–	ND[b]	ND[b]	–
	Basement	18[a]	–	–	ND[b]	ND[b]	< 0.3[b]
	Sub-slab	4,500[a]	–	–	–	–	–
400 N. East St.	First floor	17[c]	ND[c]	–	ND[b]	ND[b]	–
	Basement	26[c]	ND[c]	5.2[c]	ND[b]	ND[b]	0.7[b]
	Sub-slab	62,000[c]	140[c]	2,616[c]	–	–	–
413 E. Kensington St.	First floor	11[c]	ND[c]	–	ND[b]	ND[b]	–
	Basement	16[c]	ND[c]	9.4[c]	ND[b]	ND[b]	0.7[b]
	Sub-slab	350[c]	ND[c]	2,500[c]	–	–	–
405 East Elm St.	First floor	2.3[d]	3.3[d]	–	ND[e]	ND[e]	–
	Basement	22[a]	2.6[d]	10.4[b]	ND[e]	ND[e]	–
	Sub-slab	2,800[a]	–	–	–	–	–
408 East Elm St.	First floor	11[d]	ND[d]	–	ND[e]	ND[e]	–
	Basement	17[d]	ND[d]	21.8[b]	ND[e]	ND[e]	–
	Sub-slab	1,900[a]	–	–	–	–	–

[a] Sample collected for analysis on March 27 and April 7, 2009. Carbon tetrachloride and chloroform analyses on-site by EPA Method 8021.

[b] Sample collected for analysis on January 26, 2010. Carbon tetrachloride and chloroform analyses by Method TO-15 at TestAmerica. Radon analysis through National Radon Program Services at Kansas State University. ND indicates no detection at the laboratory analytical reporting limit.

[c] Sample collected for analysis on February 4, 2009. Carbon tetrachloride and chloroform analyses by Method TO-15 at Calscience Environmental Laboratories (for indoor air) or H&P Mobile Geochemistry (for sub-slab samples). Radon analysis by scintillation counting at the University of Southern California.

[d] Sample collected for analysis on August 12, 2009. Carbon tetrachloride and chloroform analyses by Method TO-15 at TestAmerica.

[e] Sample collected for analysis on June 17, 2010. Carbon tetrachloride and chloroform analyses by Method TO-15 at TestAmerica.

FIGURE 3.1 Homes in which mitigation systems were installed to treat carbon tetrachloride in indoor air. Source of photograph: NAIP (2008).

4 Interpretation of Results

This section presents the interpretation of data acquired during the 2009-2010 investigations at Hanover. As discussed in the previous sections, all investigation activities were designed and implemented to address the seven specific technical objectives stated in Section 1.2. The results of the investigation are discussed and interpreted below in the context of these specific objectives.

4.1 Identification of Contaminant Sources and the Extent of Soil Contamination

In 2007, Argonne collected near-surface soil samples (1.8-2 ft BGL) at 61 locations and tested indoor air in 9 residences across the former CCC/USDA property. On the basis of these findings, Argonne identified four areas with trace-level carbon tetrachloride contamination and two homes potentially impacted by carbon tetrachloride VI to indoor air (Figure 2.1). For further evaluation of the areas potentially associated with the soil contamination and the impacted homes, vertical-profile soil sampling for VOCs analysis was performed in 2009 in two steps: (1) collection of soil samples from the unconsolidated subsurface intervals in the areas of potential contamination and (2) collection of rock samples from the underlying consolidated bedrock at locations selected on the basis of the results for the unconsolidated sediments. The results of VOCs analyses on all soil samples are in Table 3.1.

4.1.1 Contaminant Distribution in Soils at the Former CCC/USDA Facility

The vadose zone (an unsaturated zone of soils and/or rocks from the land surface to uppermost water-bearing Zone 1) in the study area includes the shallow unconsolidated intervals from the ground surface to depths of 9-25 ft BGL and the underlying bedrock to the depth of water-bearing Zone 1 (typically < 35 ft BGL). The soil sampling was designed to identify potential sources of contamination throughout the vadose zone beneath the former CCC/USDA facility.

Soil samples were collected at 4-ft intervals through the unconsolidated soil profile at 25 boring locations (TI01-TI25) within the footprint of the former CCC/USDA facility (Figure 4.1). The samples were recovered by using a portable Geoprobe unit. With few

exceptions, no carbon tetrachloride was detected in the unconsolidated soils. In boring TI01 (Table 3.1), a trace level of carbon tetrachloride was present at 18 ft BGL, while a concentration of 30 µg/kg occurred at 21 ft BGL. In boring TI05, a trace level of carbon tetrachloride was found in a single sample collected at 20.5 ft BGL (Table 3.1). Both borings TI01 and TI05 were targeted for evaluation of the potentially contaminated central area of the former CCC/USDA facility (Figure 2.1), identified by Argonne in its near-surface soil sampling event in 2007.

On the basis of the results of soil sampling at the 25 boring locations, samples of the underlying bedrock were collected at 7 selected locations (MW01-MW05, MW12, TI26) within the former facility (Figure 2.2). Additional samples from the underlying bedrock were collected at 6 locations adjacent to the former facility (MW07-MW09, MW34, TI28, TI30; Figure 2.2). The bedrock sampling locations were targeted to complete the vadose zone evaluation in the potentially contaminated areas and near the potentially impacted homes. All samples of consolidated soils were recovered by using a minisonic drilling rig.

Trace to low concentrations of carbon tetrachloride (up to 35 µg/kg) were identified in samples from the bedrock formation at 7 locations (MW01-MW03, MW08-MW09, TI26, TI30; Table 3.1). The maximum concentrations at each location ranged from traces at MW08 and MW12 to 35 µg/kg at MW02 (Table 3.1 and Figure 4.1). Chloroform was detected at only 2 locations (MW02 and TI30), with the highest concentration of 44 µg/kg similarly at MW02 (Table 3.1 and Figure 4.2).

Table 3.1 demonstrates that carbon tetrachloride and chloroform contamination were detected only in the lower portion of the vadose zone. Figure 4.3 shows typical vertical distributions of carbon tetrachloride and chloroform at boring locations along a north-south line through the center of the CCC/USDA facility, where the highest soil contamination was observed. The contaminated soils were located primarily near or at the uppermost water-bearing zone (Zone 1). For example, the highest concentrations of carbon tetrachloride were identified in the soils at 29-33 ft BGL (27-35 µg/kg) in boring TI05/MW02 and at 18-21 ft BGL (15-18 µg/kg) in boring TI30/MW09, as shown in Figure 4.3. Soil contamination associated with the water-bearing Zone 1 was also observed in borings MW05 and TI26 (Table 3.1 and Figure 4.1). In one boring only (TI01/MW01), the highest concentration of carbon tetrachloride (30 µg/kg) was found at 21 ft BGL, near the boundary between the unconsolidated soils and the consolidated (bedrock) formation (Figure 4.3). The results of the soil profiling indicate that the distribution and concentrations of carbon tetrachloride within the vadose zone are very limited

and suggest that the remaining carbon tetrachloride in vadose-zone soils would not provide a significant source of contamination to groundwater. The highest concentration of chloroform detected in the soils (44 µg/kg at 33 ft BGL at TI05/MW02; Table 3.1 and Figure 4.3), is low in absolute value but is greater than the carbon tetrachloride concentration (27 µg/kg) in the same soil sample. Chloroform can be formed in the subsurface as a product of biologically mediated degradation of carbon tetrachloride (reductive dechlorination) under anaerobic conditions. The observed higher concentration of chloroform suggests that natural biodegradation might have assisted in reducing the levels of carbon tetrachloride in the vadose zone soils at this location beneath the former CCC/USDA facility.

Soil samples were collected below water-bearing Zone 1 at locations MW01 and TI30 (on and directly adjacent to the former facility; Figure 2.2). The results for these samples are in Table 3.1, and the vertical relationships of the soil samples to water-bearing Zone 1 are illustrated in Appendix A. No contamination was detected.

Vadose zone soils were also sampled at boring location MW45, approximately 900 ft west of the former CCC/USDA facility and near North Hanover Street. No soil contamination was identified at this location (Table 3.1).

4.1.2 Human Health and Environmental Risks Associated with Contaminated Soils

In this section, the human health and environmental risks associated with the identified contamination in soils are examined. This initial screening evaluated two potential exposure pathways: (1) *direct exposure*, including ingestion of contaminated soil, direct inhalation of contaminated vapors or airborne contaminated soil particles, and direct dermal contact, and (2) *indirect exposure* via the soil-to-groundwater pathway. The screening is based on a comparison of the analytical results to the KDHE Tier 2 risk-based standards (for carbon tetrachloride and chloroform) associated with these pathways (Table 2.1).

4.1.2.1 Direct Exposure

The results from soil sampling at 38 locations (Table 3.1, Figures 4.1-4.2) within and adjacent to the footprint of the former CCC/USDA facility indicate that carbon tetrachloride and chloroform (1) are not present in the near-surface soils but (2) appear at trace to low levels in

subsurface soils, at maximum concentrations of 35 µg/kg (carbon tetrachloride) and 44 µg/kg (chloroform). As summarized in Table 2.1, the KDHE Tier 2 standards for direct exposure to carbon tetrachloride in soils are 2,500 µg/kg for the residential setting and 7,000 µg/kg for the non-residential setting. The corresponding risk-based standards for chloroform in soils are 3,900 µg/kg (residential) and 6,000 µg/kg (non-residential). The results of soil analyses at Hanover to date (Table 3.1 and Figures 4.1-4.2) are lower by approximately two orders of magnitude than the risk-based standards, demonstrating that no unacceptable health risks are associated with potential direct human exposure to the near-surface and subsurface soils at the former CCC/USDA facility.

Risk-based standards have not been established by the KDHE for potential environmental risks associated with direct exposure to soils. In general, risk-based standards are much more stringent for potential human exposure than for environmental risks. No environmental risks are therefore expected in conjunction with the low levels of contamination identified in the soils.

4.1.2.2 Indirect Exposure

For the soil-to-groundwater contamination pathway, the KDHE Tier 2 risk-based standards for carbon tetrachloride and chloroform in soils are 200 µg/kg and 960 µg/kg, respectively. Comparison indicates that the maximum contaminant levels identified in soils at the former CCC/USDA facility (35 µg/kg for carbon tetrachloride and 44 µg/kg for chloroform) are well below these standards, and hence these soils pose no unacceptable health risk to groundwater.

4.2 Identification of the Hydrogeologic Setting and the Distribution of Groundwater

This section presents the interpretation of the local geologic stratigraphy and the groundwater-bearing system at Hanover, as constructed on the basis of the investigation data. The following data were collected and integrated for the interpretation: (1) geologic logs generated from shallow borings at 48 locations, (2) geologic logs from deep borings at 6 locations, (3) supporting geologic data including drillers' logs for local private wells, and (4) topographic survey data for all of the borings and private wells. These data were analyzed to provide a detailed interpretation of the stratigraphic sequence and the spatial distribution of the

lithologic units that host the groundwater-bearing system. The lithologic logs (for the investigative borings and monitoring wells) and the survey data are in Appendix A and Appendix L, respectively.

4.2.1 Local Lithostratigraphic Units and Water-Bearing Zones

The city of Hanover and its surroundings are located in an area that includes the upland lying northeast of the Little Blue River and its floodplain and northwest of Cottonwood Creek (Figure 2.9 in the *Final Work Plan* [Argonne 2008a]). The former CCC/USDA facility northeast of Hanover lies on the upland, at land surface elevations of approximately 1,310-1,330 ft AMSL (Figure 4.4). Regional geologic information indicates that the geologic sequence at Hanover includes (1) surficial and near-surface Pleistocene eolian (wind-blown) deposits on upland areas and alluvial sediments in the floodplains along the Little Blue River, overlying (2) Permian bedrock, probably consisting of Sumner Group and underlying Chase Group (Argonne 2008a). The Sumner Group consists principally of gray and red silty shale, limestone, dolomite, anhydrite, and gypsum, as well as salt, while the underlying Chase Group contains seven alternating shale and chert-bearing limestone units (Merriam 1963). The local geologic data obtained in this investigation confirm the presence of Pleistocene eolian deposits or alluvium unconformably overlying the Permian Sumner Group in the upper part of the subsurface sequence at Hanover and provide a detailed picture of the site-specific bedrock stratigraphy.

Figure 4.5 summarizes the general sequence of lithostratigraphic units by combining elements of representative logs from the vicinity of the former CCC/USDA facility. Locally, at the former facility, the uppermost approximately 150 ft of the soil profile consists of 9 primary lithologic units. In order of increasing depth, these units are (1) surficial silt and clay with a lower section of sand and sandy silt; (2) Permian weathered shale; (3) interbedded limestone and shale; (4) gray shale with siltstone and limestone; (5) upper red shale; (6) an upper evaporitic deposit or gray shale with thin limestone; (7) gray dolostone and shale; (8) lower red shale with multiple, thin gray shale, dolomite, and limestone layers; and a (9) lower evaporitic deposit. The main characteristics of each unit are as follows:

- *Unit 1 — Silt and clay*. This uppermost unit consists of Pleistocene fine-grained eolian (wind-blown) silts and clays identified only on the upland, with a varying thickness up to 25 ft. In the eastern and southern parts of the upland, the lower portion of the unit may include a layer of sand and sandy silt

developed on the eroded unconformable surface of the Permian bedrock. The former CCC/USDA facility is situated on the upland in the Hanover area.

- *Unit 2 — Weathered shale*. A thin weathered shale (≤ 12 ft) in various colors locally marks the top of the Permian age bedrock. Erosion or removal of this unit from most locations in the Hanover area left remnants constituting the upland where the former CCC/USDA facility was located (Figure 4.4).

- *Unit 3 — Interbedded limestone and shale*. This unit consists predominately of light brown to brownish gray, highly weathered limestone beds alternating with shale or laminated shale. This lithostratigraphic unit hosts the uppermost water-bearing unit, groundwater Zone 1. The presence of thin moist-to-wet intervals was most frequently identified along the bedding planes between the limestone and shale intervals or within the shale units themselves. The unit is relatively thick (up to 10 ft) along the upland and progressively pinched out toward its flank because of the effects of surface bedrock erosion.

- *Unit 4 — Gray shale*. This lithostratigraphic unit is less weathered, consisting primarily of dark gray silty shale with thin beds of siltstone and limestone. The thickness of the unit ranges from 5 ft to 19 ft along and near the upland. It is evidently not water bearing.

- *Unit 5 — Upper red shale*. The distinctive upper red shale unit is composed mainly of red shale with multiple thin lenses of calcareous gray shale. Thin, soft, moist intervals with iron oxide staining that were often identified along the bedding planes near the base of the upper red shale unit — where the intervals locally overlie the evaporitic facies of Unit 6 (described below) — suggest presence of the water movement through the intervals. The upper red shale unit has a relatively consistent thickness of approximately 20 ft at most locations.

- *Unit 6 — Upper evaporitic deposit or gray shale with limestone*. This locally distinctive unit consists of white anhydrite and gypsum, identified in upland borings MW49, MW03, and MW51. The depositional facies of the unit appears to change gradually to shale with soft limestone away from the

upland, as identified at MW44 and MW45 toward the west and at MW48 toward the south, as well as possibly at several private monitoring wells (BSMW09-BSMW10 and BSMW14-BSMW15) toward the east (Figures 2.3-2.5). The unit's thickness ranges from 9 ft to 18 ft. Saturated intervals are often associated with the soft limestone in the shale with limestone facies of Unit 6, whereas thin moist intervals were restricted to the lower part of the overlying upper red shale (Unit 5) where the latter unit overlies the evaporitic facies of Unit 6. These moist and saturated intervals form a second water-bearing interval, groundwater Zone 2.

- *Unit 7 — Gray dolostone and shale*. This unit consists of dark gray, hard, massive dolomite (15-25 ft thick) overlying dolomitic shale with thin beds of limestone or limy dolomite (4-9 ft thick). Thin moist-to-wet intervals were found in the limy dolomitic shale near the base of the unit. These thin horizons form a water-bearing interval, groundwater Zone 3.

- *Unit 8 — Lower red shale*. The lower red shale consists of distinctive dark red shale interbedded with several thin layers of dark gray or gray to greenish gray limy shales, limy dolomites, and limestones. The thickness of the unit is relatively consistent, ranging from 27 ft to 33 ft. Moist-wet intervals often found in the limy shale along bedding planes near the base of the unit constitute the basal water-bearing interval, groundwater Zone 4.

- *Unit 9 — Lower evaporitic deposit*. The lower evaporitic deposit is another distinctive marker layer, consisting of white anhydrite, gypsum, and occasionally bluish gray dolomite. This unit was recovered in all of the deep wells, unlike the upper evaporitic deposit, which was present only beneath the upland.

Within the Permian bedrock stratigraphic sequence, thin, moist-to-wet horizons can be identified and traced laterally as groundwater-bearing units, even though thick saturated intervals are rarely encountered (except for groundwater-bearing Zone 2 at boring MW48). Most of the thin, moist-wet horizons were located in the cores as follows (Figure 4.5):

1. In the interbedded shale and limestone of Unit 3.

2. At the base of the upper red shale of Unit 5 or in the soft limestone and shale facies of Unit 6.

3. In the limy dolomitic shale near the base of Unit 7.

4. In the limy shale near the base of Unit 8.

For the purposes of this investigation, these intervals have been identified as groundwater-bearing Zones 1-4, respectively (Figure 4.5). The groundwater present in these zones appears to occur primarily in secondary porosity developed along bedding planes and fractures in the bedrock formations.

To obtain a more detailed understanding of the distribution and nature of the water-bearing zones, the sequence of lithologies, moisture content, and water availability identified in geologic logs obtained at 54 unique locations (Appendix A) were qualitatively compared and correlated. The three-dimensional geometry and structure of the main stratigraphic sequences and the significant water-bearing zones are illustrated in two interpretive hydrogeologic cross sections (A-A' and B-B') constructed at the locations shown in Figure 4.6.

Hydrogeologic cross section A-A' (Figure 4.7) extends from west to east and depicts the relationships among the main stratigraphic units and water-bearing zones identified at the former CCC/USDA facility and in the surrounding areas. All nine stratigraphic units are represented by combining seven shallow boring logs that penetrate the upper units and three deep logs that penetrate the lower units, along with information from three local private wells.

Cross section A-A' (Figure 4.7) illustrates several features. Pleistocene eolian deposits are developed and preserved primarily on the upland near the former CCC/USDA facility, at or above an elevation of approximately 1,300 ft AMSL. A significant hiatus represented at the erosional unconformity intersects the weathered shale (Unit 2) and the interbedded limestone and shale (Unit 3) in the upland area. The erosional unconformity cuts progressively deeper into the underlying less-weathered gray shale (Unit 4) and the upper red shale (Unit 5) along the flanks of the topographic high. The erosion surface is expected to extend farther into the deeper units (such as the shale with limestone [Unit 6]) farther to the west, approaching the Little Blue River.

Because of the erosion effect, the presence of Unit 3 and the associated groundwater-bearing Zone 1 (also indicated as WZ1 in the cross section depictions) is spatially limited to the upland in the vicinity of the former CCC/USDA facility. The underlying stratigraphic intervals that host groundwater Zones 2, 3, and 4 become progressively shallower at greater distances from the upland. Unit 6 appears to undergo a facies change from the distinctive dry, white anhydrite and gypsum (evaporitic deposit) beneath the upland to the shale with limestone facies that hosts groundwater-bearing Zone 2 (WZ2) along the upland flanks toward the west and east (Figure 4.7). The gray dolostone and shale (Unit 7) and the lower red shale (Unit 8) are found at relatively consistent elevations (approximately 1,240 ft AMSL and 1,210 ft AMSL at the tops of the respective units) throughout cross section A-A' (Figure 4.7). The basal sections of these two units host groundwater Zone 3 (WZ3) and Zone 4 (WZ4), respectively.

Hydrogeologic cross section B-B' (Figure 4.8) extends from north to south across the former CCC/USDA facility and roughly follows the trend of the upland, with limited erosional effects, to the location of well MW48 and farther southward. The sequence of the 9 identified stratigraphic units was confirmed by recovery and examination of 10 shallow boring logs penetrating the upper units and 3 deep logs penetrating the lower units, along with information from 1 local private well.

Cross section B-B' (Figure 4.8) confirms the primary hydrostratigraphic units and features identified in cross section A-A' (Figure 4.7), as discussed above. The interbedded limestone and shale (Unit 3) extends from north to south across the entire cross section (Figure 4.8) beneath the upland. Groundwater-bearing Zone 1 (within Unit 3), however, is bounded by boring TI27 at the north and continues southward from the former CCC/USDA facility to the location of boring MW48. A relatively thick layer of evaporitic deposits was identified in Unit 6 beneath most of the upland area. This layer gradually pinches out toward the south and is replaced, near the MW48 location, by shale with soft limestone. A thick saturated zone identified in the upper portion of the Unit 6 shale and limestone facies (together with thin horizons in the overlying upper red shale [Unit 5]) hosts groundwater-bearing Zone 2. As shown in cross section A-A' (Figure 4.7), the tops of the deeper units — gray dolostone and shale (Unit 7) and lower red shale (Unit 8) — were penetrated at relatively consistent elevations of approximately 1,240 ft AMSL and 1,210 ft AMSL, respectively. A few discrete moist-wet intervals along bedding planes were recovered near the bases of both of these units, forming groundwater-bearing Zone 3 and groundwater-bearing Zone 4, respectively.

All defined water-bearing zones in the Permian bedrock stratigraphic sequence are very thin and appear to follow erosional or bedding plane surfaces between units or fractures representing secondary porosity.

4.2.2 Four Water-Bearing Zones

4.2.2.1 Groundwater Zone 1

Groundwater Zone 1 is the uppermost water-bearing zone in the bedrock sequence at Hanover. Zone 1 consists primarily of two or three discrete, thin, saturated intervals (each typically less than 1 ft thick) within the interbedded limestone and shale (Unit 3). The saturated intervals were found in the upper to middle portion of Unit 3 in the northern part of the former CCC/USDA facility (at MW09, MW49, MW05, and MW02 [Figures 4.7-4.8]) and in the middle to lower portion of Unit 3 near and to the south of the former facility (MW06, MW21, MW28, MW29, MW37, and MW48 in Figure 4.8). The combined thickness of the saturated horizons at each location is limited (generally to 1-3 ft) and primarily reflects secondary porosity developed along bedding planes and fractures in the limestone and shale.

The lateral extent of groundwater Zone 1 is bounded by the erosional limits of Unit 3. Zone 1 is therefore found primarily beneath the upland (cross section A-A' in Figure 4.7). Groundwater Zone 1, in general, has limited water availability and low, heterogeneous permeability because of its limited areal extent and the nature of the host bedrock formation. Water recovery from Zone 1was extremely slow at many wells. Near the lateral limits of Unit 3, groundwater accumulation sufficient for water sampling required days after installation of many wells. At the end of the groundwater sampling program for the 2009-2010 investigation (months after installation), six monitoring wells along the northwest (MW25-MW26), west (MW39 and MW41), and southwest (MW42-MW43) limits of the unit still remained dry. These locations and others with slow recovery were used to predict estimated boundaries of groundwater Zone 1 to the north, northwest, west, and southwest (Figure 4.9). The hydraulic properties of groundwater Zone 1 are discussed further in Section 4.6.1.

Groundwater Zone 1 is under confined to leaky-confined conditions;[3] water level measurements confirmed that the potentiometric surface (water level) in each well is higher than the vertical position of the saturated intervals that host groundwater at that location (Section 4.6.1). The multiple, thin, saturated bedding planes that form groundwater Zone 1 are confined mainly by the surrounding low-permeability bedrock matrix, with downward vertical leakage possibly occurring along fractures. This relationship is illustrated in cross sections A-A' and B-B' (Figures 4.7-4.8).

The observed groundwater levels in Zone 1 wells are mutually consistent and roughly mimic the local variations in surface topography. These relationships support the interpretation that the multiple discrete moist-wet intervals along the bedding planes in Unit 3 are in hydraulic communication and together represent a single groundwater-bearing unit (Zone 1; Figures 4.7-4.8). The groundwater levels in the Zone 1 monitoring wells are discussed further in Section 4.3.1.

4.2.2.2 Groundwater Zone 2

Groundwater Zone 2 consists of relatively thick saturated intervals in the shale with limestone facies (Unit 6), or of thin, moist-wet intervals along bedding planes near the base of the overlying upper red shale (Unit 5). As illustrated in cross sections A-A' and B-B' (Figures 4.7 and 4.8), Unit 6 changes in facies from evaporitic deposits beneath the upland (MW49 and MW51) to shale with limestone along the upland flanks (MW44-MW45 and MW48). With this change in facies, groundwater Zone 2 crosses the lithostratigraphic units from the base of Unit 5 (upland) and into Unit 6 (flanks of the upland). Where developed near the base of Unit 5, the combined thickness of the moist-wet bedding planes that host groundwater Zone 2 is limited to 1-2 ft. In contrast, where Zone 2 is found within the Unit 6 shale with limestone facies, the total thickness of the saturated intervals ranges from approximately 3 ft at MW44, MW45, and MW50 to 5 ft at MW48 (Figures 4.7-4.8). At most locations, groundwater Zone 2 occurs at or above an elevation of 1,240 ft AMSL.

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[3] In a confined condition, the rock layers above and below the water-bearing zone (the confining layers) are impermeable to water. In a leaky-confined condition, the rock layers are somewhat less impermeable, and consequently some water is lost to or gained from the surrounding confining layers.

The areal extent of groundwater Zone 2 is much broader than that of localized Zone 1. Zone 2 lies approximately 30 ft or more below Zone 1, and hence Zone 2 has been less seriously truncated by the erosional unconformity (Section 4.2.2.1). Figure 4.10 shows locations where Zone 2 has been penetrated by private wells. The presence of the water-bearing zone in these private wells suggests that Zone 2 extends significantly to the southeast (wells BSMW09-BSMW15 and R. Warren well), south (A. Bruna and T. Bruna wells), and west (D. Martin, B. Bruna, and Schlabach-west wells) of the former CCC/USDA facility.

Groundwater Zone 2 is predominantly under leaky-confined conditions at most locations (Section 4.6.2). The relationships among water levels in wells and the vertical positions of the saturated intervals in Zone 2 are depicted in cross sections A-A' and B-B' (Figures 4.7-4.8).

The mutual consistency of the water levels in Zone 2 monitoring wells indicates that the multiple discrete moist-wet intervals along bedding planes at the base of Unit 5 and the thicker saturated intervals developed in Unit 6 are in hydraulic communication, forming a single Zone 2 groundwater-bearing unit. The potentiometric surface in Zone 2 (beneath the upland area) lies approximately 35-40 ft below the corresponding surface in Zone 1. The groundwater levels in the Zone 2 monitoring wells are discussed further in Section 4.3.2.

4.2.2.3 Groundwater Zones 3 and 4

Groundwater Zone 3 is hosted by the gray dolomitic shale near the base of Unit 7. The moist-wet intervals within this unit are difficult to identify. The combined thickness of the saturated horizons in Zone 3 is less than 2 ft.

Zone 3 can be traced laterally in the subsurface at elevations between 1,210 ft and 1,220 ft AMSL. This zone might be penetrated by most of the deep private water wells shown in Figure 4.4. Zone 3 appears to be confined by the massive overlying dolostone. Water recovery in the monitoring wells constructed in Zone 3 is extremely slow. The high variability observed among water levels in the Zone 3 monitoring wells to date (Section 4.3.3) suggests that the discrete, thin, saturated bedding planes that form Zone 3 do not communicate fully with each other hydraulically within the surrounding shale matrix (Figures 4.7-4.8).

Groundwater Zone 4 is developed at the base of the lower red shale (Unit 8), overlying the lower evaporitic deposit (Unit 9). The multiple thin, moist-wet intervals that form Zone 4 have a total thickness of less than 2 ft. These intervals occur at a relatively consistent elevation of 1,180-1,190 ft AMSL (Figures 4.7-4.8). Zone 4 lies approximately 30 ft below Zone 3.

The groundwater present in Zone 4 is also under confined conditions, and the water levels measured to date in Zone 4 have been less variable than those in Zone 3. The characteristics of the Zone 4 groundwater levels are discussed further in Section 4.3.3.

4.3 Determination of Groundwater Flow Patterns

Groundwater levels were monitored for all four of the identified water-bearing zones to determine the pattern of groundwater flow in each zone. Manual measurements of the water levels were obtained periodically at 44 monitoring wells installed in Zone 1; 6 wells in each of Zones 2, 3, and 4 (18 total); and 4 private monitoring wells installed previously in Zone 2. Groundwater levels were also recorded automatically at selected locations in Zones 1-4. To improve understanding of potential groundwater fluctuations in response to local precipitation events, daily rainfall data were obtained for the period of observation from the Washington County weather station (KS-WS-5; www.ksre.ksu.edu/wdl), approximately 7 mi west of Hanover. The results of these measurements are discussed below, and the full data sets for the manually and automatically recorded water levels are in Appendix E and Supplement 3, respectively.

4.3.1 Groundwater Levels and Flow Patterns in Groundwater Zone 1

For groundwater Zone 1, automatic water level recorders were used in 11 wells (MW01-MW02, MW04-MW10, and MW12-MW13) from February 10, 2009, to June 10, 2010 (Figure 2.7). Figure 4.11 illustrates the stability and consistency of groundwater levels in the 11 instrumented Zone 1 wells since June 2009. The recognizable groundwater fluctuations in response to local rainfall events had minor overall effects, with a total variation of less than 2 ft. Figure 4.11 depicts three periods in which groundwater levels were generally rising: late April to mid June 2009, mid October to mid December 2009, and mid March to late April 2010. During these periods, seasonal rainfall (or snow melt) events apparently increased. Over the 14-month period of record, the observed groundwater fluctuations appear to have had relatively little

influence on the relationships among the water levels in the individual wells (except for MW09 and MW07), indicating that the hydraulic gradients across the site in Zone 1 have remained relatively unchanged.

On February 23-24, 2009, significant drawdown occurred in several of the Zone 1 wells as a result of groundwater sampling (e.g., MW13, MW10, MW09, MW06, MW12; Figure 4.11). After sampling, however, extremely slow recovery of the water level was observed at MW12 (20 days) and MW06 (30 days), as well as (to a lesser extent) at several of the other Zone 1 wells. This slow response strongly suggests that the capacity of the Zone 1 unit to transmit groundwater to the wells at these locations is very low. (This interpretation is examined further in Section 4.6.1.)

Water levels measured manually on July 23, 2009, in 44 of the Zone 1 monitoring wells were used to generate a mechanically contoured representation of the potentiometric surface for this unit. As Figure 4.11 shows, the groundwater levels in Zone 1 were quite stable during July and August 2009, showing little short-term variation in response to local rainfall or other potential influences.

The potentiometric surface constructed for Zone 1 from the July 23, 2009, data is illustrated in Figure 4.12. The topology of the potentiometric surface generally mimics the local ground surface topography. A local groundwater "high" is indicated beneath the upland area surrounded by wells MW09, MW34, MW08, and MW02, suggesting a possible source area for local recharge to Zone 1. Figure 4.12 indicates that groundwater in Zone 1 flows toward the northwest, west, southwest, and south from the former CCC/USDA facility (on the upland), subject to the apparent hydraulic gradients and the effective permeability (or hydraulic conductivity, K_h) of the unit in each of these directions. The quantitative analysis of the preferred flow direction(s) is discussed in Section 4.6.1.4.

4.3.2 Groundwater Levels and Flow Patterns in Groundwater Zone 2

Automatic water level recorders were used in 6 wells in Zone 2 from April 1, 2009 (at MW44Z2 and MW45Z2), or November 2, 2009 (at MW48Z2-MW51Z2), to June 10, 2010 (Figure 2.8). The groundwater level trends for water-bearing Zone 2 illustrated in Figure 4.13 differ markedly from those for Zone 1 (Figure 4.11). The recorded water levels in upland wells

MW49Z2 and MW51Z2 have stayed almost constant since monitoring began in November 2009, while those in wells in more flanking positions (MW44Z2-MW45Z2, MW48Z2, MW50Z2) rose by a total of more than 5 ft during late November 2009, late January 2010, and March-April of 2010. Figure 4.13 shows that the water level increases during the last two episodes might reflect snow melting in late January and increasing spring rainfalls, respectively. The more prominent responses to local precipitation in the flanking portions of Zone 2 might be associated with progressively reduced thickness of the overlying bedrock formations away from the upland area, resulting in the complete absence of groundwater-bearing Zone 1 at locations MW44Z2 and MW45Z2.

The "spikes" in groundwater levels observed at MW51Z2 in February 2010, followed by a gradual decline (Figure 4.13), were caused by local flooding in the area surrounding this well (and in the flush-mount well housing). The flooding, observed during several field visits, was most likely associated with snow melting and/or rainfall. The groundwater levels in MW51Z2 have remained unchanged, except for this interference, and have shown no other apparent responses to local rainfall events.

Groundwater levels were measured manually several times in the Zone 2 monitoring wells after their completion in October 2009, as well as in four private monitoring wells located at a local gas station, approximately 1,000 ft southeast of the former CCC/USDA facility (Figure 2.8). Measurements obtained on January 25, 2010, reflecting a relatively stable period as indicated by the Zone 2 hydrographs (Figure 4.13), were used to estimate the potentiometric surface for Zone 2.

Figure 4.14 shows that the Zone 2 potentiometric surface (like the Zone 1 potentiometric surface illustrated in Figure 4.12) exhibits a localized "high" beneath the former CCC/USDA facility, forming a groundwater divide that extends diagonally beneath the former facility. Groundwater west of the divide flows to the west, while groundwater east of the divide flows to the southeast. Flow along the divide itself might also ultimately move to the south. The slope of the potentiometric surface (the apparent horizontal hydraulic gradient) is almost flat across the top of the divide, but it steepens to the west, south, and southeast. The highest estimated gradient (approximately 0.02, in January 2010) is in the westerly direction.

Zone 2 hydrographs (Figure 4.13) indicate that groundwater levels in downgradient wells MW50Z2, MW44Z2, and MW45Z2 increased consistently, by approximately 8 ft, from January

to June 2010, while the levels in wells on the upland (MW49Z2 and MW51Z2) remained constant. This observation suggests that the apparent hydraulic gradient in Zone 2 in the westerly direction has decreased (to about 0.01) from the representation in Figure 4.14, even though the spatial pattern of flow depicted in Figure 4.14 has not changed significantly.

Vertical groundwater flow via leakage from Zone 1 to Zone 2 appears to occur in the area beneath the uplands where groundwater mounding is observed in both Zone 1 and Zone 2. The rate of vertical leakage, however, is apparently limited, because no temporal responses are shown in Zone 2 hydrographs for the upland wells (MW49Z2 and MW51Z2). This limited leakage is supported by geochemical data (Section 4.3.4) and contaminant data (Section 4.4).

4.3.3 Groundwater Levels and Flow Patterns in Groundwater Zones 3-4

Automatic water level recorders were used in 12 deep wells in Zones 3-4 (6 wells for each zone) from April 1, 2009 (at MW44 and MW45, Z3-Z4), or November 2, 2009 (at MW48-MW51, Z3-Z4), to June 10, 2010 (Figure 2.8).

The Zone 3 hydrographs (Figure 4.15) demonstrate completely different patterns from those for Zones 1 and 2. Groundwater levels in all of the Zone 3 wells appear, in general, to be increasing. Over the monitoring period, the cumulative increases in groundwater levels range from approximately 7 ft at well MW50Z3 to 47 ft at well MW51Z3. No clear relationship is evident between the rise in water levels in Zone 3 and variations in local rainfall.

The “spike” followed by a gradual decline (late January 2010) observed in the trace for MW44Z3 reflects local flooding of the well flush mount and the surrounding area, like that observed at MW51Z2 (Section 4.3.2). The data gaps in the trace for MW45Z3 are the result of a recorder malfunction in this well. All other traces depict distinct rising patterns that differ both temporally and with location and that show no clear signs of stabilization. The apparently continuous, slow recoveries indicate that the groundwater levels in all of the Zone 3 monitoring wells had not yet reached ambient conditions 8-14 months after well installation. These observations support the interpretation that both the availability of groundwater within Zone 3 and the ability of this unit to transmit groundwater to wells are extremely limited. Because the groundwater levels in the monitoring wells have not stabilized, the potential flow patterns in Zone 3 could not be determined with certainty.

The Zone 4 hydrographs are distinct in form, as illustrated in Figure 4.16. The gradually decreasing rates of water-level rise observed in wells MW48Z4-MW51Z4 since their installation are typical of an approach to equilibrium between the water levels in these wells and the ambient groundwater levels in the surrounding formation. No correlation is evident between the water level recovery in Zone 4 and variations in the local rainfall. The slow recovery (taking several months) in these wells again suggests that the capacity of Zone 4 to produce groundwater to wells is limited.

Although the groundwater levels in the Zone 4 wells might not be fully recovered, the present levels in MW49Z4 and MW51Z4 on the upland area at the former CCC/USDA facility are higher than those in the corresponding Zone 2 wells at these locations (Figure 4.17). This apparent upward hydraulic gradient strongly suggests that groundwater Zone 4 is not locally recharged via downward leakage through Zones 2 and 3 beneath the upland at Hanover. The data suggest that groundwater Zone 4 is recharged from a source area other than the local upland.

Figure 4.17 compares hydrographs for selected wells in groundwater Zones 2, 3, and 4. The exact relationships of the ambient groundwater levels in Zone 3 to the levels in Zone 2 and Zone 4 cannot be determined with certainty at this time because of the very slow recovery of the Zone 3 monitoring wells and the absence of any evidence that water levels are equilibrating in those wells. In the upland area, the groundwater levels in the Zone 3 wells have increased by approximately 41 ft (MW49Z3) and 46 ft (MW51Z3) since well installation. For the period February-June 2010, Figure 4.17 indicates relatively constant water level increases of approximately 8 ft per month in well MW49Z3 and 4 ft per month in well MW51Z3, suggesting that the Zone 3 water level in these wells is gradually approaching the Zone 2 ambient groundwater level. If these observed rates of water level rise continue, the groundwater levels in the Zone 3 wells at the MW51 and MW49 locations will exceed the Zone 2 ambient water levels in the near future. The observed relationships imply that, *in the upland area*, the ambient groundwater level might be higher in Zone 3 than in Zone 2. In contrast, no present observations for the wells along the flanks of the upland area (MW44, MW45, and MW50) suggest that the Zone 3 water levels at these locations will reach or exceed the ambient water levels in Zone 2.

The Zone 4 groundwater levels at adjacent wells MW44Z4 and MW45Z4 have followed distinctly different trends (Figure 4.16). The groundwater in MW44Z4 was temporarily depleted because of sampling on October 16, 2009, and then recovered slowly. No similar response to sampling occurred at well MW45Z4, however, indicating a potentially greater producing

capacity at the latter location. Multiple distinct downward groundwater "spikes" (approximately 3 ft) are present in the hydrograph for well MW45Z4 from early April to early October 2009 and starting again in early June 2010, in apparent association with slowly declining water level trends during these periods (Figure 4.16). These drawdown events are believed to be associated with pumping of the private (B. Bruna) lawn and garden well approximately 90 ft west of well MW45Z4 (across Hanover Street; Figures 2.4 and 2.5). The hydrograph for well MW45Z4 is different from those of the other Zone 4 wells, but it is qualitatively similar to that in Zone 2 at the same location (MW45Z2; Figure 4.17), suggesting some possible correlation with local rainfall. This apparent relationship might reflect the presence of several nearby private wells (B. Bruna, K. Jueneman, D. Martin, R. Schlabach; Figure 2.5) that are believed to be constructed with continuous gravel packs connecting Zone 2 and the deeper groundwater-bearing zones.

Although the Zone 4 hydrographs (Figure 4.16) suggest that the water levels in Zone 4 wells MW44Z4 and MW45Z4 might be approaching equilibrium, the spatial relationships and hence the hydraulic gradients represented by the groundwater levels in all of the Zone 4 wells are still subject to change. The latest water level data measured in June 2010 suggest that wells MW49Z4 and MW51Z4, and possibly MW48Z4, are located in the upgradient portion of the Zone 4 flow system, while wells MW50Z4, MW44Z4, and MW45Z4 (to the west of the topographic upland) lie in downgradient positions. An accurate representation of the detailed groundwater flow patterns in this unit cannot, however, be predicted at this time. Therefore, no attempt has been made to generate water level contours for Zone 4.

4.3.4 Geochemical Indicators of Possible Groundwater Movement

Groundwater sampling for nitrate and tritium isotopes was conducted to provide additional geochemical lines of evidence that might help to determine the origin and three-dimensional patterns of groundwater movement (and hence possible contaminant migration) within the Hanover flow system.

A total of 12 groundwater samples were collected for nitrate analysis (Figure 2.6). Of these, 7 samples were obtained from upland monitoring wells MW05, MW09-MW11, MW13, MW28, and MW29 in groundwater Zone 1; 3 were from wells MW48Z2, MW49Z2, and MW51Z2 in the eastern portion of Zone 2, along the upland; and 2 were from wells MW44Z2 and MW45Z2 in the western portion of Zone 2 along the flanks of the upland area (Figure 4.7). The results of the nitrate analyses are summarized in Table 3.4.

The identified nitrate concentrations in the Zone 1 and Zone 2 groundwater samples demonstrate a spatial variability that suggests a plausible interpretation of vertical recharge in the upper portions of the groundwater flow system. Nitrate concentrations ranging from 1.8 mg/L to 6.3 mg/L were detected in all of the sampled Zone 1 wells. Similar levels of nitrate (2.5-4.11 mg/L) were also identified in Zone 2 wells MW44Z2 and MW45Z2, located in the downgradient, western portion of Zone 2, in the area where much of the overlying Pleistocene and bedrock cover (lithostratigraphic Units 1-4; Section 4.2.1), including the Zone 1 groundwater-bearing unit, has been removed by erosion (Figures 4.7 and 2.6). In these areas (Zone 1 and the western portion of Zone 2), the geochemical analyses suggest that a significant component of the groundwater flow is derived from the infiltration of (nitrate-bearing) surface water into the water-bearing units.

The nitrate concentrations noted above were consistently greater, by approximately an order of magnitude, than the nitrate levels of < 0.1 mg/L to 0.5 mg/L (within the range of natural background concentrations in groundwater [Panno et al. 2006]) identified in samples from Zone 2 wells MW48Z2-MW51Z2. At the latter, more upland well locations, the Zone 2 groundwater-bearing unit is more deeply buried and is overlain by groundwater Zone 1 (Figure 4.8). At these locations, the results of nitrate analyses suggest that the component of the Zone 2 groundwater flow originating via infiltration of surface (nitrate-bearing) water through Zone 1 is minimal, probably not exceeding 8-10% (if such infiltration is occurring at all).

Tritium is a short-lived isotope of hydrogen with a half-life of 12.32 yr (Lucas and Unterweger 2000). Water derived from precipitation that fell before 1953 (sub-modern water) would be expected to have a tritium concentration of less than 0.5 TU as a result of radioactive decay. From 1953 to 1969, however, aboveground testing of nuclear weapons contributed highly elevated levels of tritium to the atmosphere (up to 10,000 TU in 1963) and resulted in the presence of relatively higher levels of tritium in water derived from more recent (modern or post-testing) precipitation (currently approximately 4 TU). Tritium concentrations in groundwater can therefore be used in the temporal evaluation of groundwater sources as an indicator of relatively older (sub-modern or pre-testing), younger (modern or post-testing), and mixed waters.

Eight groundwater samples were collected for tritium analysis from groundwater Zone 1 (wells MW05 and MW46), Zone 2 (wells MW44Z2 and MW45Z2), Zone 3 (well MW45Z3; 2 samples), and Zone 4 (wells MW44Z4 and MW45Z4). The results of the analyses (Table 3.3)

indicate that tritium concentrations generally decrease from Zone 1 to Zone 4 (except at well MW45Z4), as follows:

- Zone 1: 4.25-5.70 TU (modern water)
- Zone 2: 3.68-4.42 TU (mixed modern and sub-modern water)
- Zone 3: 2.72-3.05 TU (mixed modern and sub-modern water)
- Zone 4: 0.12 TU (MW44Z4; sub-modern water)

The relatively high tritium levels identified in the Zone 2 groundwater samples from wells MW44Z2 and MW45Z2 are consistent with the nitrate concentrations detected at these locations, suggesting that the downgradient portion of the Zone 2 water-bearing unit (and also possibly Zone 3) might receive a significant component of recharge via vertical infiltration. Together, the nitrate and tritium analyses for these wells qualitatively support an interpretation of leaky-confined conditions in the Zone 2 unit at MW44Z2 and MW45Z2. (See also Section 4.6.2.)

A relatively high concentration of tritium (3.6 TU) was detected in the Zone 4 groundwater sample from well MW45Z4. This value suggests that the Zone 4 groundwater near MW45Z4 might contain a greater component of modern water than is indicated in nearby (more upgradient) well MW44Z4. As noted in Section 4.3.3, well MW45Z4 is located near several deep private wells that are believed to be continuously gravel packed through the shallower portions of the stratigraphic sequence. We therefore postulate that the higher tritium concentration observed at well MW45Z4 might reflect localized mixing of shallow and deeper groundwater via the vertical conduits provided by these private wells.

4.4 Delineation of Groundwater Contamination

The lithostratigraphic and hydrologic characteristics of the subsurface environment at Hanover define the hydrogeologic framework controlling the potential distribution and the movement of carbon tetrachloride contamination potentially associated with the former CCC/USDA facility. Groundwater sampling to delineate the groundwater contamination at Hanover was therefore guided by the interpretation of multiple water-bearing zones and

groundwater flow patterns, as presented in Sections 4.2-4.3, in conjunction with the contaminant source characteristics identified in Section 4.1.

Extensive characterization was performed to determine the distribution and concentrations of carbon tetrachloride in groundwater-bearing Zone 1, to support an assessment of the potential health and environmental risks associated with the contamination in this interval. Groundwater samples were collected successfully from 38 wells and 1 borehole in Zone 1. Attempts to obtain groundwater samples were made at 2 additional boreholes, 2 temporary wells, and 6 permanent monitoring wells in Zone 1, but no water could be recovered from these locations during the investigation period (Figures 2.3 and 4.9).

Groundwater samples were also collected for analyses from 6 dedicated monitoring wells in each of the 3 deeper groundwater-bearing units (Zones 2-4; Figure 2.4) and from 24 private wells (with various completion depths) that were accessible for this investigation (Figure 2.5).

The results of the groundwater analyses for VOCs are summarized in Table 3.2 and are discussed below.

4.4.1 Contaminant Distribution in Groundwater Zone 1

The spatial distributions of carbon tetrachloride and chloroform in samples collected from groundwater Zone 1 are shown in Figures 4.18 and 4.19, respectively. The vertical distribution of carbon tetrachloride in Zone 1 is illustrated in hydrogeologic cross sections A-A' and B-B' (Figures 4.20 and 4.21). Figure 4.22 depicts the lateral extent of carbon tetrachloride in the Zone 1 groundwater, as interpreted on the basis of data from the 48 sampling points shown. The lateral margins of the contaminant distribution were inferred from sampling locations with no detectable concentrations or low levels (< 5 µg/L) of carbon tetrachloride, as well as from locations having little or no recoverable groundwater in Zone 1. Figure 4.22 represents a conservative estimate of the area in which carbon tetrachloride might be present at a concentration equal to or greater than the KDHE standard of 5 µg/L for this contaminant.

The identified carbon tetrachloride concentrations in Zone 1 range from maximum values of 617 µg/L (at MW11) and 548 µg/L (at MW02) in the northern part of the former CCC/USDA facility, to 1.0 µg/L (the method quantitation limit for purge-and-trap analysis; at MW27).

Figures 4.18 and 4.22 indicate that the highest concentrations of carbon tetrachloride in Zone 1 are generally located beneath the upland area that extends to the northwest and southwest from the former CCC/USDA facility, suggesting pathways for preferred contaminant migration in these directions. Figures 4.18, 4.20, and 4.22 show that the carbon tetrachloride concentrations in Zone 1 tend to decrease rapidly away from the upland area and toward the erosional limits of lithostratigraphic Unit 3 (Section 4.2.2.1) and the Zone 1 groundwater-bearing interval. The locations of numerous wells and borings that remained dry (or had extremely limited water availability) throughout the investigation at Hanover help to delimit the southwestern, western, northwestern, and northern margins of the carbon tetrachloride (and groundwater) distribution in Zone 1, as shown in Figures 4.18 and 4.22.

Cross sections A-A' and B-B' (Figures 4.20 and 4.21) indicate that the contaminated groundwater in Zone 1 is generally present at depths of less than 40 ft BGL (ranging from 17 ft BGL at well MW14 to 31 ft BGL at well MW02). The interpreted lateral contaminant margins shown in Figure 4.22 therefore provide a basis to guide investigation of possible VI associated with the Zone 1 contamination. The results of the Zone 1 VI studies conducted as part of the present investigation at Hanover are discussed in Section 4.8.

The spatial distribution of chloroform in Zone 1 is illustrated in Figure 4.19. The highest identified concentration of chloroform was 18 µg/L (at MW12). In the northern part of the former CCC/USDA facility (where high carbon tetrachloride concentrations were identified; Figure 4.18), the abundance of chloroform relative to carbon tetrachloride was generally less than 2%. However, near the estimated edges of the carbon tetrachloride distribution, the ratios of chloroform to carbon tetrachloride in the Zone 1 groundwater were much higher. Examples of this increase were observed at wells MW16 and MW24 (> 36%) near the northwest margin of the contaminated area; at wells MW30 and MW47 (> 64%) near the southeast edge; and at wells MW37 and MW38 (13-18%) near the southwestern edge. The elevated ratios of chloroform to carbon tetrachloride observed at these and several other locations (Table 3.2) suggest that some degradation of carbon tetrachloride (by reductive dechlorination) is occurring in the Zone 1 groundwater. The observed concentration relationships empirically suggest that natural biodegradation might assist, to a limited extent, in reducing the carbon tetrachloride concentrations in Zone 1 along the downgradient margins of the contaminant distribution.

4.4.2 Contaminant Distribution in Groundwater Zone 2

Groundwater Zone 2 underlies a much larger area at the Hanover site than does groundwater Zone 1, as shown in cross sections A-A' and B-B' (Figures 4.20, 4.21, and 4.10). Many local private wells were either completed in Zone 2 or constructed to tap groundwater by intercepting Zone 2 *and* deeper water-bearing zones via continuous gravel packs. Of the 24 private wells that were accessible to Argonne in the present investigation, 16 (Figure 4.10) were identified that possibly intercept groundwater from Zone 2.

The distribution of carbon tetrachloride and chloroform in groundwater Zone 2 was determined on the basis of samples collected from 6 monitoring wells installed exclusively in Zone 2 and the 16 private wells identified in Figure 4.10. The results of analyses of these samples for carbon tetrachloride and chloroform (Table 3.2) are summarized in Figures 4.23 and 4.24, respectively. The vertical distribution of carbon tetrachloride in Zone 2 is illustrated in Figures 4.20 and 4.21. Figure 4.25 depicts the lateral distribution of carbon tetrachloride in the groundwater in Zone 2, as interpreted from the 22 sampling points shown. The lateral margins of the contaminant distribution were interpreted on the basis of sampling locations with no detectable concentrations or low levels (< 5 µg/L) of carbon tetrachloride. The interpretation in Figure 4.25 represents an estimate of the area in which carbon tetrachloride might be present in Zone 2 at a concentration greater than the KDHE standard of 5 µg/L for this contaminant.

Carbon tetrachloride concentrations in Zone 2 ranged from a maximum of 35 µg/L (at upgradient well MW49Z2) to 1.5 µg/L (in a private well northwest of monitoring well MW45Z2; Figure 4.23), within a relatively narrow, elongate area extending to the west from the former CCC/USDA facility (Figures 4.23 and 4.25). A carbon tetrachloride concentration of 9.7 µg/L was identified at well MW50Z2, near the interpreted southern margin of the Zone 2 contaminant distribution. Carbon tetrachloride levels of 11-28 µg/L were found at wells MW44Z2 and MW45Z2 in the downgradient portion of groundwater Zone 2. Low levels of carbon tetrachloride were also detected in four private wells west and northwest of MW45Z2, in the apparent direction of groundwater flow. All four private wells were drilled to the deeper groundwater zones but are likely to intercept Zone 2 via continuous gravel packs, as illustrated in cross section A-A' (Figure 4.20). Topographic relationships indicate that Zone 2 is likely absent approximately 1,000 ft west of well MW45Z2, because of progressive downcutting along the flanks of the upland to the east. The approximate location of the western Zone 2 erosional limit is

illustrated in Figure 4.25. No carbon tetrachloride was detected in private wells south, east, and north of the former CCC/USDA facility (Figure 4.23).

In the upland area where vertical groundwater flow could possibly occur from Zone 1 to Zone 2 (as discussed in Section 4.3.2), carbon tetrachloride concentrations are significantly lower in Zone 2 than to Zone 1. Comparison of carbon tetrachloride concentrations of 35 µg/L in Zone 2 well MW49Z2 with concentrations in nearby in Zone 1 wells (395 µg/L in MW09 to 617 µg/L in MW11; Figures 4.18 and 4.23), suggests that 9% or less of the contamination in the Zone 2 groundwater originates from Zone 1 groundwater. This observation is consistent with depletion of nitrate in Zone 2 (Section 4.3.4), indicating that potential leakage from groundwater Zone 1 to Zone 2 is apparently limited in the upland area.

As cross section B-B' (Figure 4.21) shows, groundwater Zone 2 is generally encountered at depths greater than 40 ft BGL beneath the upland areas of the Hanover site. However, primarily because of variations in topography, groundwater Zone 2 becomes shallower than 40 ft BGL in the western, downgradient flank area near MW44Z2 (approximately 30 ft) and MW45Z2 (approximately 20 ft).

The identified distribution of chloroform in Zone 2 is shown in Figure 4.24. The highest concentration of chloroform, 8.6 µg/L, was detected in a private well (BSMW14) at a location where petroleum compounds (not associated with past grain storage operations at the former CCC/USDA facility) were also found in the groundwater. Chloroform concentrations at all of the other Zone 2 monitoring and private wells were very low, ranging from 1 µg/L to 4.4 µg/L. The relative abundance of chloroform to carbon tetrachloride in Zone 2 groundwater, 9-22%, is higher than the abundance of < 2% in the “hot-spot” area in Zone 1 in the northern part of the former CCC/USDA facility and equal to or less than the abundance along the edges of the Zone 1 contamination (13% to > 64%). The observed ratios of chloroform to carbon tetrachloride imply the possibility of a limited amount of carbon tetrachloride degradation in the Zone 2 groundwater via reductive dechlorination.

4.4.3 Potential Contamination in Groundwater Zones 3-4

Groundwater samples were collected from wells installed exclusively in groundwater Zone 3 and Zone 4 at each of 6 locations (MW44-MW45 and MW48-MW51; Figure 2.4). No

carbon tetrachloride was identified in Zone 3 or Zone 4 in these wells. Trace to low amounts of carbon tetrachloride (ranging from 1.5 µg/L to 7.8 µg/L) were identified, however, in four private wells (B. Bruna, D. Martin, R. Schlabach-west, and K. Jueneman) west and northwest of wells MW45Z3 and MW45Z4 (Figure 4.23). The carbon tetrachloride in the private wells is believed to reflect contamination in the Zone 2 groundwater-bearing unit that is being intercepted via the continuous gravel packs in these wells. No contamination was found in the Zone 3 or Zone 4 groundwater at any of the sampled locations lying upgradient of the private wells.

The hydrogeologic, water level monitoring, and geochemical evidence compiled for Zones 3 and 4 further suggests that the potential for contamination of the groundwater in these zones in the upland portion of the Hanover site is limited. The observations supporting this interpretation are as follows:

- The extremely slow equilibration of the groundwater levels observed in the Zone 3 monitoring wells demonstrates that the hydraulic communication within this unit, and with potential adjacent units, is very poor. The relatively constant rate of increase in groundwater levels in Zone 3 wells on the upland area in February-June 2010 implies that the ambient groundwater level in Zone 3 might be higher than that in Zone 2, preventing downward movement.

- Currently measured groundwater levels in the Zone 4 monitoring wells are higher than those in the corresponding Zone 2 (and Zone 3) wells in the upland area, indicating no downward movement of groundwater (and potential contaminants) from Zone 2 into the deeper groundwater-bearing zones.

- The observed groundwater levels in all of the upland Zone 3 and Zone 4 wells show no apparent sensitivity to local rainfall events (as observed in Zone 1 and Zone 2), suggesting no local vertical recharge to these deeper zones.

As noted above, the present investigation data suggest that localized contamination of the Zone 3 and Zone 4 groundwater might be possible in the western portions of these units, however, as a result of the potential vertical migration conduits provided by the continuously gravel-packed private wells in this area.

4.5 Human Health and Environmental Risks Associated with Contaminated Groundwater

As shown in Table 2.1, the standard for carbon tetrachloride adopted by the KDHE (5 µg/L) is identical to the MCL value established by the EPA under the federal Safe Drinking Water Act. Carbon tetrachloride contamination was found in Zone 1 and Zone 2 in this investigation (Figures 4.18 and 4.23) at concentrations exceeding this KDHE standard. Chloroform was also identified in groundwater-bearing Zones 1 and 2; however, the maximum chloroform concentrations detected in these zones (18 µg/L and 8.6 µg/L, respectively; Figures 4.19 and 4.24) are below the KDHE standard of 80 µg/L for this contaminant in groundwater (Table 2.1).

In this section, an initial screening of the potential human health and environmental risks associated with the carbon tetrachloride contamination in groundwater at Hanover is presented. The initial screening evaluates two exposure pathways: (1) direct exposure, including ingestion of contaminated groundwater, direct inhalation of chemicals volatilized from contaminated groundwater, and dermal contact with contaminated groundwater and (2) indirect exposure via the groundwater-to-surface water pathway or the groundwater-to-indoor air pathway.

4.5.1 Direct Exposure

An estimate of the lateral extent of carbon tetrachloride in groundwater in Zone 1 is shown in Figure 4.22. The interpreted margins represent the area in which carbon tetrachloride might be present at concentrations equal to or greater than the KDHE standard of 5 µg/L for this contaminant. The maximum identified concentration is 617 µg/L, at well MW11 along the northern margin of the former CCC/USDA facility. The depth to the contaminated groundwater ranges from 17 ft BGL (at MW14) to 31 ft BGL (at MW02), but it is generally greater than 20 ft BGL. Under these conditions, the most probable mechanism of potential direct exposure to the carbon tetrachloride contamination in Zone 1 would be via groundwater obtained from a well tapping the Zone 1 water-bearing unit.

On the basis of information in all available Kansas well registration records and information obtained in a community meeting led by the KDHE on May 28, 2009, no active private (or public) wells are known to be either present within the area of Zone 1 contamination or completed in this unit. The potential routes of direct exposure to the contaminated

groundwater in Zone 1 (via ingestion, inhalation, or dermal contact) are therefore incomplete under the current conditions at Hanover. No unacceptable health risks are associated with potential human exposure to the contaminated groundwater in Zone 1, if the current conditions remain unchanged.

An estimate of the lateral extent of carbon tetrachloride in groundwater Zone 2 is shown in Figure 4.25. The maximum identified carbon tetrachloride concentration in Zone 2 is 35 µg/L, at well MW49Z2 along the northern margin of the former CCC/USDA facility.

Four private wells were identified that penetrate the downgradient toe of the Zone 2 contaminant distribution (B. Bruna, K. Jueneman, D. Martin, R. Schlabach-west; Figure 4.25). Carbon tetrachloride levels in the groundwater from these wells ranged from 1.5 µg/L to 7.8 µg/L; however, these wells are used only for lawn and garden purposes. Therefore, no unacceptable health risks are presently associated with potential human exposure to the contaminated groundwater in Zone 2 via ingestion, and only minimal health risks might be posed by exposure to the contaminated groundwater via potential outdoor inhalation of vapors or dermal contact.

4.5.2 Indirect Exposure

Potential indirect pathways for exposure to contaminated groundwater include groundwater discharge to surface waters and groundwater (and contaminant) evaporation to soil vapor that could potentially facilitate VI to residential or non-residential structures.

The occurrence of groundwater Zone 1 is spatially limited to the area beneath the upland portion of the Hanover site. The lithostratigraphic unit that hosts groundwater-bearing Zone 1 (Unit 3; Section 4.2.1.1) is completely eroded at elevations below approximately 1,280 ft AMSL and hence is absent along the flanks of the upland area, as illustrated in cross section A-A' (Figure 4.20) and Figure 4.22. Field reconnaissance along the projected limits of the Zone 1 unit (Figure 4.22) revealed no springs or seepage to suggest direct drainage from Zone 1 to the surface. The pathway for potential indirect exposure to contaminated groundwater via surface discharge from Zone 1 is therefore incomplete.

Groundwater Zone 2 is more widely distributed than Zone 1 beneath the Hanover site. The estimated limit of Zone 2 along the identified contaminant migration pathways is shown in Figure 4.25. Detailed field reconnaissance conducted in the projected area of Zone 2 groundwater migration and potential surface discharge west of monitoring wells MW44Z2 and MW45Z2 (Figure 4.25) identified no springs or seepage. The pathway for potential indirect exposure to contaminated groundwater via surface discharge from Zone 2 is therefore also incomplete.

The results indicate that no unacceptable health risks are associated with potential indirect human exposure to the contaminated groundwater in Zone 1 and Zone 2, via possible discharge of the groundwater to surface waters at Hanover.

The depth of contaminated groundwater in Zone 1 ranges from 17 ft BGL to 31 ft BGL, and the depth to the contaminated groundwater in the more downgradient part of Zone 2 (on the western flank of the upland area; Figure 4.25) is also less than 40 ft BGL. On the basis of the health risk criteria recommended by the KDHE (2007b), the presence of contaminated groundwater at depths of less than 40 ft BGL in these units might pose a risk of indirect exposure via VI to indoor air. This potential exposure route was investigated extensively, and the results were analyzed to determine whether this exposure pathway is complete. The details of the VI investigation are discussed separately in Section 4.8.

4.6 Quantitative Evaluation of the Hydraulic Properties of Groundwater Zone 1 and Zone 2

The results of the Hanover investigations presented in Sections 4.2-4.4 demonstrate that carbon tetrachloride is present in groundwater, at levels that exceed the KDHE standard of 5 µg/L for this contaminant, in Zones 1 and 2 of the four groundwater-bearing zones identified at this site. An initial screening of these results, summarized in Section 4.5, indicates that the identified groundwater contamination currently poses no unacceptable risks to human health via potential direct or indirect exposure pathways. (See also Section 4.8.) Because the identified concentrations of carbon tetrachloride are, however, above the acceptable KDHE target levels, the KDHE requires an assessment of possible alternatives for the restoration of groundwater Zones 1 and 2in the context of a Corrective Action Study (CAS) for the Hanover groundwater system. Initial recommendations for the development of a CAS are outlined in Section 6 of this report.

The hydraulic properties of the contaminated water-bearing zones and the potential variations of these properties across the Hanover site are factors that govern groundwater flow and contaminant migration. These factors must be determined to support quantitative evaluation of the expected Zone 1 and Zone 2 responses to several available groundwater restoration technologies. The identification of these parameters is particularly critical to the analysis of potential use of groundwater extraction, fluid injection, or hydraulic containment of the contaminant distribution in these units. Similarly, these parameters provide a basis for quantitative estimation of the rates (and potential directions) of groundwater and contaminant migration under alternate restoration scenarios.

To address these data needs, the following program of hydraulic testing was performed in conjunction with the 2009-2010 site investigations at Hanover, at the request and with the approval of the KDHE (2009b,c,d,h, 2010b,d):

- Single-well response ("slug") testing of 20 monitoring wells to generate data on the range and distribution of hydraulic conductivity values in Zone 1.

- Step-drawdown testing to determine the specific capacity and potential ROI of Zone 1 monitoring wells MW05, MW09, and MW10.

- Constant-rate pump testing at Zone 1 monitoring well MW05, to determine the long-term sustainable pumping rate.

- Slug testing of 6 monitoring wells to generate data on the range and distribution of the K_h values in Zone 2.

- Constant-rate pump testing of well MW45Z2 to determine the long-term sustainable pumping rate in Zone 2.

This section summarizes the results of the hydraulic testing outlined above. The data sets for each element of the testing program (Appendixes F-J) are analyzed and discussed in detail in Supplements 4-8 (on CD).

4.6.1 Estimates of Hydraulic Properties for Groundwater Zone 1

4.6.1.1 Zone 1 Slug Test Results

Slug tests were conducted at 20 monitoring well locations across the area where contamination was identified in Zone 1. The water response data obtained from the tests were interpreted by using the analysis methods of Bouwer and Rice (Bouwer and Rice 1976; Bouwer 1989) and Hvorslev (1951), as implemented in the commercial well test software analysis package AqteSolv for Windows (HydroSolve, Inc.). Numerous alternative slug test analysis methods have been developed, each with advantages and disadvantages. The methods used for this study were selected in light of their relatively wide applicability, their level of documentation and general acceptance by the scientific community, and their ease of implementation to achieve the objective of estimating hydraulic parameters for the Zone 1 water-bearing interval.

Complete data (time versus residual drawdown) for the slug tests and analysis parameters are in Supplement 4 (on CD). Representative interpretive curve fits for the test data sets are in Appendix F. The resulting hydraulic conductivity estimates are summarized in Table 4.1. For each data set, the estimated K_h values calculated with the Bouwer and Rice method are of the same magnitude as, but roughly 25% lower than, the values for the same data set calculated with the Hvorslev method. The estimated K_h values for the Zone 1 water-bearing materials at Hanover range over five orders of magnitude, from approximately 0.001 ft/day at MW06 to approximately 100 ft/day at MW09. The high variation within this localized area reflects the heterogeneity of water-bearing Zone 1.

The areal distribution of the calculated *average* K_h values (averaged for all individual tests and both calculation methods; last column in Table 4.1) is illustrated in Figure 4.26. The areal distribution of the hydraulic conductivities estimated by using *either* analysis method (not shown) yields a similar spatial pattern. The highest *average* K_h values, ranging from approximately 53 ft/day to 75 ft/day, were calculated for wells MW05, MW09, MW11, and MW13, which are located on the topographic upland near the north central margin of the former CCC/USDA facility. At two locations (MW02 and MW10) within and near the eastern portion of the former facility, K_h values of approximately 3 ft/day were observed. Similar values of approximately 4.6 ft/day were estimated for adjacent wells MW28 and MW29, located near the intersection of North East and Elm Streets, in the more downgradient portion of Zone 1

(Figure 4.26). Figure 4.26 further indicates that the estimated K_h values in Zone 1 decrease rapidly in all directions from the upland area beneath the former CCC/USDA facility, to values that are consistently < 1 ft/day (in most cases < 0.1-0.01 ft/day). The estimated K_h values are lower by two to three orders of magnitude in the area west and south of the interpolated contour line representing K_h = 1 ft/day and lower by approximately one order of magnitude in the area east of this contour line.

Although the estimated K_h values observed at several of the monitoring wells noted above are relatively high (approaching or equal to values often associated with clean sand deposits), the combined slug test results suggest that the expected capacity of Zone 1 (consisting of a few discrete, thin, moist-wet intervals) to produce groundwater to wells is limited, even at the identified locations having higher K_h values. In addition to hydraulic conductivity, the factors affecting the capacity to produce groundwater to wells include (1) the restricted thickness of the Zone 1 water-bearing interval, (2) the dramatic variations in K_h values documented over short (< 150 ft) lateral distances within the study area, and (3) the relatively low groundwater head levels observed for wells in the portions of the study area having higher estimated K_h values.

The value of K_h is primarily a function of the intrinsic characteristics of the saturated pore spaces within a water-bearing interval; however, the ability of such a unit to transmit water horizontally (under a given hydraulic gradient) is determined by its transmissivity (T), which represents the product of K_h and the total saturated thickness of the unit. Because the net thickness of the saturated Zone 1 materials at Hanover ranges from only 1 ft to 3 ft, the resulting T value of this unit is limited at even the most permeable of the locations subjected to slug testing (MW05, MW09, MW11, and MW13; Figure 4.26). The significantly lower K_h values observed across much of the investigation area (Figure 4.26) will further restrict the ability of groundwater to move through Zone 1 toward the more permeable regions of the unit, under the localized hydraulic gradients that might be induced by the pumping of one (or more) wells. Finally, the low initial groundwater head levels observed in the areas of higher K_h values physically constrain the drawdown conditions under which groundwater pumping would be logistically viable for wells in these areas.

To further evaluate the hydraulic properties and assess the potential producing capacity of the Zone 1 groundwater-bearing unit, a series of step pumping and constant-rate pumping tests was performed at selected Zone 1 wells. The results of these tests are discussed in Sections 4.6.1.2 and 4.6.1.3.

4.6.1.2 Zone 1 Step Pumping Test Results

Step pumping tests were performed at Zone 1 monitoring wells MW05, MW09, and MW10, selected on the basis of slug testing results discussed in Section 4.6.1.1. The pumping rate-versus-drawdown data generated were analyzed to identify the specific capacity and potential ROI of a pumping well at each of these Zone 1 locations. The complete data sets and detailed discussions are in Supplement 6 (on CD), and the results of the tests are summarized in Appendix H.

Estimates of Specific Capacities for Groundwater Zone 1

The stepped pumping tests were conducted in multiple short-term steps (each approximately 1 hr), at incremental pumping rates, to monitor drawdown responses to pumping rates. The relationship between pumping rates and corresponding drawdowns was used to determine specific capacity.

Specific capacity is defined as the observed flow rate (for a specific pumping condition), divided by the resulting drawdown created in the well by that pumping rate. The specific capacity is not a constant; its value decreases with increasing time as the well is pumped at a constant rate and also as the pumping rate itself increases (Kruseman and deRidder 1991). The measurements obtained during the step testing of wells MW09, MW05, and MW10 were used to estimate values of the specific capacity for each well, on the basis of *nominal 1-hr pumping steps*. Figure 4.27 illustrates the relationships determined for each well.

Figure 4.27 shows that, for both wells MW09 and MW10, the physical limits on pumping rates imposed by the configuration of the pump installation and water levels in these wells were effectively reached. *The specific capacity relationships observed for wells MW09 and MW10 were very similar; they indicate a sustainable flow rate (at maximum drawdown under the conditions during the step tests) of < 0.3 gpm for these wells.*

On the basis of the lateral distribution of the K_h values determined from the slug testing in Zone 1, the specific capacity values for most of the Zone 1 wells would be expected to be similar to (within the contour line of 1 ft/d) or lower by 1-2 orders of magnitude than (outside of the contour line) the low specific capacity values identified at MW09 and MW10 (Figure 4.26). *This finding indicates that groundwater extraction (or injection) does not represent a logistically or*

hydraulically practical mechanism for area-wide mitigation of the carbon tetrachloride contamination in groundwater Zone 1 (Figure 4.18).

During the MW05 step test, the physical limits on drawdown could not be achieved in this well because of measures employed to control the pump flow at low rates. Figure 4.27 therefore shows an *estimated* projection (dashed line) of the specific capacity relationship for MW05, based on the trends of the available step test data. The resulting estimate suggested a potential maximum flow rate from this well, *for a 1-hr period*, on the order of 2.5 gpm. A further pumping test using a higher rate was therefore performed; the results are discussed in Section 4.6.1.3.

Estimates of Radius of Influence for Groundwater Zone 1

Throughout the step tests, groundwater levels were monitored, at 5-min intervals, at neighboring wells (Figure 2.10). The ROI of each pumping well was then estimated from the responses to pumping detected at the neighboring wells.

For the MW09 step test, no evidence of induced drawdown was observed at neighboring wells MW02, MW05, MW11, or MW13 in response to the pumping at well MW09. The results indicate a *maximum potential ROI for the pumping of this well* (under the conditions of this step test) that is *less than the distance from well MW09 to the closest presently available observation point (< 124 ft).*

In the MW05 step test, the data recorded for monitoring wells MW01, MW09, MW11, and MW12 also provide no evidence of drawdown at these locations in response to the pumping of well MW05. The test results suggest, however, that approximately 0.07 ft of drawdown might have occurred at the observation point closest to MW05 (well MW02, located approximately 106 ft east of MW05), in response to the pumping of MW05. The water level response observed at well MW02 appeared unusual, however, as no subsequent recovery was detected at MW02 over a 20-hr period following the pumping event.

Hydrographs recorded at monitoring wells MW01, MW07, and MW19 provide no evidence of drawdown in response to the pumping of well MW10 at these locations. The distances from MW10 to wells MW01, MW07, and MW19 range from 163 ft to 194 ft.

Drawdown of approximately 0.8 ft was observed, however, at more distant well MW04 (229 ft from MW10), while no drawdown was detected at a similar distance (234 ft) at MW18. The recorded observations therefore demonstrate that the hydraulic response of the Zone 1 water-bearing unit to pumping at MW10 (under the conditions of the step test) is highly heterogeneous and unpredictable.

4.6.1.3 Zone 1 Constant-Rate Pumping Test Results, at MW05

A constant-rate pumping test was performed by using well MW05 as the pumping well and well MW02 as the closest observation point (Table 3.8, Figure 2.11). Well MW05 was selected for this test because of the relatively high hydraulic conductivity identified at this location by slug testing, as well as the high specific capacity estimated for MW05 on the basis of the step pumping results. The constant-rate testing at MW05 was performed in two short-term events, test 1 and test 2 (instead of an originally planned 24-hr pumping test), because of unexpectedly rapid groundwater drawdown at MW05. The pumping rate, drawdown, and recovery data for each test event are summarized in Appendix I. The complete data sets are in Supplement 7 (on CD).

The results obtained from the two test events were analyzed by using the aquifer test interpretive methods provided in the commercial well test software analysis package AqteSolv for Windows (HydroSolve, Inc.). Numerous alternative analysis methods have been developed for the interpretation of aquifer tests conducted under confined or unconfined conditions, for both relatively simple and more complex aquifer and well geometries. For the present study, multiple analysis methods were screened on the basis of (1) the theoretical applicability of the method to the identified characteristics of the Zone 1 unit and the construction features of the MW05 and MW02 wells, (2) the ability to achieve a satisfactory “fit” to the experimental data with each method within these site-specific constraints, and (3) the levels of documentation and general acceptance by the scientific community. The methods used for this study are described below in the context of the individual wells’ data sets.

The hydraulic properties calculated for each well location are dependent, in part, on the assumed thickness of the water-producing interval that responded to the groundwater pumping during each test, as well as on the construction features and the position of the groundwater level within the well itself. On the basis of analysis of the MW05 lithologic log, an inferred thickness

of 2 ft was assumed for the Zone 1 producing interval at the MW02 and MW05 locations. At MW05, this interval occurs at a depth of approximately 25-26 ft BGL.

Well MW05 Results

Pumping test 1 was initiated at a flow rate of 1.3-1.4 gpm at MW05. The water level declined steadily in response to pumping and then fell rapidly after approximately 70 min, reaching the maximum recordable drawdown in 86 min. Upon full recovery of the water level at MW05, the second test (test 2) was conducted at a lower target rate of approximately 1.2 gpm. The observed water level response was similar to that of test 1; a steady decline in the first 160 min was followed by a marked increase in drawdown, until the maximum recordable drawdown was reached in 187 min.

The data recovered from well MW05 for pumping test 1 and test 2 were evaluated for the potential impacts of background trends and barometric efficiency and corrected as necessary (Supplement 7). The corrected data were analyzed by using several standard interpretive methods (Appendix I). The results for both tests yielded good fits, with one exception, to the theoretical interpretive curves of the Theis (1935) and Cooper-Jacob (1946) analysis methods for fully confined aquifers. Each of these methods returns an estimate of the aquifer transmissivity (T) for the pumping well. (Although a value of aquifer storativity is also generated by each solution technique, these values are invalid when determined from data obtained at a pumping well.) Dividing the resulting transmissivity values by the aquifer thickness (2 ft for the Zone 1 water-bearing interval) gives the estimated K_h value at the pumping well location.

The estimated K_h values derived from the Theis (1935) and Cooper-Jacob (1946) analyses of the MW05 data are summarized in Table 4.2. The calculated estimates range from 45 ft/day to 64 ft/day, and thus they are similar in magnitude to the range of K_h values previously estimated from the slug testing (Section 4.6.1.1) performed at MW05 and nearby wells MW09, MW11, and MW13 (42 ft/day to 102 ft/day; Table 4.1).

The analyses of the MW05 results indicate that a rapid increase in drawdown relative to the theoretical response curves represented by the Theis (1935) and Cooper-Jacob (1946) solutions apparently occurred at drawdowns exceeding approximately 2.0-2.4 ft and after 70 min

in test 1 or 160 min in test 2 (Appendix I). These unexpectedly rapid drawdowns in response to pumping probably reflect changes in aquifer conditions and/or boundary effects.

The identified drawdowns of 2.0-2.4 ft represent actual water levels within the MW05 well casing of approximately 25-25.4 ft TOC. These identified levels correspond very closely to the subsurface position of the Zone 1 water-bearing interval at this location, suggesting that the water-bearing zone experienced a transition from confined to unconfined aquifer conditions as the water level declined through this position. The exact response of a water-bearing unit during such a transition will depend on several site-specific parameters that are not easily predicted; however, as pumping progresses and the water level within the (now unconfined) unit falls, the effective producing thickness of the unit is no longer fixed but decreases as the interval dewaters, resulting in an increased rate of observed drawdown (Kruseman and deRidder 1991).

The rate of drawdown at MW05 might also have increased when the cone of depression generated by the pumping expanded through possible aquifer "boundaries," such as thinning of the producing thickness or decreased permeability in the heterogeneous aquifer at some distance from the pumping well (Kruseman and deRidder 1991; Fetter 1994). The slug test data (Section 4.6.1.1) indicate that the K_h value for the Zone 1 interval might vary significantly over relatively short distances in the vicinity of MW05, suggesting that the possible influence of aquifer heterogeneity on the observed drawdown in this well cannot be ruled out. An evaluation of possible hypothetical boundary impacts was attempted for the present analysis by using the simulation capabilities included as part of the AqteSolv software package; however, only simple (orthogonal) boundary orientations, types, and K_h distributions can be addressed in this manner, and an improved fit to the observed MW05 data could not be achieved.

Although the detailed heterogeneity of hydraulic characteristics in the Zone 1 water-bearing unit at location MW05 could not be uniquely determined from the present test data, as noted above, the results obtained from the step pumping and constant-rate pumping conducted at MW05 together indicate that the practical limitations on groundwater production at this location have been effectively explored.

Well MW02 Results

Well MW02 is the only nearby monitoring point at which water level responses to the constant-rate pumping at MW05 were observed. The pumping test 1 and test 2 results for well MW02 were evaluated by using the Theis (1935) method to simultaneous analyze the pumping and recovery data for these tests. Analysis of the MW02 results could not be performed with the Cooper-Jacob (1946) method, as test-specific criteria (pertaining to the duration of pumping and the MW05-MW02 separation distance) were not met by these data sets.

The measured water level responses at MW02 were very small (about 0.1 ft or less) and generally yielded a relatively poor fit to the theoretical interpretive curves. The results of the Theis (1935) analyses are in Table 4.2. The resulting estimates of K_h, 34 ft/day and 50 ft/day, are again comparable to the slug test results at nearby wells MW05, MW09, MW11, and MW13 (Table 4.1) but are greater by approximately an order of magnitude than the estimates obtained from the slug testing of MW02 (2.2 ft/day to 4.1 ft/day). This observation is again a likely artifact of the heterogeneity of the Zone 1 unit, in view of the highly restricted spatial influence of the slug test procedure (to the immediate vicinity of the wellbore being tested) in comparison to the range of influence achieved by the constant-rate pumping at MW05.

The specific capacity estimated for well MW05 on the basis of the step-test pumping results, *for 1-hr time steps,* is shown in Figure 4.27. A maximum pumping rate of approximately 1.14 gpm was achieved (for a 1-hr period) during the step test because of the configuration of the pumping equipment used. As a result of this limitation, the estimated production behavior of the MW05 well at higher flow rates was *projected* on the basis of the data existing at that time.

Figure 4.28 illustrates the result of using the drawdown levels observed after 1 hr of pumping during each of the constant-rate pumping tests to extend the original specific capacity diagram. As shown, the constant-rate pumping results are in relatively close agreement and thus consistent with the previous specific capacity estimates *for 1-hr time steps*. The results clearly demonstrate, however, that the production capacity of this well deviates sharply from the apparent relationship in Figure 4.28 as the duration of pumping and resulting levels of drawdown increase, because of the inferred characteristics of the Zone 1 groundwater-bearing unit outlined in Section 4.6.1.1.

4.6.1.4 Zone 1 Groundwater Flow Rates and Preferred Migration Pathways

The results of the Zone 1 slug test and pumping test analyses (Table 4.1 and 4.2), in conjunction with the estimated potentiometric surface for this water-bearing zone (Section 4.3.1 and Figure 4.12), provide a basis for quantitative estimation of the ambient groundwater flow rates governing carbon tetrachloride migration in Zone 1. To estimate the magnitude of groundwater movement within Zone 1, Darcy flow velocities[4] were calculated for several potential flow directions at representative locations. The results (Table 4.3) are illustrated in Figure 4.29.

The estimated Darcy velocities range over two orders of magnitude. Groundwater flow in the southwesterly direction, within the identified area having hydraulic conductivity greater than 1 ft/day (Figure 4.29) has the highest calculated velocity (average 3.8×10^{-2} ft/day or 13.97 ft/yr) in Zone 1. The estimated flows in other directions in Zone 1 appear much slower: 2.1×10^{-3} ft/day (0.76 ft/yr) to the northwest, 5.7×10^{-3} ft/day (2.07 ft/yr) to the south, and 3.1×10^{-4} ft/day (0.11 ft/yr) to the west. The results of these calculations are empirically consistent with the observed distribution of carbon tetrachloride concentrations in Zone 1 (Figure 4.30), strongly suggesting that the preferred contaminant migration pathways discussed in Section 4.4.1 are defined primarily by the hydraulic conductivity variations in this unit. The major preferred migration pathway — along a narrow, relatively permeable zone in the southwest direction — is confirmed and is primarily driven by the highest estimated Darcy flow velocity in the Zone 1 groundwater system.

4.6.1.5 Summary of the Zone 1 Results

The main findings from the hydraulic testing conducted in the Zone 1 water-bearing interval are as follows:

- *The average hydraulic conductivity values* estimated from the Zone 1 slug and pumping tests ranged from 0.001 ft/day to 75 ft/day.

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[4] The Darcy flow velocity is an apparent value calculated from Darcy's law. It represents the flow rate of groundwater per unit area of the entire porous medium, measured perpendicular to the direction of flow.

- *The demonstrated sustainable groundwater extraction rate in the area of highest hydraulic conductivity in Zone 1* (tested by pumping at well MW05; Figure 4.26), *is less than 1 gpm.* Short-term pumping rates of < 0.3 gpm were demonstrated at two additional locations (MW09 and MW10) in the relatively more permeable portion of the Zone 1 unit.

- The results of the Zone 1 tests indicate that the production capacity of this unit is restricted by the effective thickness of the few discrete, thin, moist-wet horizons along bedding planes (≤ 2 ft total thickness) that form the water-bearing interval, the heterogeneous hydraulic conductivity of the interval, and the generally limited availability of groundwater within Zone 1.

- The *radius of influence* of the pumping at MW05 was approximately 106 ft, with an observed drawdown of 0.1 ft or less at neighboring well MW02. The ROI observed in response to the pumping of wells MW09 and MW10 was highly heterogeneous and unpredictable.

- *The results of the hydraulic testing conducted in Zone 1 indicate that groundwater pumping (or injection), using conventional wells, does not represent a viable mechanism for hydraulic control or removal of the area-wide contaminated groundwater in Zone 1.*

4.6.2 Estimates of Hydraulic Properties for Groundwater Zone 2

4.6.2.1 Zone 2 Slug Test Results

Slug tests were performed at all six available Zone 2 groundwater monitoring wells. The water level response data obtained from the slug tests were interpreted by using the analysis methods of Bouwer and Rice (Bouwer and Rice 1976; Bouwer 1989) and Hvorslev (1951), as implemented in the commercial software package AqteSolv. The resulting hydraulic conductivity estimates are summarized in Table 4.4. For each data set, the estimated K_h values calculated with the Bouwer and Rice method are of the same magnitude as the values calculated with the Hvorslev method — but roughly 25% lower. The estimated hydraulic conductivities for the Zone 2 unit at Hanover range over approximately one order of magnitude, from

approximately 7.9 ft/day at MW51Z2 to approximately 43 ft/day at MW50Z2, indicating that the Zone 2 unit is less heterogeneous than water-bearing Zone 1. Complete data (time versus residual drawdown) for the slug tests and analysis parameters are in Supplement 5 (on CD). Representative interpretive curve fits for the test data sets are in Appendix G.

The slug test data recovered from monitoring wells MW48Z2 and MW49Z2 could not be analyzed to yield geologically meaningful estimates of the hydraulic conductivity at these locations (as explained in Supplement 5); however, the results obtained for MW48Z2 qualitatively suggest that the K_h value for Zone 2 at this location might be higher than the values observed at the other tested well locations. This finding is qualitatively consistent with the relatively greater thickness of Zone 2 (approximately 5 ft) developed in the shale with limestone facies of Unit 6 at this location, as well as with the rapid water recovery observed in MW48Z2 during sampling.

The combined results of the Zone 2 slug testing suggested that Zone 2 might have a greater capacity for groundwater production than does Zone 1, because of the relatively greater thickness of the Zone 2 unit, the generally less discrete nature of the Zone 2 water-bearing intervals, and the higher estimated K_h values for Zone 2. To generate data needed to test this hypothesis, a constant-rate pumping test was conducted subsequently at Zone 2 well MW44Z2.

4.6.2.2 Zone 2 Constant-Rate Pumping Test Results, at MW44Z2

A constant-rate pumping test of Zone 2 was conducted by using MW44Z2 as the pumping well. Well MW44Z2 is located at a relatively central position along the Zone 2 groundwater flow (and contaminant migration) pathway, as discussed in Section 4.4.2 (Figure 4.25). Neighboring well MW45Z2 and more distant wells MW48Z2-MW51Z2 were used as water level observation points for the test (Figure 2.12). The testing program included an initial, brief step pumping test to estimate the specific capacity at MW44Z2 and to determine appropriate flow rates for a subsequent 24-hr constant-rate test. The complete data sets are in Supplement 8 (on CD), and the results are summarized in Appendix J.

The initial step pumping test was implemented at flow rates that progressively increased from 0.53 gpm to 2.3 gpm at intervals of approximately 30 min and achieved approximately 4 ft of drawdown (35% of the maximum available head in the well). The resulting estimated specific

capacity for the well, for *nominal 30-min pumping steps*, is illustrated in Figure 4.31. On the basis of these results, a maximum potential pumping rate on the order of 4-5 gpm was projected for MW44Z2.

The 24-hr pumping test was performed at a lower rate (approximately 2 gpm) than the projected maximum, in part because of the physical limitations on pump size imposed by the 2-in.-diameter casing of the existing MW44Z2 well. The pumping rates and water level responses at MW44Z2 and the corresponding response data for neighboring observation point MW45Z2 are in Appendix J. No response to the pumping of MW44Z2 was detected any of the other Zone 2 observations points (MW48Z2-MW51Z2; Figure 2.12).

The pumping test data recovered from wells MW44Z2 and MW45Z2 were evaluated for the potential impacts of background water level trends and barometric efficiency, and appropriate corrections to the analytical data were applied (Supplement 8). The corrected data were analyzed by using several aquifer test interpretive methods in the software package AqteSolv, as discussed in Section 4.6.1.3. On the basis of analysis of the MW44Z2 lithologic log, an inferred effective thickness of 3.5 ft was assumed for the Zone 2 interval at the MW44Z2 and MW45Z2 locations. At MW44Z2, multiple thin producing intervals recognized within Zone 2 occur at depths of approximately 31.5-39 ft BGL.

Well MW44Z2 Results

The constant-rate pumping results for well MW44Z2 were evaluated by using several standard interpretive methods. Although the MW44Z2 data, in general, yield a good fit to the theoretical interpretive curve of the Theis (1935) analysis method for fully confined aquifers, the observed drawdown and recovery responses appear to deviate from the Theis curve at the later times. This observed later-time deviation suggests that “leaky-confined” aquifer conditions occur for the Zone 2 unit at the MW44Z2 location. To test this hypothesis, the MW44Z2 test data were evaluated by using the interpretive methods developed for leaky-confined aquifers by Hantush and Jacob (1955) and Hantush (1960). The results of these analyses show that the best empirical fit to the drawdown and recovery data was achieved by using the Hantush methods (Appendix J).

Each of the analysis methods returns an estimate of the aquifer transmissivity (T) for the pumping well. The resulting transmissivity value, divided by the net aquifer thickness (3.5 ft for

the Zone 2 water-bearing interval), gives the estimated K_h value at the pumping well location. The estimated K_h values derived from the Theis (1935), Hantush-Jacob (1955), and Hantush (1960) analyses of the MW44Z2 data are summarized in Table 4.5. The calculated estimates range from 11 ft/day to 14 ft/day.

Well MW45Z2 Results

The corrected pumping test responses for MW45Z2 were also evaluated by using the Theis (1935), Hantush-Jacob (1955), and Hantush (1960) methods to simultaneously analyze the pumping and recovery data for this well.

The identified drawdown response at MW45Z2 was small (about 0.14 ft); however, the analyses demonstrate that the MW45Z2 data yielded a reasonable fit to the theoretical interpretive curves for each method (Appendix J). The results of the analyses are in Table 4.5. The estimates of K_h obtained from the MW45Z2 data ranged from 16 ft/day to 42 ft/day, with the best interpretive fits (16 ft/day to 25 ft/day) again achieved by using the Hantush-Jacob (1955) and Hantush (1960) analysis methods for leaky-confined aquifers.

4.6.2.3 Zone 2 Groundwater Flow Rate and Preferred Migration Pathways

The results of the Zone 2 slug test and pumping test analyses (Tables 4.4 and 4.5), in conjunction with the estimated potentiometric surface for this water-bearing zone (Section 4.3.2 and Figure 4.14), provide a basis for quantitative estimation of the ambient groundwater flow rates governing carbon tetrachloride migration in Zone 2. As discussed in Section 4.4.2, the lateral extent of carbon tetrachloride in Zone 2 represents a relatively narrow, elongated area associated only with the westerly flow component of the Zone 2 groundwater flow system (Figure 4.25), indicating a preferred contaminant migration pathway. Along the westerly flow direction, the hydraulic gradient varied from 0.02 in January 2010 to 0.01 June 2010 (Section 4.3.2). The hydraulic conductivity estimated at well MW44, located near the center of the westerly contaminant migration pathway, ranged from 11-14 ft/day (as determined by constant-rate pumping) to 24 ft/day (as determined by slug testing). The estimated Darcy flow velocity at well MW44 is within the range 0.11-0.48 ft/day (40.15-175.2 ft/yr). These values are greater by approximately one order of magnitude than the maximum flow velocity derived in groundwater Zone 1.

4.6.2.4 Summary of the Zone 2 Results

The main findings from the analyses of the Zone 2 aquifer test data are as follows:

- *The average hydraulic conductivity* values estimated from the Zone 2 slug test and pumping test results ranged from 7.9 ft/day to 43 ft/day, under the assumption of leaky-confined aquifer conditions.

- *The results of the Zone 2 testing suggest this unit has a greater capacity for groundwater production than Zone 1*, because of the relatively greater thickness and generally less discrete nature of the Zone 2 water-bearing intervals, as well as the higher estimated K_h values for Zone 2.

- *The projected production capacity for Zone 2 at well MW44Z2 is on the order of 4-5 gpm, for a 30-min time step*.

- *A sustainable groundwater extraction rate from Zone 2 of > 2 gpm is indicated at the location of well MW44Z2*.

- *The demonstrated ROI for pumping at the MW44Z2 well location (under the conditions employed for the constant-rate testing) is at least 263 ft.*

- *Groundwater extraction as a potential treatment technology therefore appears feasible for this portion of the Zone 2 water-bearing unit.*

4.7 Conceptual Model of the Groundwater Flow and Contaminant Migration System at Hanover

4.7.1 Conceptual Model

The geologic, hydrogeologic, groundwater monitoring, geochemical, and contaminant distribution data presented in Sections 4.1-4.6 provide the technical basis for development of an integrated conceptual model of groundwater flow and contaminant migration within the Hanover

hydrogeologic system. The key elements of this working conceptual model are summarized as follows:

- *Vertical infiltration in the identified contaminant source area (migration pathway 1).* Vertical infiltration of carbon tetrachloride through the vadose zone (including the unconsolidated and bedrock lithostratigraphic Units 1, 2, and 3 [upper portion]) has occurred primarily along the north-south central axis of the former CCC/USDA facility (near locations MW09, MW02, MW05, and MW01), as shown in Figures 4.1 and 4.32. Little residual carbon tetrachloride contamination (≤ 35 µg/kg) currently remains in the vadose zone soils (Figure 4.3), providing an insignificant current and future source to groundwater. A relatively greater mass of contaminants might have been released into the underlying water-bearing Zone 1 in the northern part of the former facility, in the area of locations MW09, MW02, MW05, and MW11 (Figures 4.18 and 4.32).

- *Lateral migration in Zone 1 (migration pathway 2).* Contaminants emanating from the source area outlined above would have entered the Zone 1 groundwater-bearing unit primarily on the western to southwestern side of the prominent groundwater divide beneath the upland area at the former CCC/USDA facility (Figure 4.22), preventing contaminant migration in the groundwater to the east of this area. Groundwater flow and contaminant migration within Zone 1 occurred preferentially to the southwest and northwest, along trends of relatively more permeable materials identified within the Zone 1 unit (Figure 4.33). Migration in other directions within Zone 1 is predicted to occur more slowly, because of the very low K_h values identified in the areas away from these preferred pathways.

- *Vertical migration from Zone 1 to Zone 2 (migration pathway 3).* Vertical migration of contaminants from Zone 1 to Zone 2 is inferred primarily beneath the original vadose zone source area, where the highest Zone 1 hydraulic conductivities were identified (Figures 4.30 and 4.32) and where groundwater mounding is observed in Zone 2 (Figure 4.14). The concentrations of carbon tetrachloride presently identified in Zone 2 are lower than those in Zone 1 by at least one order of magnitude, suggesting that

approximately 10% or less of the groundwater flow within Zone 2 might have originated as vertical recharge from Zone 1. This apparent mixing ratio is empirically consistent with the variations in nitrate concentrations that were also observed in the upland area between Zone 1 and Zone 2.

- *Lateral migration in Zone 2 (migration pathway 4).* Groundwater monitoring indicates that migration of carbon tetrachloride contamination within Zone 2 from the inferred source area has primarily been toward the west, in keeping with the identified patterns of groundwater flow (Figure 4.34) in this unit.

- *Vertical migration to Zone 3 or Zone 4.* No evidence is available to suggest that further vertical migration of contaminants from Zone 2 to Zone 3 or Zone 4 has occurred in the upland source area at the former CCC/USDA facility. An upward hydraulic gradient from Zone 4 to Zone 2 (and Zone 3) is presently indicated in this area, representing an apparent hydraulic barrier to further vertical downward migration.

  As noted in Section 4.4.3, however, the present data suggest that localized contamination of the Zone 3 and Zone 4 groundwater might be possible in the western portions of these units, as a result of potential migration from overlying Zone 2 via artificial conduits provided by several continuously gravel-packed private wells to the west (and downgradient) of the MW44 and MW45 monitoring well locations.

4.7.2 Characteristics of the Contaminant System and Potential Restoration

The spatial distribution of carbon tetrachloride and the variable character of the contaminant system are analyzed and presented in detail in Sections 4.2-4.6. With the aim of achieving a better understanding of the fate of the contaminant system under potential restoration conditions, the investigation results are integrated and summarized below.

The contaminant system can be divided, on the basis of hydraulic conductivity values, into the following subsystems (Figures 4.35 and 4.25):

- Subsystem 1 of Zone 1, a relatively permeable area (K_h = 34-75 ft/day).

- Subsystem 2 of Zone 1, a low-permeability area (K_h = 1-10 ft/day).

- Subsystem 3 of Zone 1, an extremely low-permeability area (K_h = 0.001-1 ft/day).

- The Zone 2 contaminated area (K_h = 7.9-43 ft/day).

The key characteristics of the subsystems are summarized as follows:

- The relatively permeable *Subsystem 1 of Zone 1* (K_h = 34-75 ft/day) is approximately 6% of the total area of the Zone 1 contaminant system. The lateral extent of Subsystem 1 generally coincides with the distribution of high carbon tetrachloride concentrations in groundwater (> 500 µg/L). The results of pumping tests conducted in Subsystem 1 indicate a sustainable pumping rate of less than 1 gpm and an ROI value of approximately 106 ft. These findings are consistent with the extremely limited effective thickness and water availability and the high heterogeneity of the Zone 1 unit in Subsystem 1. The implication of these characteristics (Table 4.6) is that application of conventional treatment technologies in Subsystem 1 will not be a viable mechanism for removal or containment of contaminants via extraction or injection.

- The low-permeability *Subsystem 2 of Zone 1* (K_h = 1-10 ft/day) covers 31% of the total area of the Zone 1 contaminant system. Concentrations of carbon tetrachloride in this area are typically in the range 100-500 µg/L. A very low sustainable pumping rate (< 0.3 gpm) and variable ROI values were identified for this contaminant subsystem (Table 4.6). Consequently, currently available response technologies (conventional and non-conventional) will not provide a viable mechanism for removal or treatment of the contaminants in Subsystem 2 via extraction or injection.

- The extremely low-permeability *Subsystem 3 of Zone 1* (K_h = 0.001-1 ft/day) represents 63% of the total area of the Zone 1 contaminant system. In 30% of

Subsystem 3, the concentrations of carbon tetrachloride are in the range 100-500 µg/L, while in 70% of Subsystem 3, the concentrations are 5-100 µg/L. Most of Subsystem 3 has extremely low hydraulic conductivity ($K_h = 10^{-2}$ to 10^{-3} ft/day), and water level recovery in wells has been observed to be slow (requiring 20-30 days). The result is an extremely low anticipated sustainable pumping rate of 10^{-2} to 10^{-3} gpm, a value lower than that in Subsystem 2 of Zone 1 by one to two orders of magnitude (Table 4.6). Consequently, currently available response technologies (conventional and non-conventional) will not provide a viable mechanism for removal or treatment of the contaminants in Subsystem 3 via extraction or injection.

- The lateral extent of contamination in Zone 1 is effectively constrained by the erosional limits of Zone 1.

- The Zone 2 contaminated area (7.9-43 ft/day) is limited to a relatively narrow pathway extending westerly from the former CCC/USDA facility. The concentration of carbon tetrachloride in this area is low, in the range of 5-35 µg/L. The results of the pumping test conducted in this area of Zone 2 indicate an anticipated sustainable pumping rate of > 2 gpm and an ROI value of at least 263 ft. Groundwater extraction as a potential response technology appears to be feasible for at least the tested portion of the Zone 2 contaminant system.

On the basis of overall characteristics of the contaminant system in groundwater Zone 1, 94% of the total area of the Zone 1 contaminant system (including Subsystem 2 and Subsystem 3) are not amenable to extraction or injection technologies that could restore groundwater to carbon tetrachloride concentrations below the MCL and the KDHE Tier 2 standard value of 5 µg/L. Further discussions related to a CAS for the Hanover site are in Section 6.

4.8 Evaluation of Potential Vapor Intrusion Attributable to Subsurface Contamination

The migration of vapors into enclosed structures represents a potentially significant pathway for the indirect exposure of occupants to VOCs present in subsurface soils, in

groundwater, or in both. The occurrence and impacts of VI at any specific location or structure at a site can be difficult to identify and are often impossible to predict, however, because of the very complex interplay of geologic, hydrologic, geochemical, meteorologic, and building-specific factors that together affect the potential efficiency of this pathway. Positive recognition of VI to indoor air requires, at minimum, documentation of the following three critical components of a complete exposure pathway:

- A source of vapors, in the form of contamination in subsurface soils, groundwater, or both.
- Demonstrated migration of vapors from the source(s), through the vadose zone, and into structures.
- Potential receptors (occupants in residences or other private or public buildings) within the range of lateral and vertical vapor migration from the source(s).

In July 2007, in response to residents' concerns regarding possible VI, indoor air samples were collected in basement areas of nine residences on and immediately adjacent to the former CCC/USDA grain storage facility. Carbon tetrachloride was detected at low levels in four of the nine homes, at concentrations ranging from 1.4 $\mu g/m^3$ to 4.8 $\mu g/m^3$ (Figure 1.6), suggesting the possibility of VI at these locations. The results of this preliminary sampling were inconclusive, however, because VOCs (including carbon tetrachloride) can originate from numerous potential sources within a home that are not related to upward VI. On the basis of these preliminary results (Argonne 2008b), the KDHE requested further sampling to investigate for possible VI to indoor air at the Hanover site (KDHE 2007c).

4.8.1 Overview of the Vapor Intrusion Investigation Program

During 2009-2010, a series of VI-related investigations and actions (Argonne 2008b) was conducted, with the approval of the KDHE (2008b,c,e, 2009a, 2010a,c), as an integral part of the comprehensive site characterization at Hanover. The technical elements of the VI program were developed to address three primary technical objectives, as follows:

- Identify the specific areas of the site, and hence possible receptors, that might be susceptible to VI linked to carbon tetrachloride contamination (in soils or groundwater) associated with the former CCC/USDA facility.

- Investigate for the presence of a complete VI pathway at each potential receptor location, and quantitatively evaluate the impacts to indoor air arising via this pathway.

- On the basis of these findings, take actions necessary to mitigate any unacceptable risks to human health identified as a result of VI to indoor air.

In this section, the results of the soil-, groundwater-, and VI-specific investigation activities at Hanover are presented and discussed in the context of the above objectives.

4.8.2 Identification of Potential Source Areas for Vapor Intrusion

To identify areas potentially susceptible to VI, the distributions and concentrations of carbon tetrachloride in the vadose zone soils and groundwater were screened on the basis of KDHE (2007b) guidance regarding VI. Specifically, areas within a lateral distance of 100 ft and a vertical distance of 40 ft from identified soil contamination (at carbon tetrachloride concentrations above 200 μg/kg) or groundwater contamination (above 5.0 μg/L for carbon tetrachloride) were determined to be potential areas of concern for VI.

4.8.2.1 Evaluation of the Carbon Tetrachloride Distribution in Soils

The vadose zone soils at Hanover were sampled extensively to evaluate the former CCC/USDA facility as a potential source of the carbon tetrachloride contamination (Section 4.1). The 2009-2010 studies included vertical soil profiling for VOCs analyses at 38 locations in and near the former CCC/USDA facility (Figures 2.1 and 2.2). Trace to low levels of carbon tetrachloride were detected at only 8 locations, at maximum concentrations ranging from an estimated 3.0 μg/kg (at MW08) to 35 μg/kg (at MW02; Table 3.1, Figures 4.1 and 4.3).

The depths to the residual contamination in the vadose zone soils ranged from 14 ft to 33 ft BGL; however, the identified concentrations of carbon tetrachloride were well below the

KDHE target value for soils (200 μg/kg) noted above. Therefore, no areas were identified as being at risk of potential VI in association with the identified soil contamination at the former CCC/USDA facility.

4.8.2.2 Evaluation of the Carbon Tetrachloride Distribution in Groundwater

Carbon tetrachloride representing a potential concern for VI was identified in groundwater-bearing Zones 1 and 2. No carbon tetrachloride contamination was detected in the deeper groundwater-bearing Zones 3 and 4 (Section 4.4).

In groundwater Zone 1, carbon tetrachloride concentrations ranging from 1 μg/L to 617 μg/L were detected at depths ranging from 17 ft to 31 ft BGL (Figure 4.18). Figure 4.22 depicts the interpreted lateral extent (in groundwater Zone 1) of carbon tetrachloride concentrations equal to or greater than the KDHE target level for the consideration of VI (5 μg/L) for this contaminant.

In groundwater Zone 2, carbon tetrachloride was detected at concentrations (ranging from 5.1 μg/L to 35 μg/L) exceeding the target value of 5 μg/L at 6 of 22 locations sampled, and at trace levels (< 5 μg/L) at 2 additional locations (Figure 4.23). In this water-bearing unit, the identified contamination is interpreted to lie within a relatively narrow area that extends westward from the former CCC/USDA facility, toward the erosional margin of the Zone 2 interval (Figure 4.25).

Figure 4.36 summarizes the areas overlying the interpreted contaminant distributions in groundwater Zones 1 and 2 that were targeted for the 2009-2010 VI investigation, in accord with the KDHE (2007b) guidance. These areas are defined as follows:

- *VI Investigation Area 1*. The carbon tetrachloride contamination detected throughout Zone 1 lies within 40 ft of the ground surface in this area, and therefore it falls within the target depth range (≤ 40 ft BGL) recommended by the KDHE (2007b) for the consideration of VI. Figures 4.18 and 4.22 illustrate that the highest concentrations of carbon tetrachloride (> 300 μg/L) in the Zone 1 groundwater are found within, or just beyond, the limits of the former CCC/USDA grain storage facility. As noted above, the preliminary

sampling in 2007 identified carbon tetrachloride contamination in indoor air at four of nine homes that are presently associated with the former CCC/USDA property. In light of these observations, the area encompassing these homes (and the highest contaminant concentrations in the Zone 1 groundwater) was prioritized for further examination during the 2009-2010 VI investigation. This area is identified in Figure 4.36.

- *VI Investigation Area 2*. This is the remainder of the area overlying the identified carbon tetrachloride contamination in groundwater-bearing Zone 1 (Figures 4.18 and 4.22). It is associated with the southwestern, western, and northwestern portions of the Zone 1 contaminant distribution identified in Figure 4.36. Carbon tetrachloride levels ranging from 1 μg/L to 179 μg/L were detected in these more downgradient and marginal portions of the Zone 1 groundwater plume.

- *VI Investigation Area 3*. Beneath the upland area formerly occupied by the CCC/USDA facility, the depth of contaminated groundwater-bearing Zone 2 (approximately 55 ft BGL at MW49Z2) is greater than the 40-ft target depth recommended by the KDHE (2007b) for the consideration of VI. In the more downgradient portions of the Zone 2 carbon tetrachloride distribution, however, the identified contamination becomes progressively shallower as a result of topographic downcutting on the western flank of the upland area (Figure 4.20), resulting in depths to Zone 2 of approximately 20 ft BGL or less near the interpreted margin of this interval. On the basis of these relationships, VI Investigation Area 3 is delineated in Figure 4.36 as the portion of the carbon tetrachloride distribution in groundwater-bearing Zone 2 that might pose a threat of VI to nearby surface structures.

On the basis of the lateral offset criterion of 100 ft recommended by the KDHE (2007b), approximately 57 occupied residences were identified at Hanover for consideration of possible VI: 9 homes in Area 1, 38 residences in or adjacent to Area 2 (associated with the groundwater contamination in Zone 1), and 10 homes in or adjacent to Area 3 (associated with the contamination in Zone 2 at depths of ≤ 40 ft BGL).

4.8.3 Investigation of Vapor Migration Pathways and the Impacts of Vapor Intrusion to Indoor Air

A complete VI pathway requires the movement of contaminant vapors (originating from a subsurface soil or groundwater source) (1) via soil gas within the unsaturated pore space of the vadose zone soil column and (2) from the soils through the foundation and into the interior air space of a residence or other inhabited structure. To demonstrate the presence of a complete VI migration pathway, the coincident occurrence of contaminant vapors both immediately outside (in soil gas surrounding the building footprint, in "sub-slab" vapor directly beneath the building foundation, or in both) and inside a target building must ideally be demonstrated. If the results of these efforts indicate that VI is occurring, additional sampling might be required to obtain a representative indication of the longer-term impacts of the VI on indoor air quality.

The 2009-2010 VI sampling program to address these issues at Hanover was implemented in sequential steps of multiple sampling events. This approach was employed so that information gathered during each stage could be evaluated and used in the planning of subsequent stages of the investigation. An overview of the investigative tasks completed during the VI study is in Sections 1.3 and 2.5, and a detailed chronology of the individual sampling events is in Table 4.7. The analytical results for the individual sampling events are in Appendix K and Tables 3.10-3.16. For the purposes of this discussion, however, the results of these events are presented in Sections 4.8.3.1-4.8.3.3 in the context of three main initiatives that were addressed during the investigation of vapor migration pathways and VI impacts to indoor air.

4.8.3.1 Investigation for Complete Migration Pathways in Spring 2009

To investigate for evidence of migration of contaminated soil vapor into indoor air, the following methods were applied or attempted at the potentially affected residences identified in association with VI Investigation Area 1, Area 2, and Area 3 (Figure 4.36):

- Collection of soil gas samples adjacent to the foundations of selected residences, with on-site screening analysis for carbon tetrachloride (Figure 2.13; Section 3.9.2).

- Coupled sampling of sub-slab vapor and indoor air in Area 1 residences for laboratory VOCs analysis, as well as sampling at selected locations for

analysis of radon as a supplemental tracer of soil gas movement (Section 3.9.1).

- Coupled sub-slab vapor and indoor air sampling in Areas 2 and 3 for on-site screening for carbon tetrachloride (Section 3.9.2).

The KDHE standard for carbon tetrachloride in indoor air (Table 2.1) was used as the primary standard value for consideration of the soil gas, sub-slab vapor, and indoor air samples collected throughout the 2009-2010 VI investigations. As discussed in detail in Section 2.6.3, however, the value of this standard was revised by the KDHE on March 31, 2010, from an initial concentration of 1.6 $\mu g/m^3$ to an adjusted concentration of 4.055 $\mu g/m^3$. The quantitative evaluations of carbon tetrachloride levels detected in samples during the February-April 2009 field activities described in this section, which served as the basis for decision making during the course of the field program, are therefore presented in reference to the standard of 1.6 $\mu g/m^3$ that was in force at that time. An attenuation factor of 0.01 (KDHE 2007b) was used for the consideration of both soil gas and sub-slab vapor values, yielding a target maximum concentration for carbon tetrachloride of 160 $\mu g/m^3$ in these sample types at the time of the February-April 2009 sampling events.

Results of the Soil Gas Survey

A systematic soil gas survey was initiated at Hanover in late March 2009 in an attempt to locate contaminated subsurface soil gas in the immediate vicinity of more than 50 residences, located primarily in Area 2 and Area 3 (Figure 4.36), that might be affected by VI (Section 4.8.2). The use of this approach permitted the VI sampling program to proceed with minimal disruption at the relatively large number of locations targeted for investigation. The soil gas samples were collected at an average depth of 8 ft BGL, equivalent to the foundation depth of the residential structures. The samples were screened on-site for carbon tetrachloride by using a GC-ECD analysis technique to permit rapid evaluation of the resulting analytical data as the survey progressed (Section 3.9.2). The results for the soil gas analyses for carbon tetrachloride (Table 3.11) are illustrated in Figure 4.37.

In Areas 2 and 3, soil gas samples were collected initially at 47 locations, primarily surrounding residential structures. Carbon tetrachloride was identified at 9 locations, at

concentrations ranging from 9 μg/m^3 to 700 μg/m^3. The highest concentration of carbon tetrachloride in soil gas (700 μg/m^3) was detected at a location between the two homes at 408 E. Elm Street and 412 E. Elm Street; however, this value was not corroborated by the concentrations (ranging from no detection to 22 μg/m^3) identified at any of the adjacent sampling locations (Figure 4.37). The concentration identified at this location represented the only sample result that exceeded the calculated target screening value of 160 μg/m^3 for carbon tetrachloride in soil gas.

To assist in the evaluation of the soil gas data, four soil gas samples were collected from points surrounding a residence in Area 1 (Figure 4.37) that is known, on the basis of sub-slab vapor and indoor air analyses, to have been affected by VI (see below). Carbon tetrachloride was detected (at a concentration of 85 μg/m^3) in only one of the four soil gas samples, while a concentration of 62,000 μg/m^3 was detected in the corresponding sub-slab sample. A similar lack of correlation between analytical results for soil gas samples and adjacent sub-slab samples was also noted at other locations within the study area, bringing into question the reliability of the soil gas analysis method for identification of residences susceptible to VI at this site. On the basis of these observations, further implementation of the soil gas sampling technique was discontinued, with the approval of the KDHE project manager, in favor of the more direct approach of coupled sub-slab vapor and indoor air sampling and analysis.

Results of Coupled Sub-Slab Vapor and Indoor Air Sampling

Coupled sampling of sub-slab vapor and indoor air was initially conducted (in February and early March 2009) at the nine residences identified in VI Area 1 (Figure 4.36). Indoor air samples were collected, over a 24-hr period, in the lowest level (basement) and on the first floor of each home. Grab samples of sub-slab vapor were collected at four of the nine residences. In light of the previous (2007) detections of carbon tetrachloride in indoor air in several of these homes, the sub-slab vapor and indoor air samples collected in Area 1 were submitted for laboratory analysis of VOCs by EPA method TO-15 (Section 3.9.1). To provide a secondary line of evidence for potential VI in Area 1, sub-slab vapor and indoor air samples were also collected in three selected homes for radon analyses. The radon analyses were conducted at the University of Southern California, Los Angeles, California.

The results of the sampling in the Area 1 residences (Table 3.10) in February-March 2009 are summarized in Figure 4.38. Carbon tetrachloride was detected in indoor air at five of

the nine Area 1 homes, at concentrations ranging from 1.8 μg/m^3 to 26 μg/m^3. At each of these locations, an increased level of carbon tetrachloride was identified in the basement air relative to first-floor air. This apparent trend of increasing carbon tetrachloride concentration with depth was confirmed by analysis of sub-slab vapor samples collected at four of the Area 1 residences (400 N. East Street, 400 E. Kensington Street, 413 E. Kensington Street, and 298 N. Belgrave Street), as well as by the results of radon analyses for samples collected at the 400 N. East Street, 400 E. Kensington Street, and 413 E. Kensington Street locations (Figure 4.38). The demonstrated presence of an upward gradient in concentrations from the sub-slab vapor to indoor air at these locations confirms an influence of upward vapor migration and intrusion to certain structures in VI Investigation Area 1, in association with the contamination in groundwater Zone 1.

Carbon tetrachloride levels ranging from 11 μg/m^3 to 26 μg/m^3 were detected in the indoor air at two of the Area 1 residences: 400 N. East Street and 413 E. Kensington Street (Figure 4.38). These concentrations are greater by roughly one order of magnitude than the KDHE standard of 1.6 μg/m^3 (in force at the time of these analyses) for this contaminant in indoor air. Radon levels ranging from 5.2 pCi/L to 9.4 pCi/L (above the EPA action level of 4.0 pCi/L for this contaminant in air; Section 2.6.3) were also detected in these homes (Figure 4.38). On the basis of these analyses, in spring 2009 the homes at 400 N. East Street and 413 E. Kensington Street were mutually identified by the CCC/USDA and the KDHE as candidates for response action. The efforts of the CCC/USDA to provide mitigation of the indoor air contamination at these homes, with the approval of the KDHE, are discussed in Section 4.8.4.

Carbon tetrachloride concentrations ranging from no detection to 2.9 μg/m^3 were identified in the first-floor air of the three remaining Area 1 homes (400 E. Kensington Street, 414 E. Kensington Street, and 301 N. Belgrave Street) that showed evidence of upward VI (Figure 4.38). Radon was also identified in the residence at 400 E. Kensington Street, at a concentration of 8.0 pCi/L (twice the EPA action level for this contaminant). At the request of the KDHE, additional monitoring of the indoor air was conducted to verify the impact of VI at these three locations (Section 4.8.3.2).

Low levels of chloroform (3.4-3.6 μg/m^3) were detected in the indoor air samples from one of the residences in Area 1 (298 N. Belgrave Street). No evidence of carbon tetrachloride VI was found in association with this contaminant, however, and no chloroform was identified in

the associated sub-slab soil vapor sample collected at this location. These observations indicate that the chloroform contamination at this home does not reflect upward VI by this contaminant.

Coupled sampling of sub-slab vapor and indoor air was performed in late March and early April 2009 at approximately 51 locations associated with investigation Areas 2 and 3 (Figure 4.36) upon termination of the soil gas sampling effort described above. At each of these locations, grab samples of sub-slab vapor, basement air, and/or first-floor air were collected, subject to access approval and the specific characteristics of the structure under investigation. The sampling locations in Areas 2 and 3 included private residences, several parking areas adjacent to public buildings, and a multi-tenant housing facility. The samples were screened on-site for carbon tetrachloride (by using a GC-ECD analysis technique) to permit evaluation of the resulting analytical data as the study progressed. At selected locations, samples were also collected for laboratory verification analyses by EPA Method TO-15 (Section 3.9.2). The results of the analyses for carbon tetrachloride (Table 3.12) are summarized in Figure 4.39.

Carbon tetrachloride was detected in sub-slab vapor samples collected at 22 locations associated with the contamination identified in groundwater Zone 1 and Zone 2, at concentrations ranging from 7.2 $\mu g/m^3$ to 4,500 $\mu g/m^3$. Sub-slab carbon tetrachloride concentrations exceeding the calculated target screening value of 160 $\mu g/m^3$ for this contaminant (in soil gas) were detected at only 14 of these locations, however, in each case in close association with the contamination identified in groundwater Area 2 of Zone 1 (Figures 4.39 and 4.36). Figure 4.39 illustrates that no indoor air contamination was identified at any location associated with groundwater Zone 1 or Zone 2 and having a sub-slab carbon tetrachloride concentration below the target screening value of 160 $\mu g/m^3$.

Carbon tetrachloride was detected in indoor air at 12 of the 14 locations (noted above) having elevated (> 160 $\mu g/m^3$) contaminant levels in sub-slab vapor. At each of these 12 homes, a pattern of decreasing contaminant levels was identified, with vertical progression from the sub-slab to the basement and first-floor indoor air samples. At the remaining 2 homes (401 E. Elm Street and 404 E. North Street; Figure 4.39), carbon tetrachloride was detected in the sub-slab vapor (at 400 $\mu g/m^3$ and 180 $\mu g/m^3$, respectively), but no indoor air contamination was detected. The demonstrated presence of an upward gradient in concentrations from the sub-slab vapor to indoor air at these locations confirms an influence of upward vapor migration and intrusion (to certain structures) in VI Investigation Area 2, in association with the contamination in groundwater Zone 1 (Figure 4.39).

Carbon tetrachloride levels of 18 μg/m^3 and 14 μg/m^3 were detected, respectively, in the basement and first-floor air samples from the home at 311 N. East Street, directly west of the former CCC/USDA facility (Figure 4.39). These concentrations are greater by roughly one order of magnitude than the KDHE standard of 1.6 μg/m^3 (in force at the time of these analyses) for this contaminant in indoor air. On the basis of these results, in spring 2009 the CCC/USDA and the KDHE identified this residence as a third candidate for response action. With the KDHE's approval, the CCC/USDA took action to provide mitigation of the indoor air contamination at this home, as described in Section 4.8.4.

Relatively low levels of carbon tetrachloride, ranging from no detection to 2.7 μg/m^3, were identified in the first-floor air of the 11 remaining homes that showed evidence of indoor air contamination by VI (Figure 4.39). Carbon tetrachloride concentrations ranging from 1.7 μg/m^3 to 22 μg/m^3 were identified in the basements at these locations.

On the basis of these findings, 13 residences associated with the carbon tetrachloride contamination in groundwater-bearing Zone 1 (in addition to the 3 homes previously identified in Area 1 and Area 2) were identified in VI Investigation Area 2 for further indoor air monitoring to confirm the impact of VI at these locations (Section 4.8.3.2). The 13 homes selected include all of those identified as having carbon tetrachloride concentrations in sub-slab vapor greater than the calculated target screening value of 160 μg/m^3 for this contaminant (Figure 4.39). The street addresses of these 13 homes are as follows:

- On N. East Street: 211
- On E. Elm Street: 309, 311, 400, 401, 405, 406, 408, 409, 412, 513
- On E. North Street: 312, 404

The results of the coupled sub-slab vapor and indoor air analyses for carbon tetrachloride and radon can be used to estimate the apparent attenuation factors affecting the concentrations of these contaminants as they pass from the sub-slab vapor through each building foundation and into the basement of the structure. The calculated attenuation factors range from 0.0004 to 0.0457 for carbon tetrachloride and from 0.0020 to 0.0062 for radon. Although the resulting attenuation factors vary relatively widely, a majority of the calculated values (with only two exceptions) fall below the empirical factor of 0.01 employed in this study for the consideration of

soil gas and sub-slab concentrations, indicating that the latter value represents a reasonable conservative estimate for this parameter.

4.8.3.2 Confirmation of Vapor Intrusion Impacts to Indoor Air Quality in Summer 2009 and Winter 2010

On the basis of the sub-slab vapor and indoor air analyses reviewed in Section 4.8.3.1, 16 residences (3 homes in Area 1 and 13 in Area 2) were identified for additional monitoring and further evaluation of the impacts of VI to indoor air. Two subsequent residential indoor air sampling studies were conducted. The first occurred during the summer (August) of 2009, and the second (at the request of the KDHE) was in the winter (January-February) of 2010. In keeping with the KDHE (2007b) guidance, these time periods were selected for the sampling under the assumption that the potential effects of external (outdoor) air circulation and exchange would be minimized in most homes during these seasons.

Summer 2009 Confirmation Sampling

In summer 2009, indoor air samples were collected, over a 24-hr period, in the basement and on the first floor of each home tested. The samples were submitted for laboratory analysis of VOCs by EPA method TO-15. In addition to the 16 locations identified in Section 4.8.3.1, samples of sub-slab vapor and of basement and first-floor indoor air were also collected in August 2009 at 1 home (303 N. East Street) adjacent to the former CCC/USDA facility that had been inaccessible during the previous (spring 2009) sampling events (Section 3.9.3). The results of these analyses (Table 3.13) are summarized in Figure 4.40.

Carbon tetrachloride was detected in indoor air at 14 of the 17 residences sampled in summer 2009, at concentrations ranging from 1.4 $\mu g/m^3$ to 17 $\mu g/m^3$. Figures 4.38, 4.39, and 4.40 indicate that the carbon tetrachloride levels at all but two of the locations tested in summer 2009 (on the basis of 24-hr composite samples) were comparable to the corresponding values identified during the spring 2009 sampling events, showing only small increases or decreases relative to the earlier results. The maximum carbon tetrachloride concentrations in both basement and first-floor air (17 $\mu g/m^3$ and 11 $\mu g/m^3$, respectively) during the summer 2009 sampling event occurred at 408 E. Elm Street, reflecting an approximate threefold increase in the levels at this location. In contrast, an approximate sevenfold decrease in the concentration of carbon

tetrachloride (from 22 μg/m^3 to 2.9 μg/m^3) was observed in the basement air sampled at 405 E. Elm Street, while little change was noted in the corresponding first-floor air samples.

Low levels of chloroform, generally ranging (with one exception) from 1.1 μg/m^3 to 4.6 μg/m^3, were detected in seven of the homes sampled in August 2009. At 309 E. Elm Street, more elevated levels (9.3 μg/m^3 and 18 μg/m^3, respectively) were found in the basement and first-floor air (Figure 4.40). At each of these locations, no clear pattern is evident of decreasing contaminant concentrations from basement to first-floor air (as observed for the associated carbon tetrachloride levels). In light of this observation and the relatively common occurrence of low levels of chloroform in many household materials and chemicals (including in public water supplies as a by-product of chlorination), the identified presence of chloroform in these homes does not suggest an origin via upward contaminant vapor migration to indoor air. This interpretation is further supported by the winter 2010 sampling results (outlined below), which showed a decrease in chloroform concentrations at all of the August 2009 sampling locations; no chloroform was detected in basement air at any of these homes, and only low levels (0.98 μg/m^3 to 1.3 μg/m^3) were identified in first-floor air, at three locations.

Winter 2010 Confirmation Sampling

In January 2010, at the KDHE's request, indoor air samples were collected at 15 of the 17 homes sampled in August 2009. The other 2 of the 17 homes (301 N. Belgrave Street and 414 E. Kensington Street, at the former CCC/USDA facility in Area 1; Figures 4.36 and 4.38) were not accessible for this January 2010 sampling event.

In February 2010, indoor air samples were collected at three of the homes (309 and 310 N. Hanover Street, and 314 N. Hollenberg Street; Figure 4.39) previously investigated in spring 2009, as well as at six additional homes along North Hanover Street (address 211) and North Hollenberg Street (addresses 208, 212, 300, 304, and 308), in light of further information on the distribution of carbon tetrachloride contamination in groundwater Zone 2 that had been obtained during Zone 2-Zone 4 characterization studies conducted in October 2009.

In view of the historically elevated radon levels identified in the Hanover region of Washington County, the CCC/USDA offered radon testing to residents whose homes were being sampled for VOCs in January and February 2010, to serve as a possible supplemental indicator

of upward VI to the indoor air at these locations. Radon test kits obtained from the Washington County offices were placed in the basements of the participating homes and were retrieved for analysis after three or four days (Section 3.9.3).

In both the January and February 2010 sampling events, indoor air samples for VOCs analyses were collected over a 24-hr period in the basement and on the first floor of each home and analyzed by EPA Method TO-15. Samples for radon analysis were submitted through the National Radon Program Services at Kansas State University, Manhattan, Kansas. The results of the winter 2010 analyses for VOCs and radon are in Tables 3.14 and 3.15. The results of the analyses for VOCs are illustrated in Figure 4.41.

The results of the winter 2010 VOCs analyses (Figure 4.41) were again generally comparable to the spring 2009 screening results (Figure 4.39; Section 4.8.3.1) and the summer 2009 results (Figure 4.40) for the homes sampled in each of these events, suggesting that the carbon tetrachloride VI to indoor air at these locations has been consistent over time. Carbon tetrachloride was detected in indoor air at 10 of the 15 homes sampled in association with the Zone 1 groundwater contamination, at levels ranging from 1.3 $\mu g/m^3$ to 6.9 $\mu g/m^3$. No carbon tetrachloride was detected in any of the homes associated with the contamination in groundwater Zone 2 (Figure 4.41). The highest concentrations of carbon tetrachloride were again detected in both basement and first-floor air (6.9 $\mu g/m^3$ and 5.9 $\mu g/m^3$, respectively) at 408 E. Elm Street (Zone 1). Carbon tetrachloride was also detected at 4.7 $\mu g/m^3$ in the basement air sample collected at 405 E. Elm Street (also Zone 1). In August 2009, a carbon tetrachloride concentration of only 2.9 $\mu g/m^3$ had been detected in the basement air at this home (Figure 4.40); however, a concentration of 22 $\mu g/m^3$ was identified at this location during the spring 2009 screening event in association with a sub-slab carbon tetrachloride level of 2,800 $\mu g/m^3$ (Figure 4.39).

No chloroform was detected in basement air at any of the homes sampled in winter 2010. Low levels (0.98 $\mu g/m^3$ to 1.7 $\mu g/m^3$) of chloroform were identified in the first-floor air at five locations. These isolated, first-floor detections show no evidence of an origin from upward contaminant VI.

The results of the radon analyses conducted as part of the winter sampling events are summarized in Tables 3.14 and 3.15. The radon levels detected ranged from 2.1 pCi/L to 27.6 pCi/L, with values of approximately 8 pCi/L or more (equal to or greater than twice the

EPA action level of 4.0 pCi/L for this contaminant in air) occurring in 15 of the 23 homes tested in these events (Figure 4.42). The relatively elevated levels of radon identified in these homes indicate that each structure has some susceptibility to the intrusion of vapors from the subsurface soils; however, only a qualitative correlation could be established, among the tested locations, between the occurrence of radon and the occurrence of carbon tetrachloride in the indoor air (Figure 4.43). A similar relationship was noted for the radon and carbon tetrachloride analyses of sub-slab vapor and indoor air samples from selected homes at the former CCC/USDA facility, as discussed in Section 4.8.3.1. The results of these analyses demonstrated that radon data could not be readily used as a surrogate tracer of probable carbon tetrachloride VI to indoor air.

Comparison of Results over Time

Comparison of the results of the spring 2009, summer 2009, and winter 2010 VI sampling events indicates that the levels of carbon tetrachloride contamination attributable to VI in the homes selected for additional monitoring (Section 4.8.3.1) have been relatively stable over time and hence provide reasonable estimates of the present indoor air exposure levels for these locations. Only three homes (in addition to the three homes previously designated for response action on the basis of the spring 2009 data alone; Section 4.8.3.1) demonstrated indoor air carbon tetrachloride levels that exceed the present KDHE standard of 4.055 $\mu g/m^3$ for this contaminant. These three additional homes are as follows:

- *408 E. Elm Street.* Carbon tetrachloride levels detected ranged from 6.0 $\mu g/m^3$ to 17 $\mu g/m^3$ in basement air and from 2.7 $\mu g/m^3$ to 11 $\mu g/m^3$ in first-floor air during all three of the sampling and monitoring episodes at this home, in association with a sub-slab vapor concentration of 1,900 $\mu g/m^3$.

- *405 E. Elm Street.* A carbon tetrachloride concentration of 22 $\mu g/m^3$ was detected in basement air during the spring 2009 screening at this location, in association with a sub-slab level of 2,800 $\mu g/m^3$. The contaminant level in basement air decreased (to 2.9 $\mu g/m^3$) in summer 2009, but then it returned to a concentration (4.7 $\mu g/m^3$) exceeding the KDHE standard of 4.055 $\mu g/m^3$ in winter 2010. The first-floor contaminant levels at this home ($\leq$ 2.3 $\mu g/m^3$) remained below this standard throughout the 2009-2010 investigations.

- *406 E. Elm Street.* Carbon tetrachloride was detected at a concentration of 9.4 μg/m^3 in basement air during the spring 2009 screening, in association with a sub-slab vapor level of 410 μg/m^3. The basement air contaminant levels at this home progressively decreased, however, to a value (3.9 μg/m^3) below the KDHE standard of 4.055 μg/m^3 in winter 2010. The first-floor contaminant levels at this home (≤ 2.1 μg/m^3) remained below this standard throughout the 2009-2010 investigations.

On the basis of these findings, the CCC/USDA and the KDHE determined, in early spring 2010, that response action was also warranted at the 408 and 405 E. Elm Street residences, bringing the total number of homes designated for treatment of the indoor air to five (Figure 4.44). The mitigation efforts implemented by the CCC/USDA at these homes are discussed in Section 4.8.4.

4.8.3.3 Investigation for Possible VI to Indoor Air at the Hanover Public School Facility and St. John's School in Winter 2010

The areas targeted for the 2009-2010 VI investigation were selected through critical evaluation of the subsurface carbon tetrachloride distribution documented at the Hanover site (Sections 4.1-4.4) and KDHE (2007b) guidance for the consideration of possible VI to occupied structures. As discussed in Section 4.8.2, Figure 4.36 illustrates the interpreted areas of concern that were identified in association with the carbon tetrachloride contamination in groundwater-bearing Zone 1 (VI Investigation Areas 1 and 2) and in the shallower (< 40 ft BGL; VI Investigation Area 3) portion of Zone 2. The results of the subsequent VI studies (Sections 4.8.3.1 and 4.8.3.2) indicate that only five homes, all lying within the footprint of the Zone 1 groundwater contamination, were recognized as having clear evidence of carbon tetrachloride VI at levels that exceed the current KDHE standard for this contaminant (4.055 μg/m^3) in indoor air (Figure 4.44). The actions taken by the CCC/USDA to mitigate the contamination at these homes are discussed in Section 4.8.4.

To address health concerns expressed by the Hanover community, however, the CCC/USDA VI investigation was expanded in February 2010, with the approval of the KDHE (2010c), to include an assessment of potential VI to indoor air at the Hanover public school facilities and at St. John's School. The schools are located southwest of the former CCC/USDA facility, beyond the limits of the carbon tetrachloride contamination identified in groundwater-

bearing Zone 1 and Zone 2 but along an apparent direction of groundwater flow in Zone 1 (Figure 4.36).

The studies performed included an initial screening of indoor air grab samples (with on-site analysis by a GC-ECD method) collected at 38 locations in classrooms, cafeterias, bathrooms, gyms, locker rooms, shops, and offices in the Hanover public school facility, and at 16 comparable locations in the adjacent St. John's School. On the basis of the results of the screening analyses, composite air samples were collected at selected locations in each school, both overnight (12 hr) and during the school day (8 hr), for confirmation of the screening data by laboratory VOCs analyses by EPA Method TO-15.

Sampling for radon was also performed at each location in conjunction with the VOCs sampling, by using kits obtained from the Washington County offices. Although not required by the KDHE, the testing for radon was conducted by the CCC/USDA in light of the recognized occurrence of radon at levels exceeding the EPA action level for this contaminant in other local structures (Section 4.8.3.2). These samples were submitted for radon analysis through the National Radon Program Services at Kansas State University, Manhattan, Kansas.

The results of the VOC and radon analyses are in Table 3.16. No carbon tetrachloride was detected in any of the screening or confirmation air samples collected at the Hanover public school facility or at St. John's School. Low levels of chloroform were identified in the screening air samples from four rooms in the public school facility; however, as discussed in Section 4.8.3.2, these isolated occurrences provide no evidence of upward VOCs VI in the context of the associated carbon tetrachloride results.

With only two exceptions (one room at the Hanover public school facility and one room at St. John's School), radon was detected at various levels in all of the indoor air samples from both schools. Concentrations detected ranged from 0.7 pCi/L to 6.0 pCi/L at the St. John's School and from 0.6 pCi/L to 14.2 pCi/L in the public school facility. The presence of radon at various levels suggests some degree of influence of subsurface VI to the indoor air at these structures. In contrast, no VOCs were detected in any of school structures, indicating an absence of VOCs sources that would support the VI migration of VOCs beneath the school structures. This result is consistent with the interpretation that all school structures lie outside the identified limits of the carbon tetrachloride and chloroform distributions.

4.8.4 Mitigation of the Identified Indoor Air Contamination at Hanover in August 2009 and May 2010

The investigations summarized in Section 4.8.3 demonstrated that only five homes, all overlying the documented VOCs contamination in groundwater-bearing Zone 1, were recognized as having clear evidence of carbon tetrachloride VI to indoor air at levels that exceed the current KDHE standard for this contaminant (4.055 $\mu g/m^3$) in indoor air (Figure 4.44). No carbon tetrachloride was detected at either the Hanover public school facility or St. John's School, which lie outside the identified limits of the carbon tetrachloride distributions in both groundwater-bearing Zone 1 and Zone 2 (Figure 4.36).

Three homes with unacceptable levels of carbon tetrachloride in indoor air were identified during the initial studies of potential VI migration pathways conducted in February-April 2009. These three homes (311 N. East Street, 400 N. East Street, and 413 E. Kensington Street) all lie within or immediately adjacent to the limits of the former CCC/USDA facility (Figure 4.44). The concentrations of carbon tetrachloride detected in these homes ranged from 11 $\mu g/m^3$ to 28 $\mu g/m^3$, with the highest levels occurring at the 311 and 400 N. East Street locations, at the western edge of the former facility. Elevated levels of radon (5.2 pCi/L and 9.4 pCi/L, respectively) were also present at the 400 N. East Street and 413 E. Kensington Street locations. (No radon analysis was obtained for the home at 311 N. East Street.)

Two additional homes were determined to have unacceptable levels of carbon tetrachloride VI as a result of the confirmation sampling performed at selected homes in summer 2009 and winter 2010. At 408 E. Elm Street, carbon tetrachloride levels ranging (with one exception, for the first floor in spring 2009) from roughly 6 $\mu g/m^3$ to 17 $\mu g/m^3$ were detected in both basement and first-floor air during each of the 2009 and 2010 sampling events. Relatively low ($\leq$ 2.3 $\mu g/m^3$) levels of carbon tetrachloride were consistently observed in the first-floor air at 405 E. Elm Street; however, variable but recurring carbon tetrachloride concentrations exceeding the current KDHE standard (4.055 $\mu g/m^3$) were documented for the basement air at this location, in association with a sub-slab vapor level of 2,800 $\mu g/m^3$. High levels of radon (10.4 pCi/L at 405 E. Elm Street and 21.8 pCi/L at 408 E. Elm Street) were again discovered in association with the occurrence of VI to indoor air at these homes.

Upon discovery of the contaminant concentrations at these five locations, mitigation was recommended by the CCC/USDA and was implemented with KDHE (2009g, 2010e) approval. At the request of the CCC/USDA, a VI mitigation (sub-slab depressurization) system was

designed for each home by EnviroGroup Limited, Lawrence, Kansas, as described in Supplement 10 and Supplement 11. The systems were installed on August 25-27, 2009 (at 311 N. East Street, 400 N. East Street, and 413 E. Kensington Street), and on May 12-13, 2010 (at 405 and 408 E. Elm Street; Figure 4.44). At each location, sub-slab vacuum/pressure levels and soil gas flow rates were monitored after the initial 30 days of operation, to verify system performance.

To further assess the performance of these systems, indoor air samples were collected for VOCs and radon analyses at the 311 N. East Street, 400 N. East Street, and 413 E. Kensington Street locations (after approximately five months of operation), in conjunction with the January 2010 monitoring event discussed in Section 4.8.3.2. Indoor air samples were also collected for VOCs analysis (after approximately one month of operation) in the residences at 405 E. Elm Street and 408 E. Elm Street. The results of these analyses are in Table 3.17. No carbon tetrachloride or chloroform was detected in indoor air samples from the five mitigated homes. (Trace levels of radon were identified at two of the homes: 400 N. East Street and 413 E. Kensington Street.) These observations confirm the effectiveness of the installed systems.

4.8.5 Summary

The primary findings from the 2009-2010 VI studies at Hanover are as follows:

- On the basis of KDHE (2007b) guidance, approximately 60 occupied residences at Hanover were identified for the consideration of possible VI that might be linked to the carbon tetrachloride contamination identified in groundwater-bearing Zone 1 or to the contamination present in the western, more downgradient portion of Zone 2 at depths of ≤ 40 ft BGL. No risk of upward VI was recognized in association with the localized, low residual levels of carbon tetrachloride detected in subsurface soils at the former CCC/USDA facility.

- The results of comprehensive indoor air testing and subsequent periodic monitoring demonstrated that only five homes, all overlying the documented VOCs contamination in groundwater-bearing Zone 1, were impacted by

carbon tetrachloride VI at levels greater than the KDHE standard of 4.055 $\mu g/m^3$ for this contaminant in indoor air (Figure 4.44).

- With the approval of the KDHE, mitigation systems were installed by the CCC/USDA at each of the five homes impacted by VI. Performance testing of these systems has demonstrated that they are effectively reducing VOCs concentrations in indoor air to acceptable levels.

- No carbon tetrachloride was detected in indoor air at either the Hanover public school facility or the St. John's School, which lie outside the identified limits of the carbon tetrachloride distributions in both groundwater-bearing Zone 1 and Zone 2.

Radon analyses performed as a possible supplemental indicator of subsurface VI to indoor air identified elevated levels of radon (up to 7 times the EPA action level of 4.0 pCi/L) in 22 of 25 homes tested for this contaminant (Figure 4.42), as well as at selected locations in the Hanover public school facility and the St. John's School. These observations demonstrate that upward VI by radon, at unacceptable health risk levels, is a widespread phenomenon at the Hanover investigation site.

TABLE 4.1 Summary of interpreted results for slug tests in Zone 1 monitoring wells in August 2009.

	Calculated Hydraulic Conductivity[a] (ft/day)								
Well	Bouwer and Rice Method Result for Each Test				Hvorslev Method Result for Each Test				Average[b]
MW01	0.71	0.48	0.60	0.46	0.98	0.66	0.83	0.63	0.67
MW02	2.9	2.2	3.0	2.4	4.0	3.0	4.1	3.3	3.1
MW04	0.67	0.49	0.64	0.43	0.92	0.67	0.89	0.59	0.66
MW05	45	47	42	42	62	65	59	59	53
MW06	0.001	–	–	–	0.001	–	–	–	0.001
MW07	0.017	0.012	–	–	0.024	0.017	–	–	0.018
MW09	69	73	40	67	97	102	55	93	75
MW10	2.8	2.7	3.0	2.8	3.9	3.7	4.1	3.9	3.4
MW11	56	39	55	56	78	53	78	77	62
MW12	0.005	–	–	–	0.007	–	–	–	0.006
MW13	55	48	51	46	75	66	70	63	59
MW16	0.043	0.025	–	–	0.059	0.034	–	–	0.040
MW18	0.25	0.22	0.28	–	0.34	0.30	0.40	–	0.30
MW20	0.011	–	–	–	0.015	–	–	–	0.013
MW21	0.002	–	–	–	0.003	–	–	–	0.003
MW28	2.6	5.9	2.8	4.1	3.6	8.3	3.9	5.7	4.6
MW29	3.0	4.5	3.4	4.8	4.1	6.3	4.8	6.6	4.7
MW34	0.24	0.07	0.21	–	0.33	0.09	0.29	–	0.20
MW37	0.003	–	–	–	0.004	–	–	–	0.004
MW38	0.017	–	–	–	0.024	–	–	–	0.021

[a] Calculated with the assumption of a thickness of 2 ft for the water-bearing interval.

[b] Averaged for all tests and both calculation methods.

TABLE 4.2 Summary of hydraulic conductivity estimates generated by the Theis (1935) and Cooper-Jacob (1946) methods from the results of the MW05 constant-rate pumping tests.

	Hydraulic Conductivity (ft/day) in Well Indicated		
	MW05		MW02
Test	Theis	Cooper-Jacob	Theis
First	45	48	50
Second	61	64	34

TABLE 4.3 Darcy flow velocities in groundwater Zone 1 at selected locations.

Location	Hydraulic Gradient (dh/dl)	Average Hydraulic Conductivity (K_h, ft/day)	Darcy Flow Velocity $V_D = K_h \times dh/dl$ (ft/day)	Darcy Flow Velocity (V_D, ft/yr)	Flow Direction
MW16	0.0520	0.04	2.1×10^{-3}	0.76	Northwest
MW12	0.0520	0.006	3.1×10^{-4}	0.11	West
MW28/MW29	0.0083	4.6	3.8×10^{-2}	13.97	Southwest
MW18	0.0189	0.3	5.7×10^{-3}	2.07	South

TABLE 4.4 Summary of interpreted results for slug tests in Zone 2 monitoring wells in January 2010.

	Calculated Hydraulic Conductivity[a] (ft/day)								
Well	Bouwer and Rice Method Result for Each Test				Hvorslev Method Result for Each Test				Average[b]
MW44Z2	23	18	20	20	31	25	27	27	24
MW45Z2	16	26	15	26	22	36	20	35	25
MW48Z2	NA[c]	NA	NA	NA	NA	NA	NA	NA	NA
MW49Z2	NA	NA	NA	NA	NA	NA	NA	NA	NA
MW50Z2	29	41	30	43	40	56	42	59	43
MW51Z2	4.4	7.3	4.9	10	6.1	10	6.7	14	7.9

[a] Calculated with the assumption of a thickness of 3.5 ft for the water-bearing interval.

[b] Averaged for all tests and both calculation methods.

[c] Results could not be analyzed; see Section 4.6.2.1.

TABLE 4.5 Summary of hydraulic conductivity values estimated from the MW44Z2 constant-rate pumping test.

	Hydraulic Conductivity (ft/day) Calculated by Method Indicated		
		Hantush Method (leaky-confined aquifer)	
Well	Theis Method (confined aquifer)	Without Storage[a]	With Storage[b]
MW44Z2	14	13	11
MW45Z2	42	25	16

[a] Method assumes that no water is released from storage in the confining aquitard.

[b] Method assumes that water is released from storage in the confining aquitard.

TABLE 4.6 Three subsystems of carbon tetrachloride contamination in groundwater Zone 1, with hydrogeologic characteristics and the feasibility of treatment technologies.

Subsystem	Area (ft^2)	Percent of Total Contaminated Area	Typical Carbon Tetrachloride Concentrations (µg/L)	Average K_h from Slug Tests (ft/day)	K from Pumping Test (ft/day)	Sustainable Pumping Rate (gpm)	ROI (ft)	Extraction or Injection Technology
1	52,970	6	> 500	53-75	34-64	< 1	~ 106	Conventional technology is not feasible. Horizontal well technology needs to be evaluated. Potential logistic barriers need to be identified and addressed for horizontal technology.
2	273,200	31	100-500	> 1	–	< 0.3	< 124 to 229	Technically and logistically impractical to implement any available technology.
3	557,570	63	100-500 (30%) 5-100 (70%)	10^{-2} to 10^{-3}	–	10^{-2} to 10^{-3} or less	–	Technically and logistically impractical to implement any available technology.

TABLE 4.7 Summary of vapor intrusion investigation activities and response actions at Hanover, 2007-2010.

Date	Activity	Objective	Methodology
July 10-11, 2007	Indoor air sampling in the basements of 9 residences on the former CCC/USDA property, in response to resident concerns.	Conduct an initial evaluation of indoor air contamination.	Air collection over 24 hr in Summa canisters; analysis by TestAmerica, Burlington, Vermont, by EPA Method TO-15.
February 2-4, 2009	Investigation of upward VI in 3 residences on the former CCC/USDA property where carbon tetrachloride was detected in July 2007.	Evaluate indoor air contamination during optimal winter sampling period when homes are most closed to outside air.	Collection of vapor/air samples from sub-slab, basement, and first-floor spaces for analysis of VOCs and tracer radon.
March 12-13, 2009	Investigation of upward VI in the remaining 6 residences on the former CCC/USDA property, where carbon tetrachloride was not detected in July 2007.	Evaluate indoor air contamination during the optimal winter sampling period when homes are most closed to outside air.	Collection of basement and first-floor indoor air samples for analysis by TestAmerica with EPA Method TO-15.
March 25-27, 2009	VI evaluation at residences outside the former CCC/USDA property (completed April 7-10, 2009).	Screen all residences in the identified groundwater contaminant distribution area for potential VI.	Collection of vapor/air samples from sub-slab, basement, and first-floor spaces for on-site analysis, with submittal of selected samples for off-site verification analysis.
April 7-10, 2009	Continuation of the VI evaluation at residences outside the former CCC/USDA property.	Screen all residences in the identified groundwater contamination area for potential VI.	Collection of vapor/air samples from sub-slab, basement, and first-floor spaces for on-site analysis, with submittal of selected samples for off-site verification analysis.
August 12-13, 2009	Monitoring of 17 residences where carbon tetrachloride was identified in prior indoor air sampling.	Conduct summertime monitoring of indoor air.	Collection of basement and first-floor indoor air samples for analysis by TestAmerica with EPA Method TO-15.
August 25-27, 2009	Completion of vapor mitigation of 3 homes.	Reduce identified carbon tetrachloride contamination in indoor air.	–
September 28, 2009	Retesting of indoor air in 3 homes after installation of sub-slab VI mitigation systems in August.	Verify elimination of identified carbon tetrachloride contamination in indoor air.	Indoor air sampling.

TABLE 4.7 (Cont.)

Date	Activity	Objective	Methodology
January 25-26, 2010	Monitoring of 17 residences where carbon tetrachloride was identified in prior indoor air sampling.	Conduct wintertime monitoring of indoor air contamination.	Collection of basement and first-floor indoor air samples for analysis at TestAmerica with EPA Method TO-15.
February 22-25, 2010	Indoor air sampling at Hanover public school and St. John's School, at the request of residents; sampling of 9 residences potentially at risk for VI from groundwater Zone 2.	Determine the potential for upward VI of carbon tetrachloride, chloroform, and radon contamination from the subsurface to indoor air.	Indoor air sampling with on-site analysis in accessible rooms in the schools, with follow-up sampling and quantitative analysis for rooms selected per the screening results; quantitative VOCs analysis by TestAmerica with EPA Method TO-15.
May 12-13, 2010	Completion of vapor mitigation of 2 homes.	Reduce identified carbon tetrachloride contamination in indoor air.	–
June 17, 2010	Retesting of indoor air in 2 homes after installation of sub-slab VI mitigation systems in May 2010.	Verify elimination of identified carbon tetrachloride contamination in indoor air.	Indoor air sampling.

FIGURE 4.1 Maximum concentrations of carbon tetrachloride in soil samples collected at and near the former CCC/USDA facility during the 2009-2010 investigation. Source of photograph: NAIP (2008).

FIGURE 4.2 Maximum concentrations of chloroform in soil samples collected at and near the former CCC/USDA facility during the 2009-2010 investigation. Source of photograph: NAIP (2008).

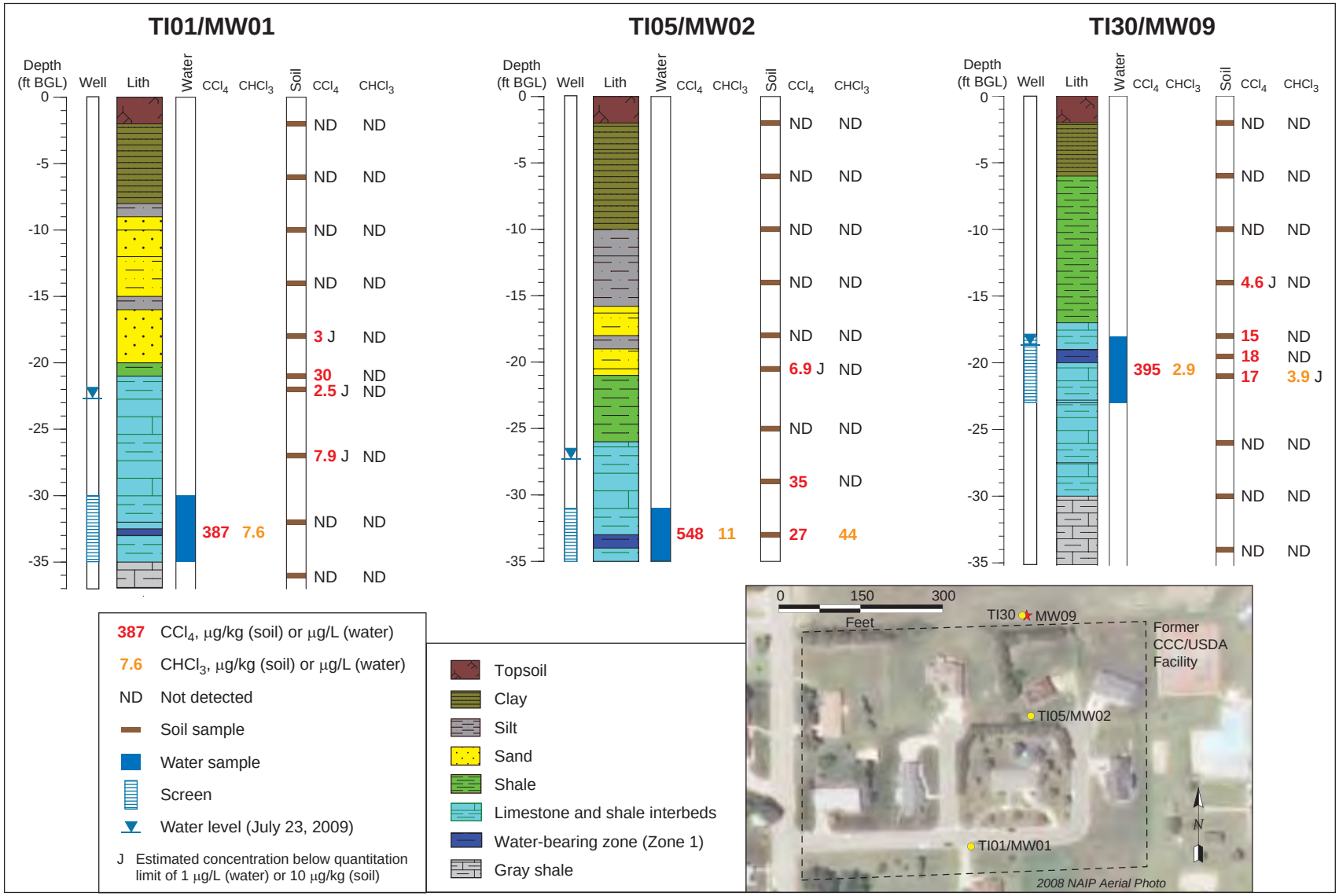

FIGURE 4.3 Vertical distribution of carbon tetrachloride (CCl_4) and chloroform ($CHCl_3$) in subsurface soil and shallow groundwater (Zone 1) samples collected at locations TI01/MW01, TI05/MW02, and TI30/MW09, at and near the former CCC/USDA facility. Source of photograph: NAIP (2008).

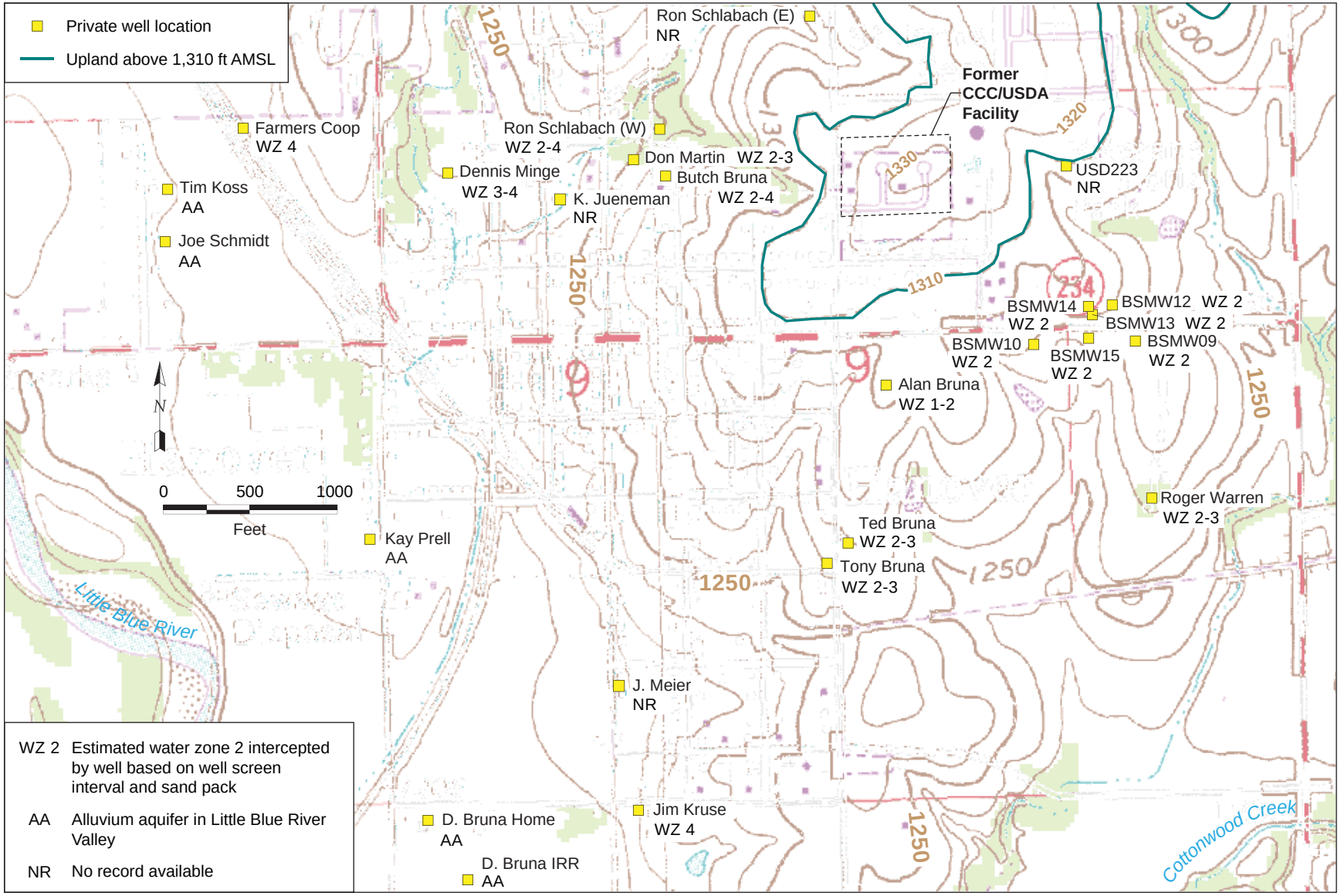

FIGURE 4.4 Surface topography in the Hanover area, the location of the former CCC/USDA facility, and water-bearing zones intercepted by private wells. Source of map: USGS (1997).

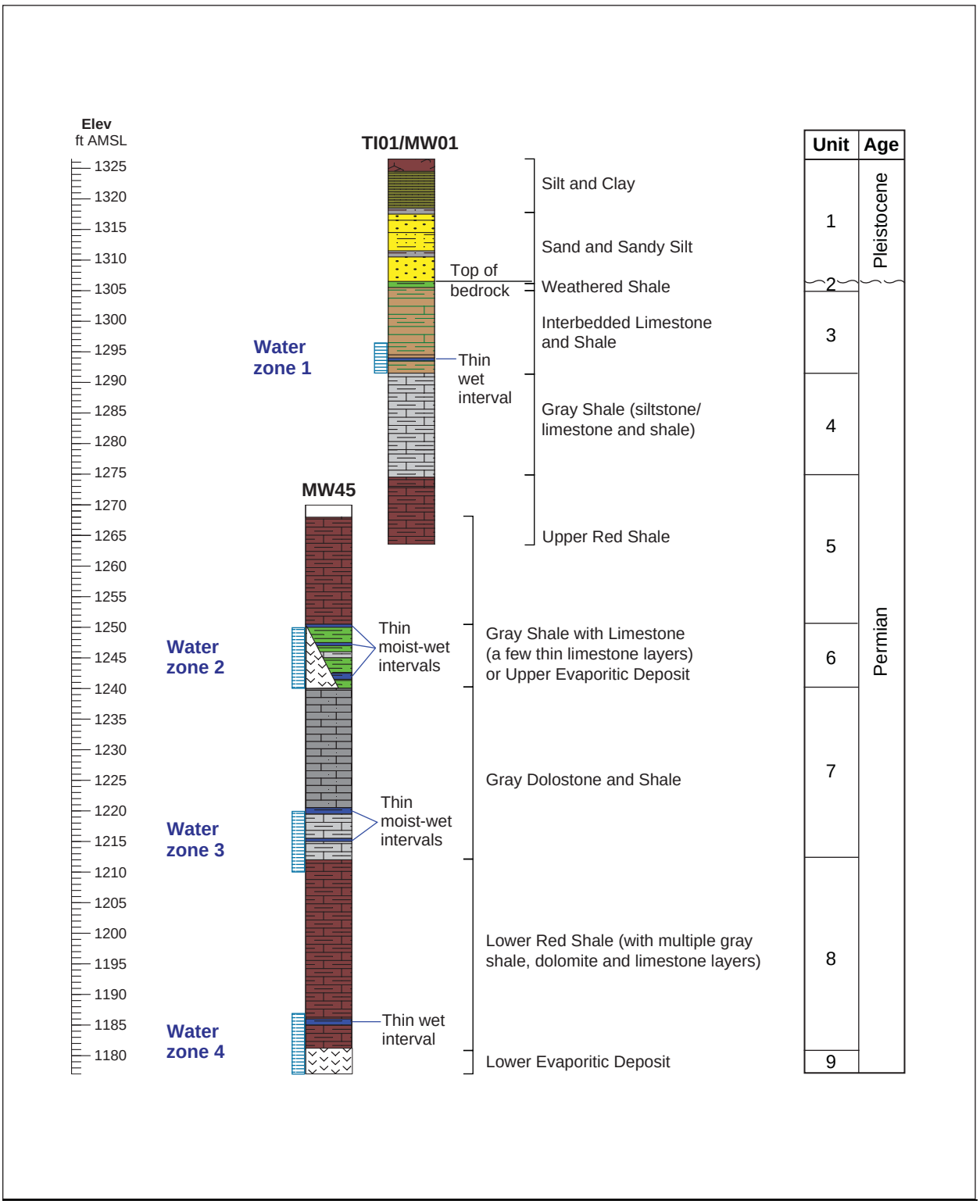

FIGURE 4.5 Combined lithology logs for borings TI01/MW01 and MW45, showing the local stratigraphic units at Hanover.

FIGURE 4.6 Locations of wells and hydrogeologic cross sections. Source of photograph: NAIP (2008).

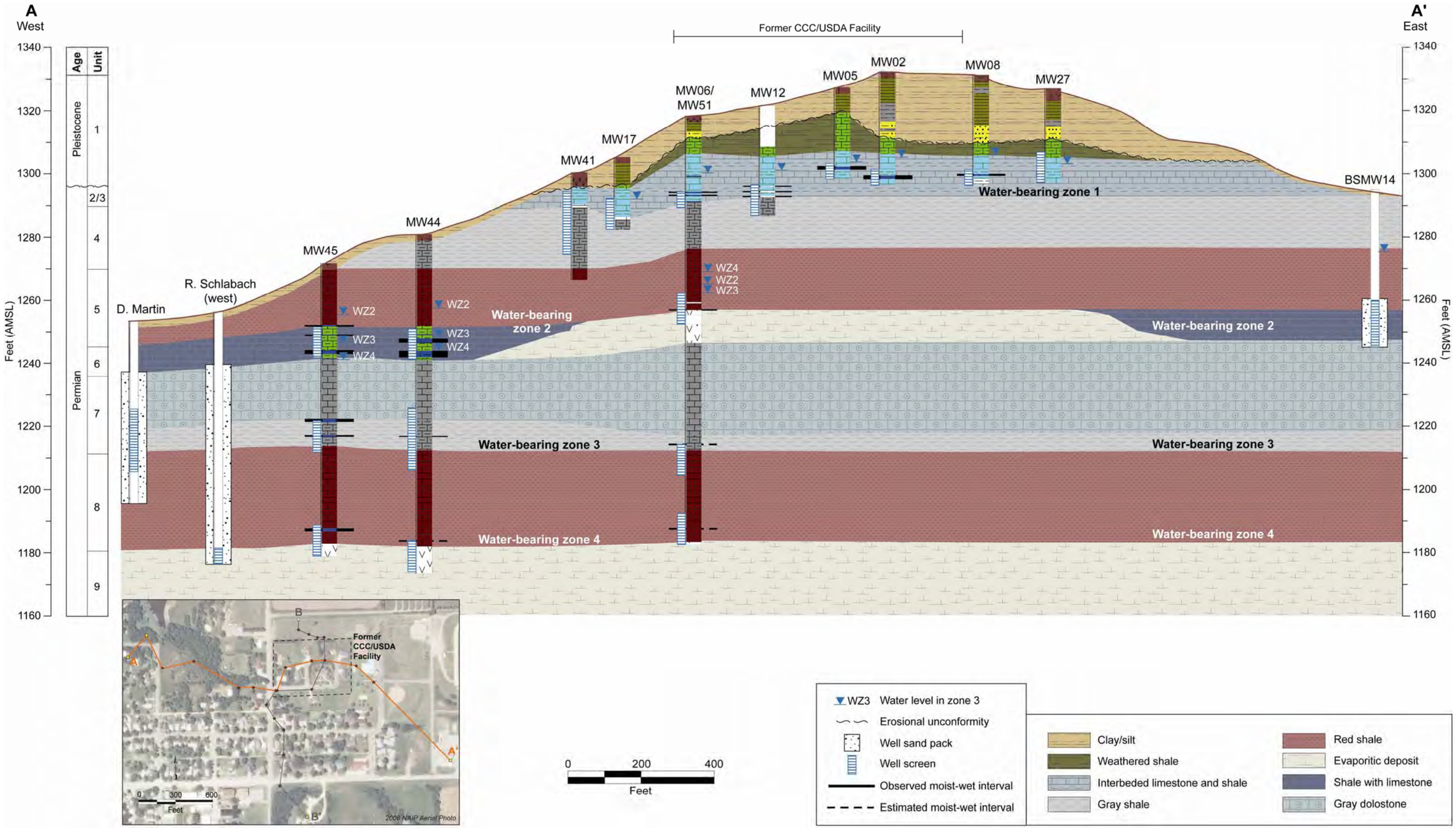

FIGURE 4.7 Interpretive west-to-east hydrogeologic cross section A-A'. Source of photograph: NAIP (2008).

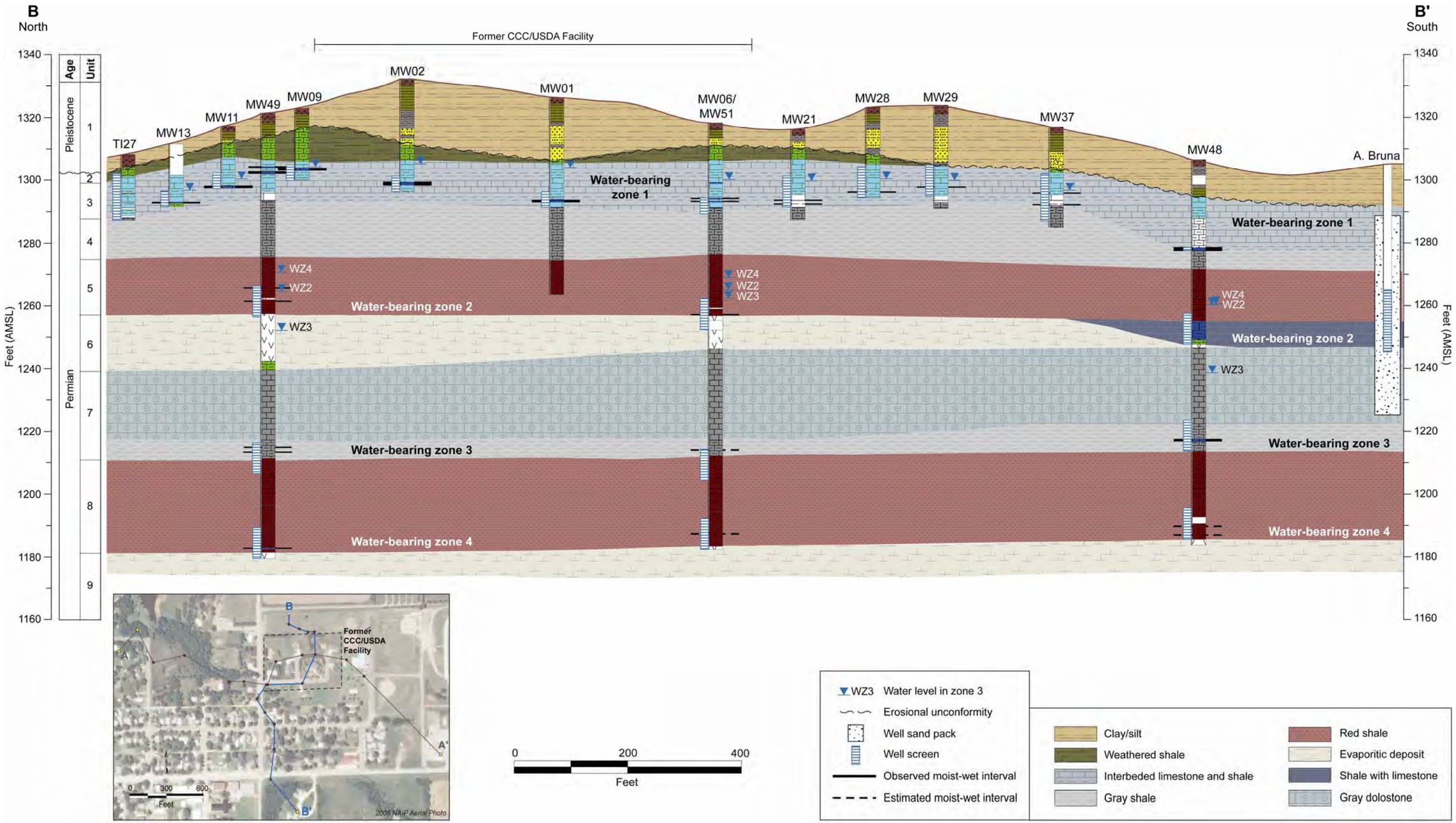

FIGURE 4.8 Interpretive north-to-south hydrogeologic cross section B-B'. Source of photograph: NAIP (2008).

FIGURE 4.9 Interpreted north, northwest, west, and southwest limits of groundwater Zone 1, as determined by the availability and recovery of groundwater in Zone 1. Source of photograph: NAIP (2008).

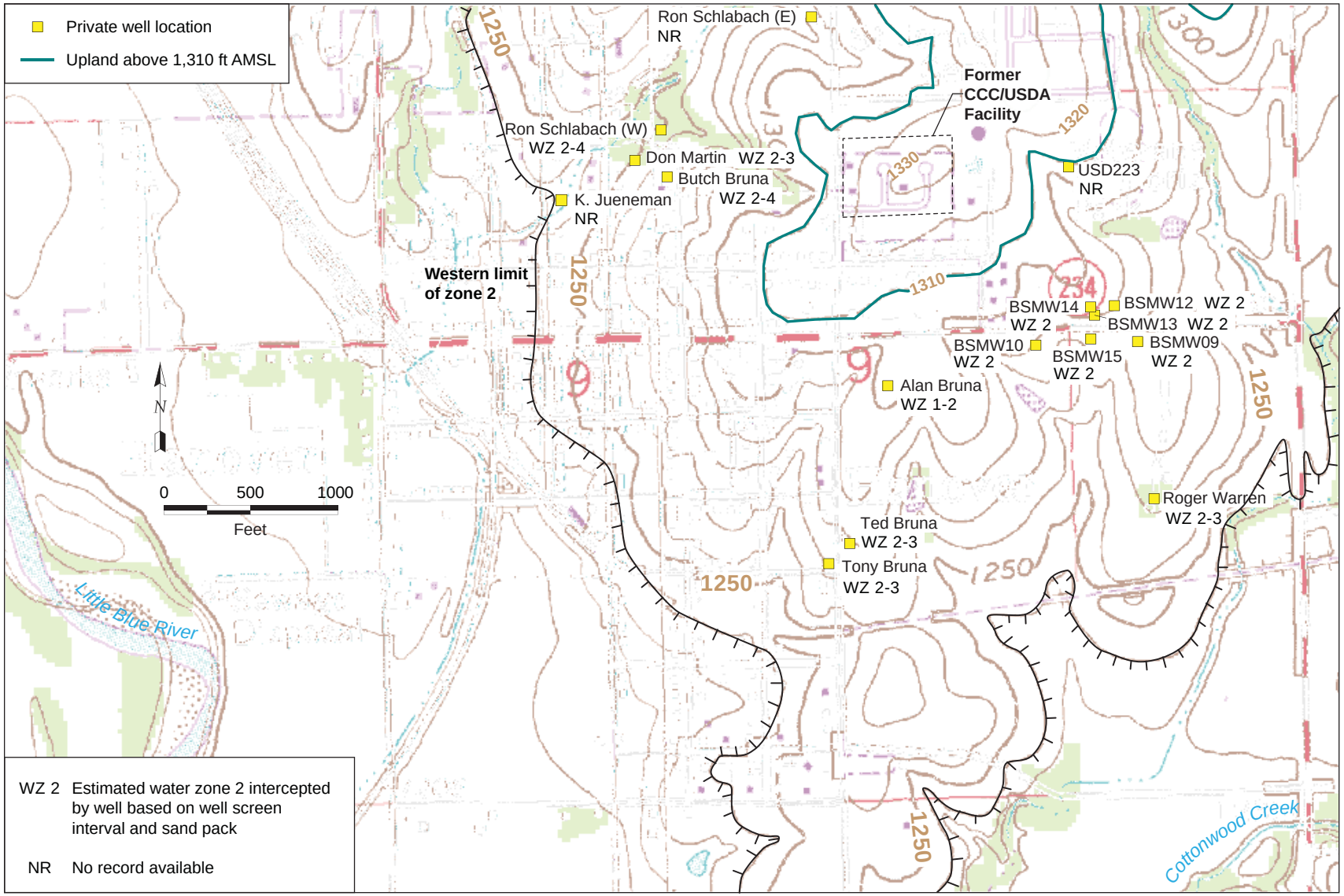

FIGURE 4.10 Estimated lateral limits of groundwater Zone 2 and locations of private wells that apparently intercept groundwater Zone 2. Source of map: USGS (1997).

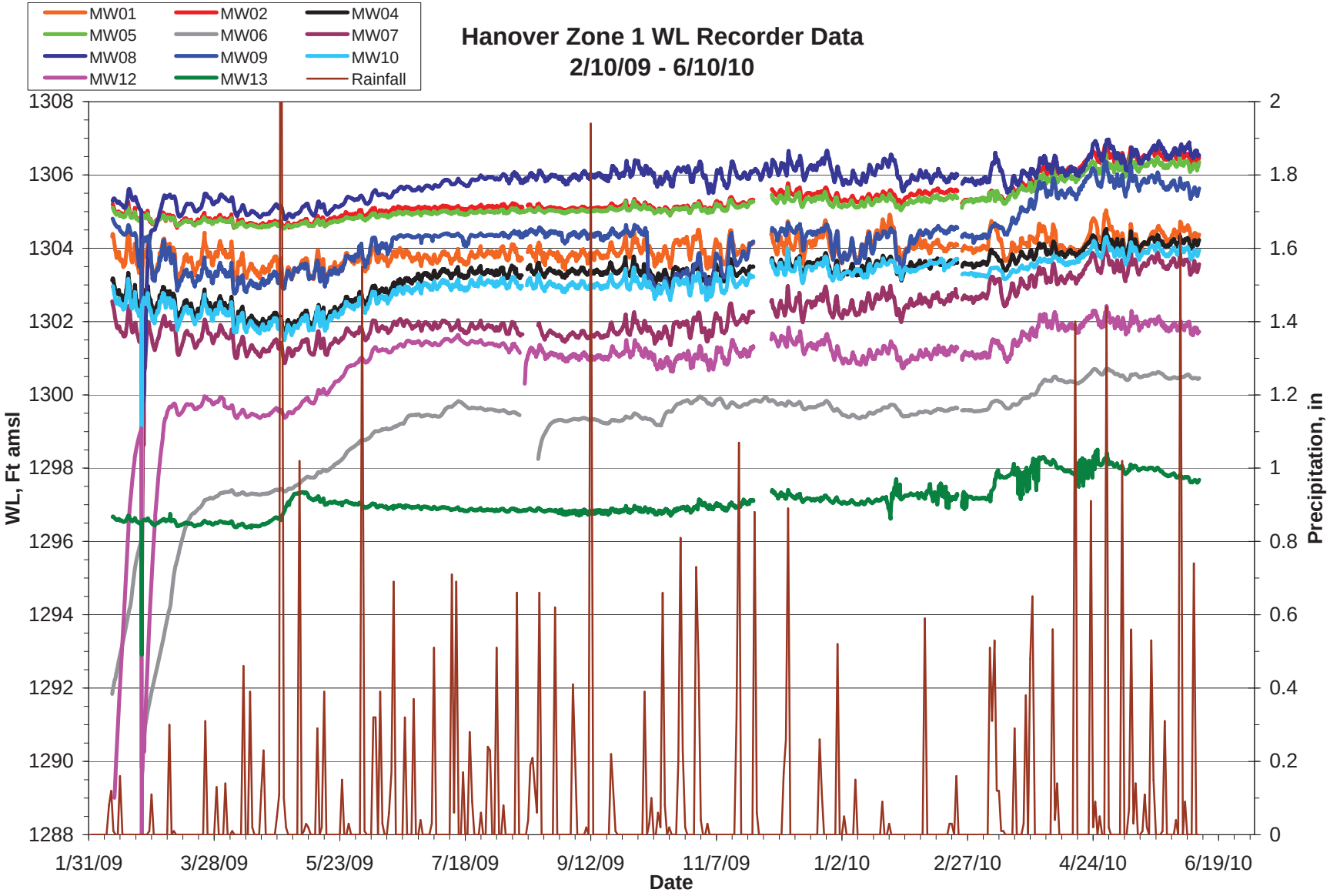

FIGURE 4.11 Water level records for selected groundwater Zone 1 monitoring wells during the 2009-2010 investigation.

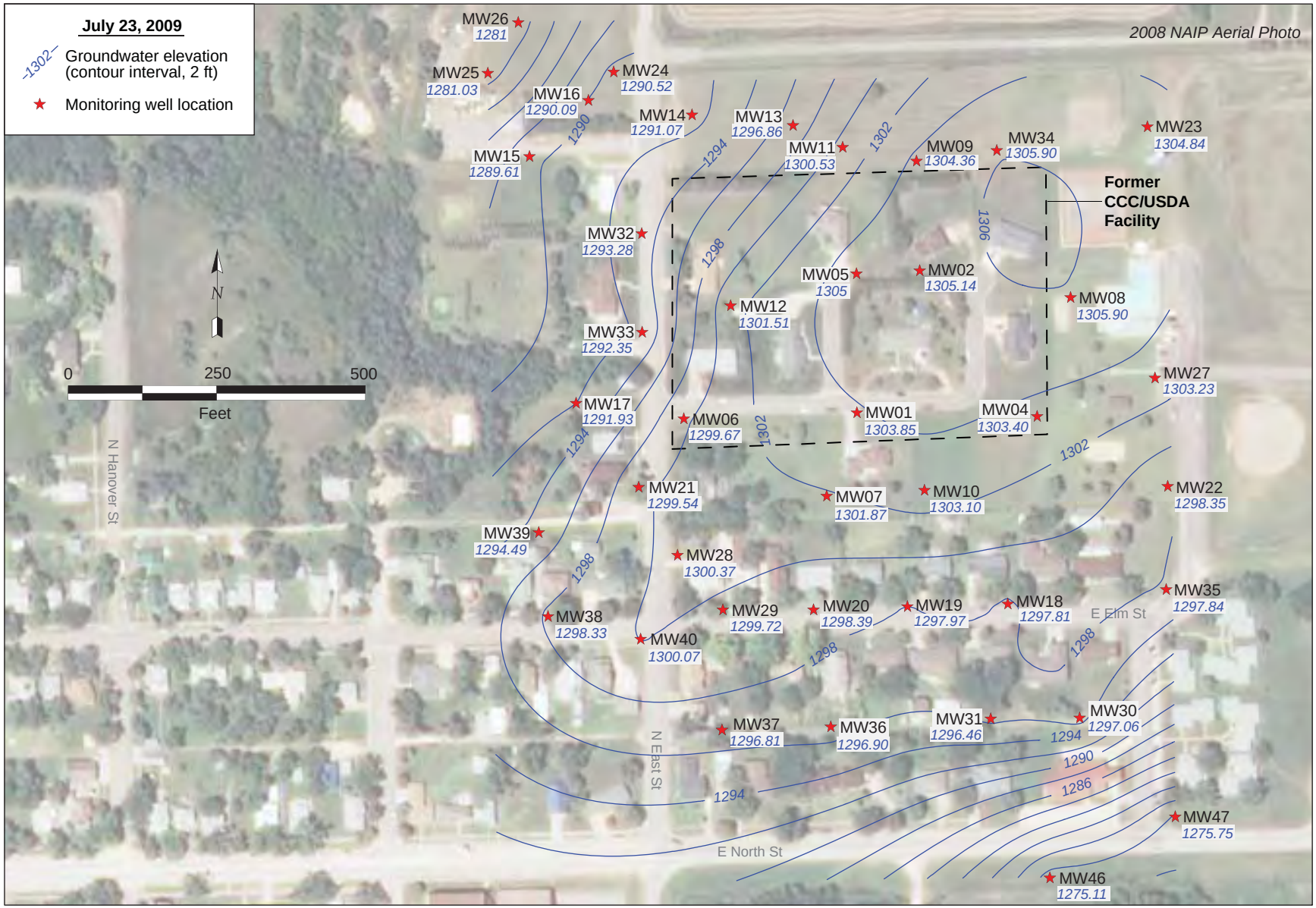

FIGURE 4.12 Potentiometric surface for groundwater Zone 1 on July 23, 2009. Source of photograph: NAIP (2008).

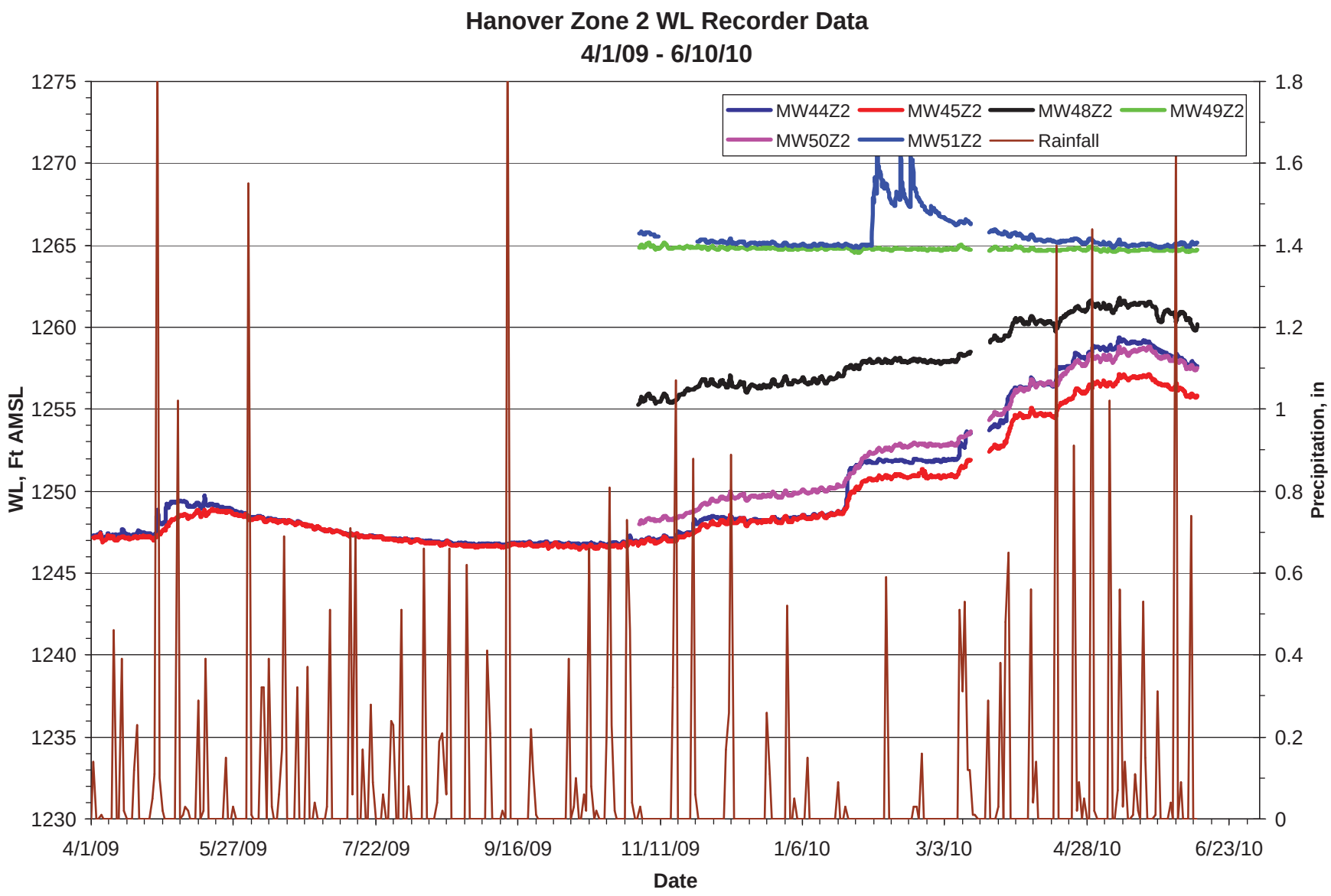

FIGURE 4.13 Water level records for groundwater Zone 2 wells during the 2009-2010 investigation.

FIGURE 4.14 Potentiometric surface for groundwater Zone 2 on January 25, 2010. Source of photograph: NAIP (2008).

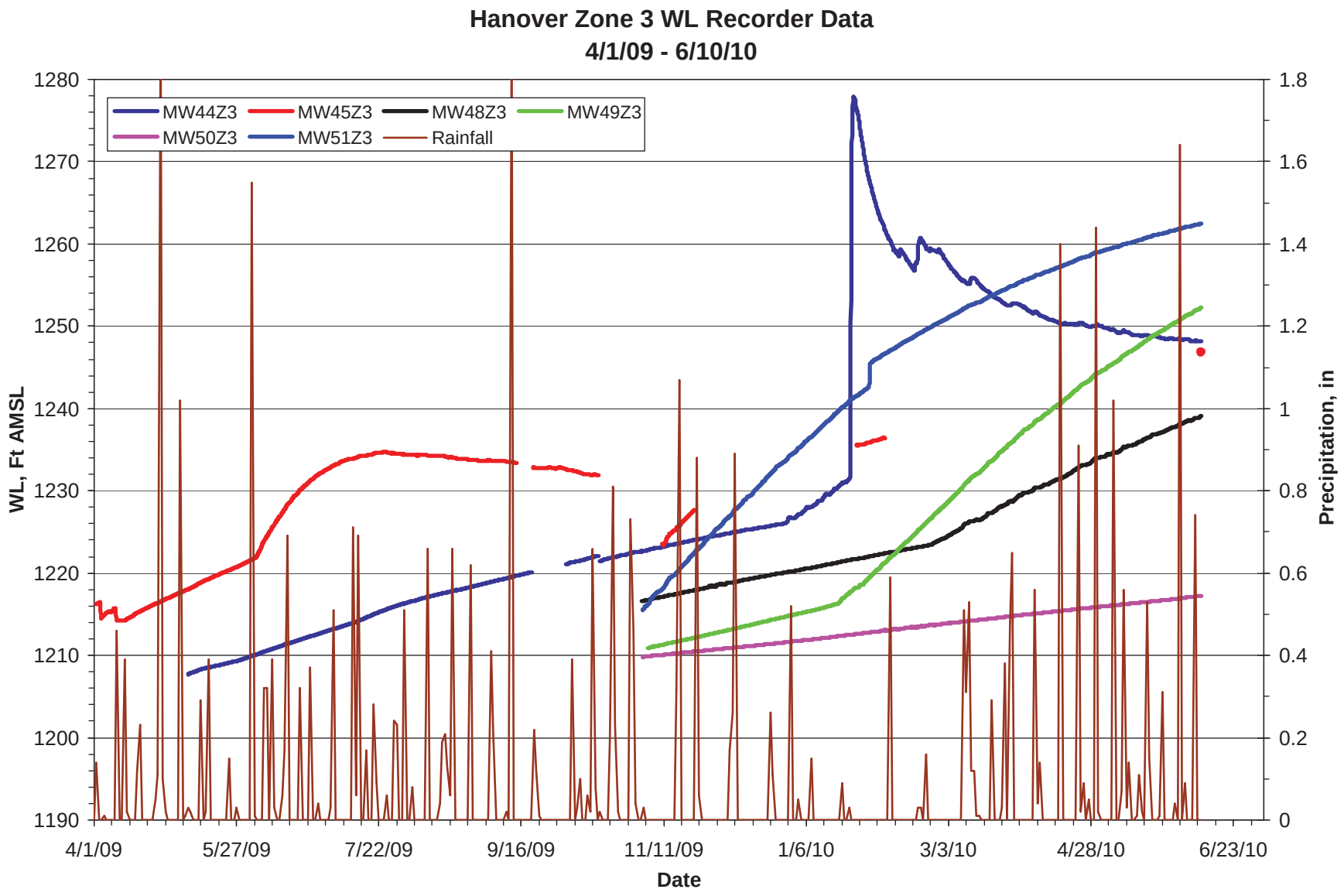

FIGURE 4.15 Water level records for groundwater Zone 3 wells during the 2009-2010 investigation.

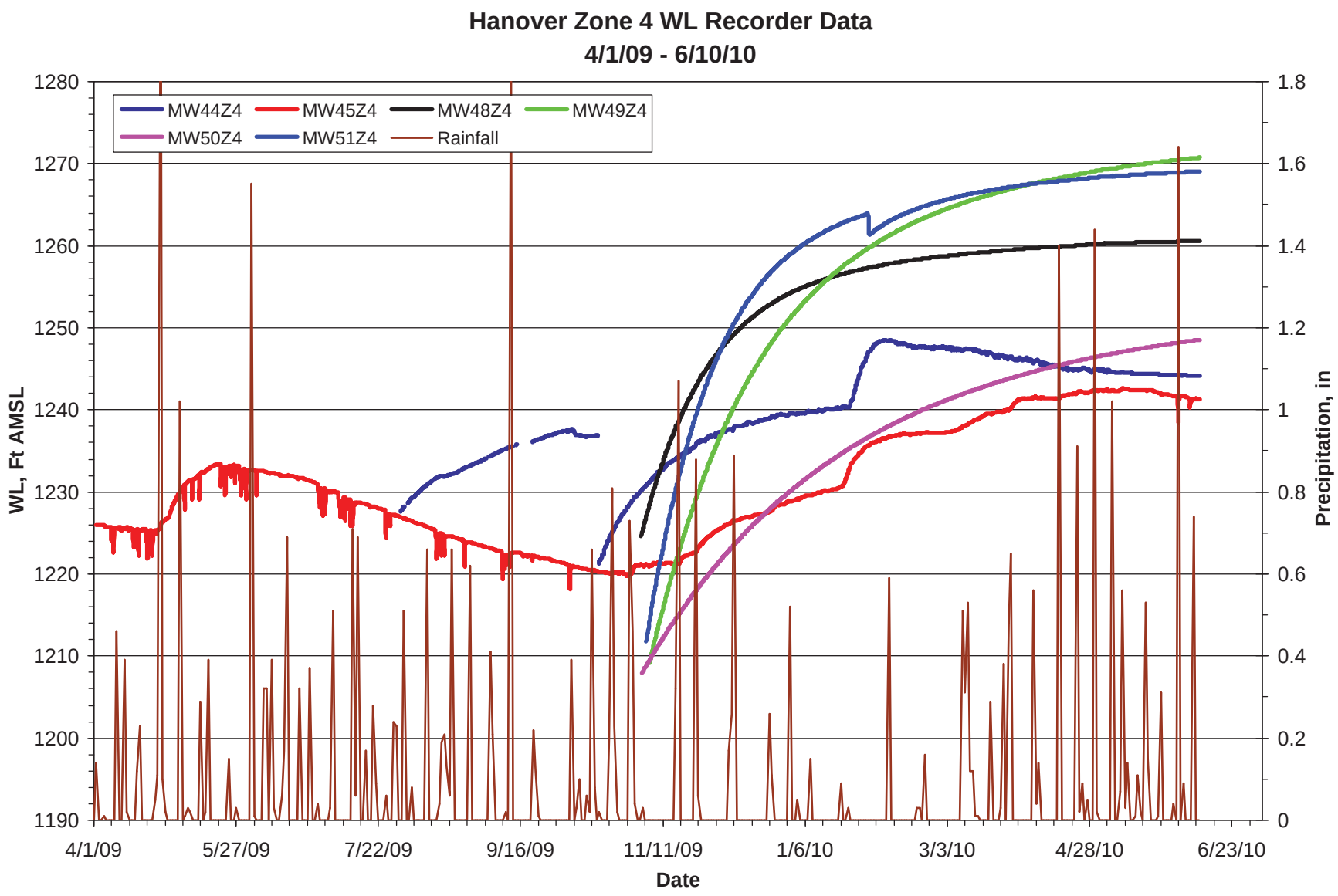

FIGURE 4.16 Water level records for groundwater Zone 4 wells during the 2009-2010 investigation.

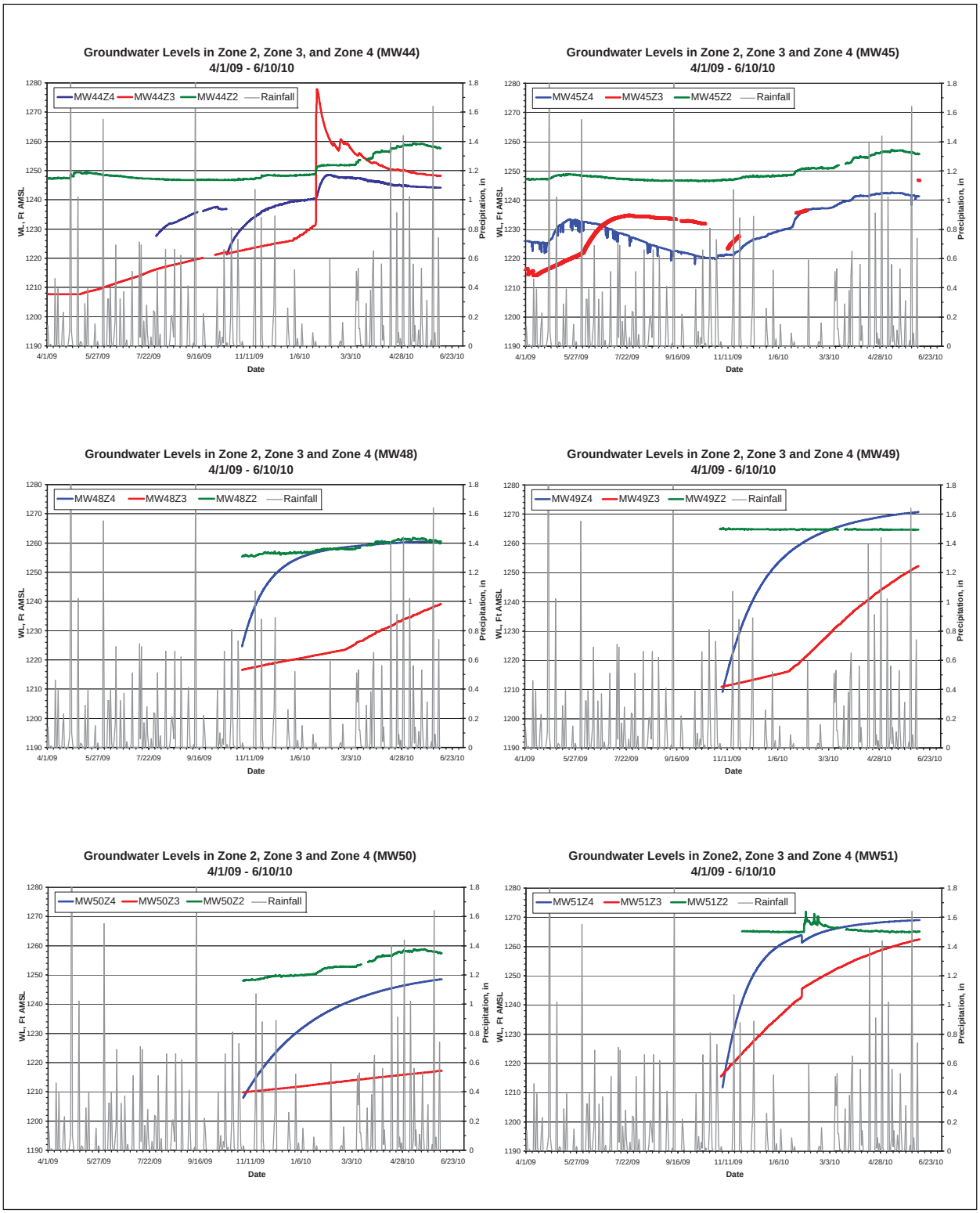

FIGURE 4.17 Water level records for wells completed in groundwater Zone 2, Zone 3, and Zone 4 at locations MW44, MW45, and MW48-MW51, during the 2009-2010 investigation.

FIGURE 4.18 Lateral distribution of carbon tetrachloride in groundwater Zone 1 during the 2009-2010 investigation. Source of photograph: NAIP (2008).

FIGURE 4.19 Lateral distribution of chloroform in groundwater Zone 1 during the 2009-2010 investigation. Source of photograph: NAIP (2008).

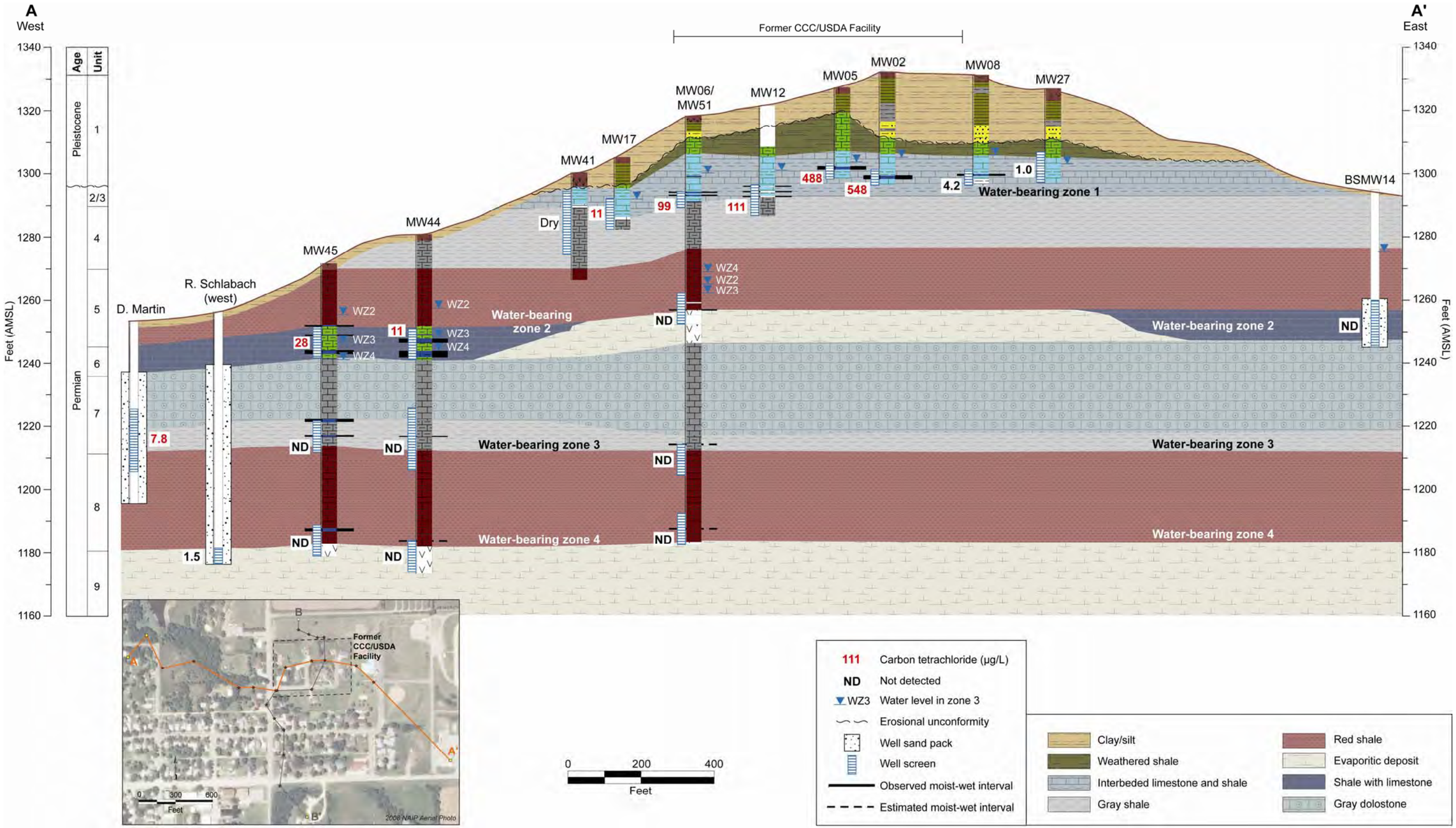

FIGURE 4.20 Vertical distribution of carbon tetrachloride in groundwater along west-to-east hydrogeologic cross section A-A' during the 2009-2010 investigation. Source of photograph: NAIP (2008).

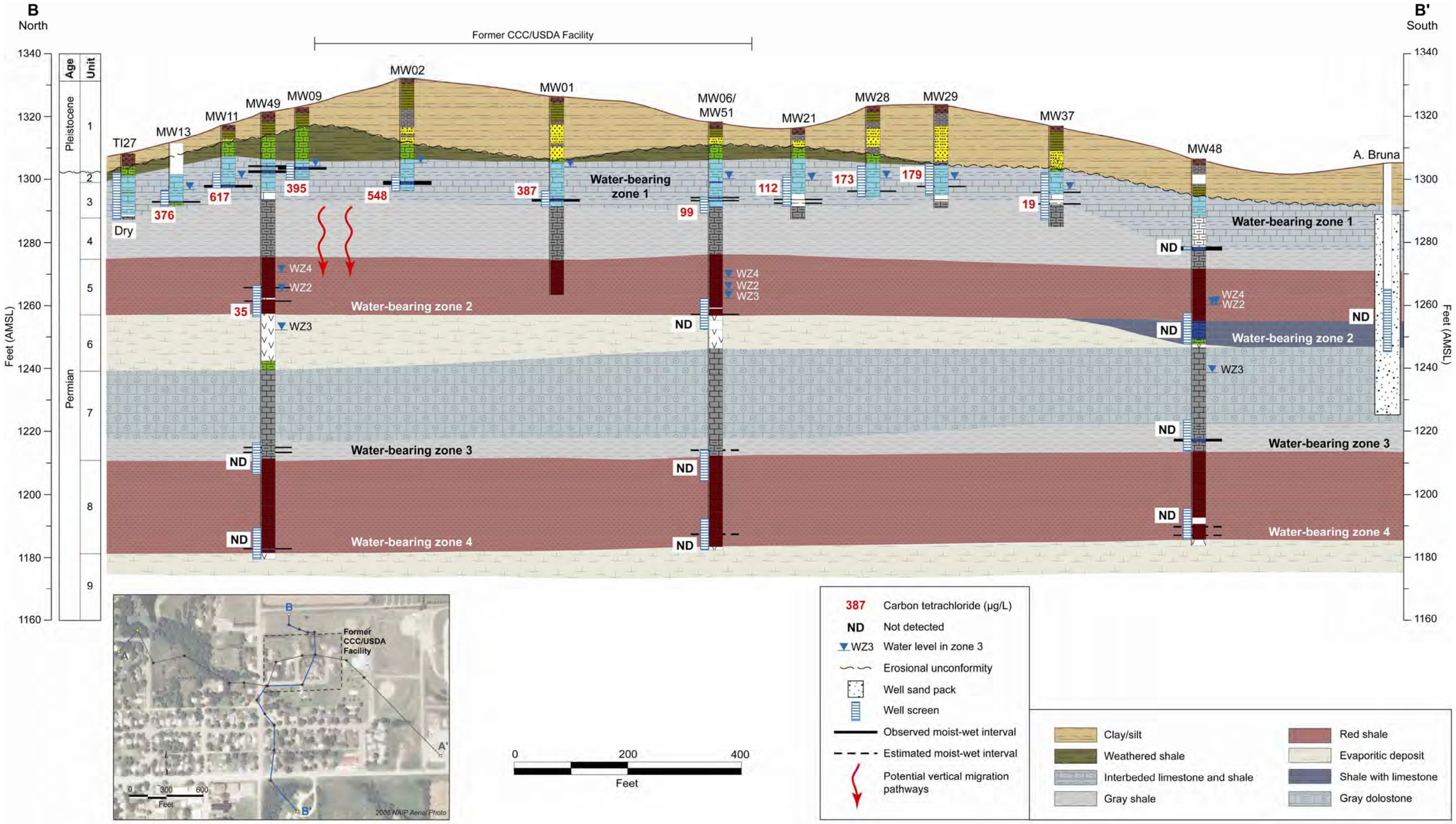

FIGURE 4.21 Vertical distribution of carbon tetrachloride in groundwater along west-to-east hydrogeologic cross section B-B' during the 2009-2010 investigation. Source of photograph: NAIP (2008).

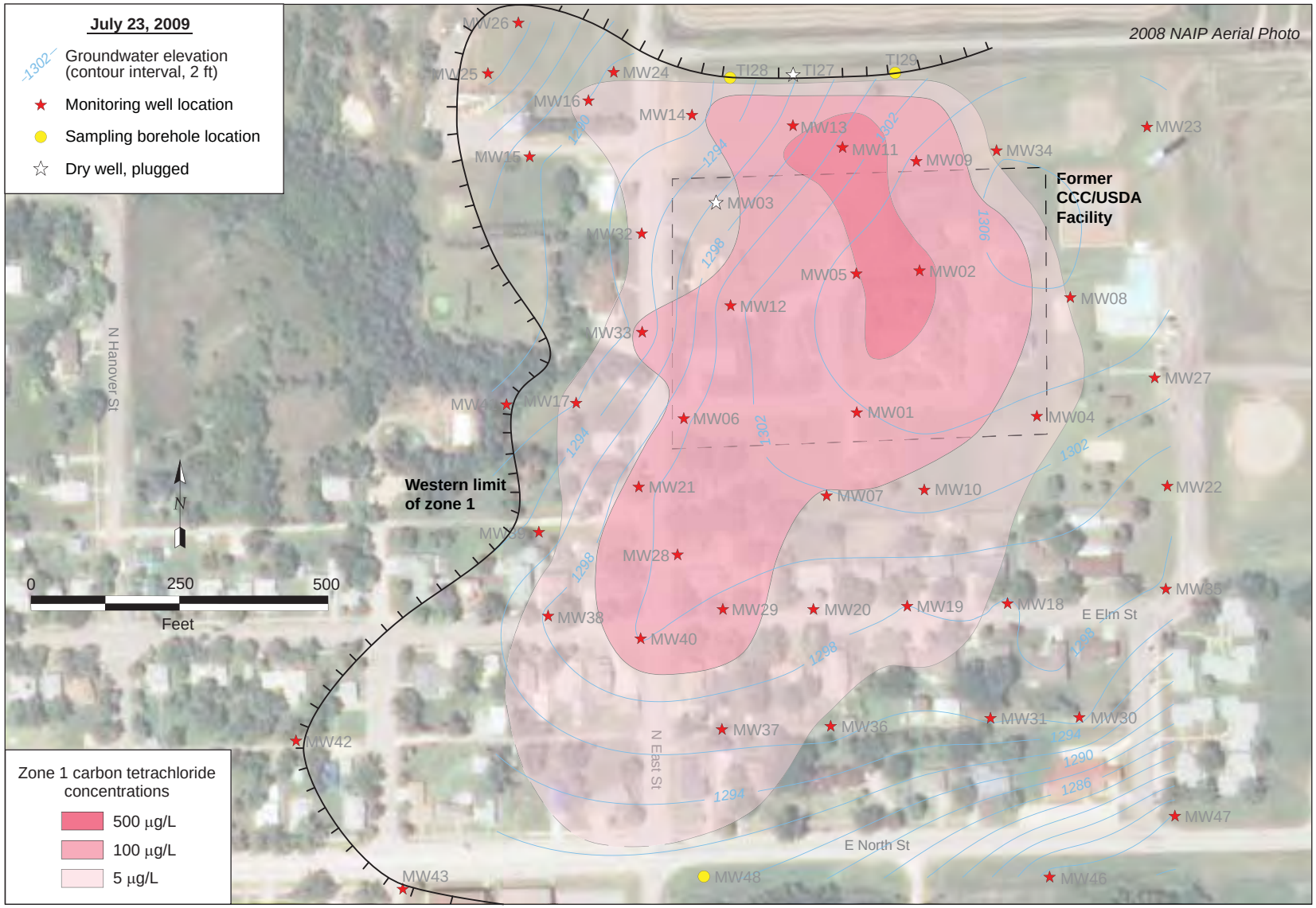

FIGURE 4.22 Interpreted lateral extent of carbon tetrachloride contamination and potentiometric surface in groundwater Zone 1, with estimated western limits of groundwater Zone 1. Source of photograph: NAIP (2008).

FIGURE 4.23 Lateral distribution of carbon tetrachloride in groundwater Zone 2 during the 2009-2010 investigation. Source of photograph: NAIP (2008).

FIGURE 4.24 Lateral distribution of chloroform in groundwater Zone 2 during the 2009-2010 investigation. Source of photograph: NAIP (2008).

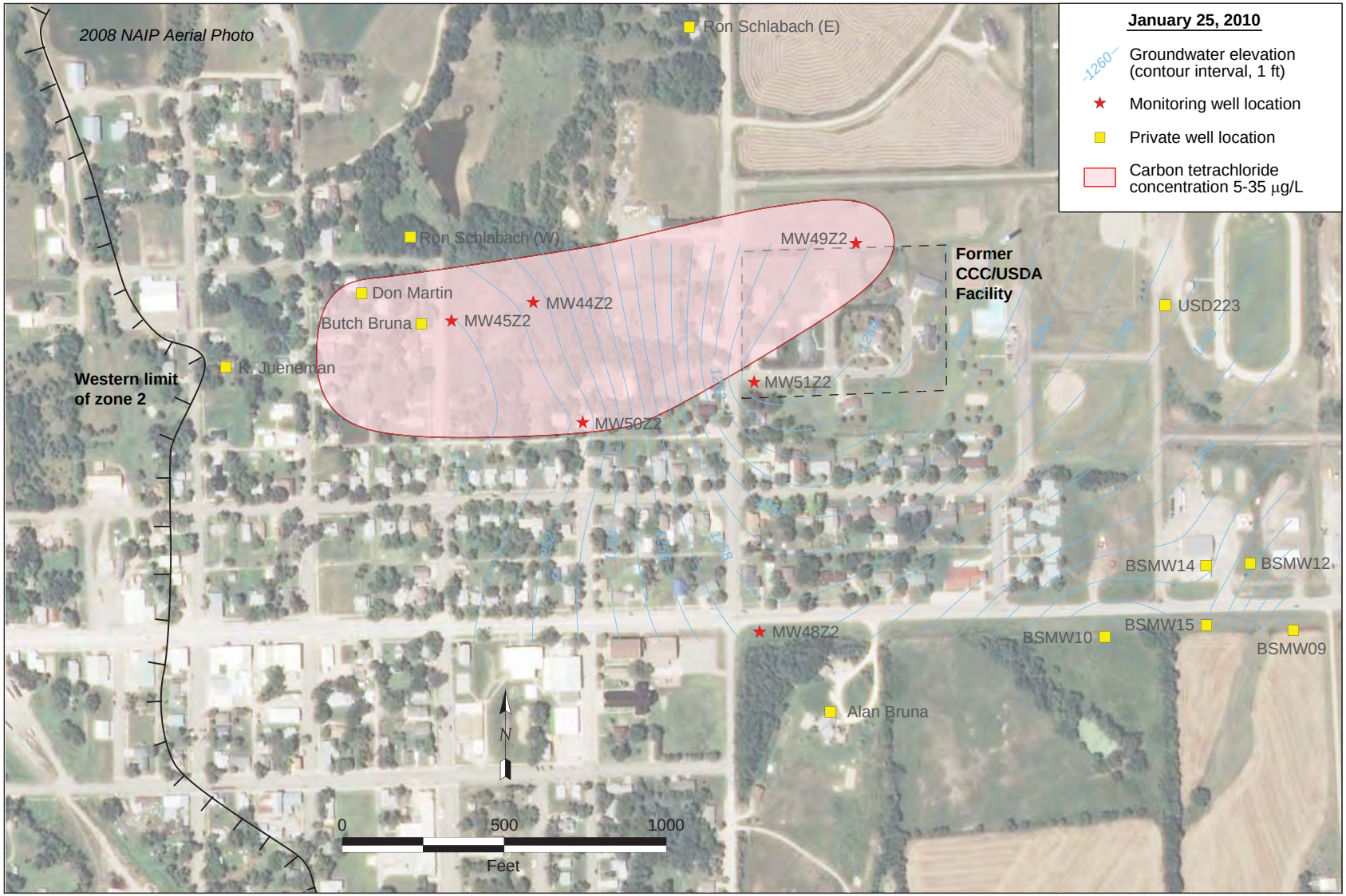

FIGURE 4.25 Interpreted lateral extent of carbon tetrachloride contamination and potentiometric surface in groundwater Zone 2, with estimated western limits of groundwater Zone 2. Source of photograph: NAIP (2008).

FIGURE 4.26 Lateral distribution of average estimated hydraulic conductivity values for groundwater Zone 1, as determined by analysis of the data generated by the August 2009 slug testing. Source of photograph: NAIP (2008).

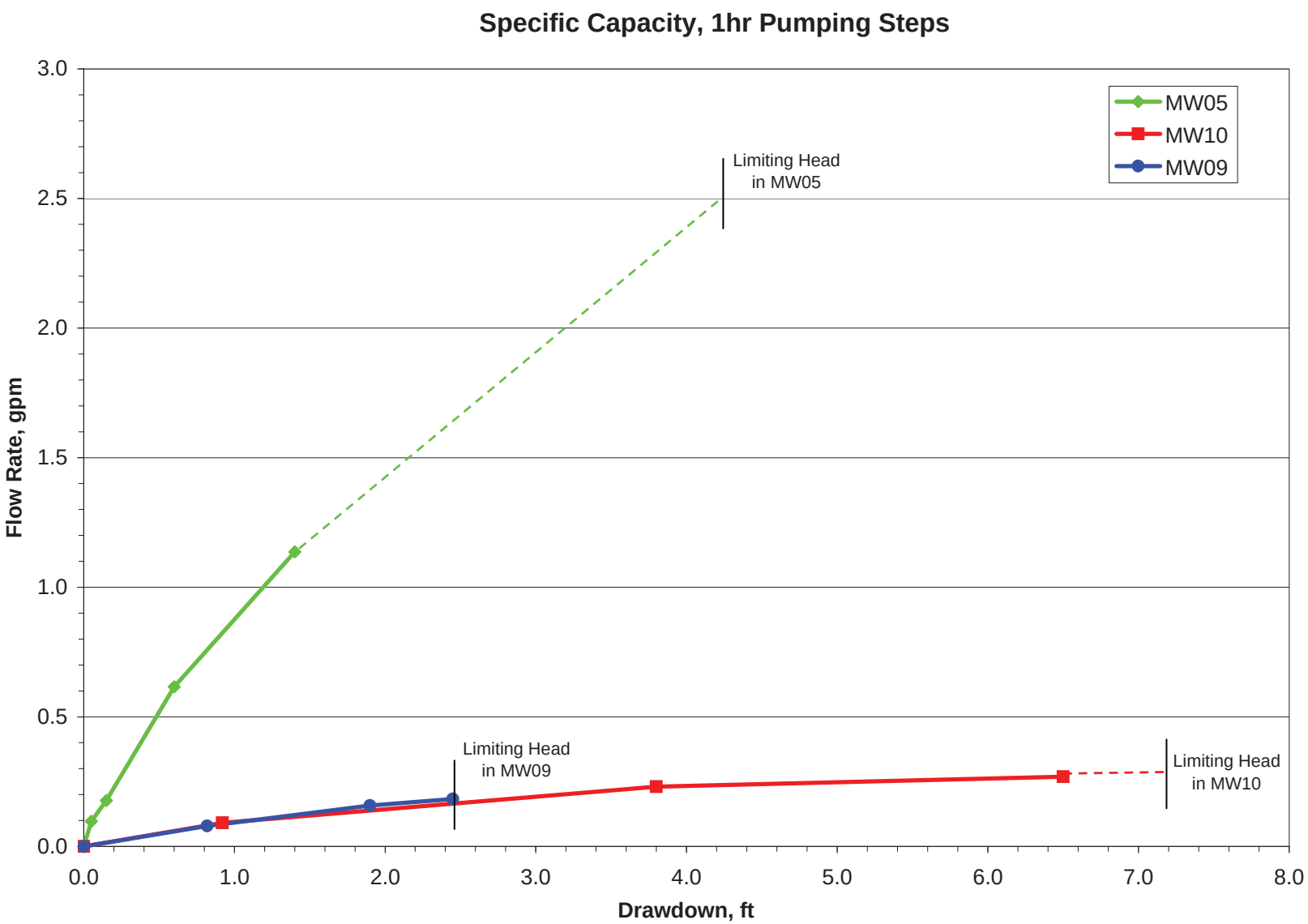

FIGURE 4.27 Specific capacity estimates for Zone 1 wells MW09, MW05, and MW10, calculated on the basis of 1-hr pumping steps.

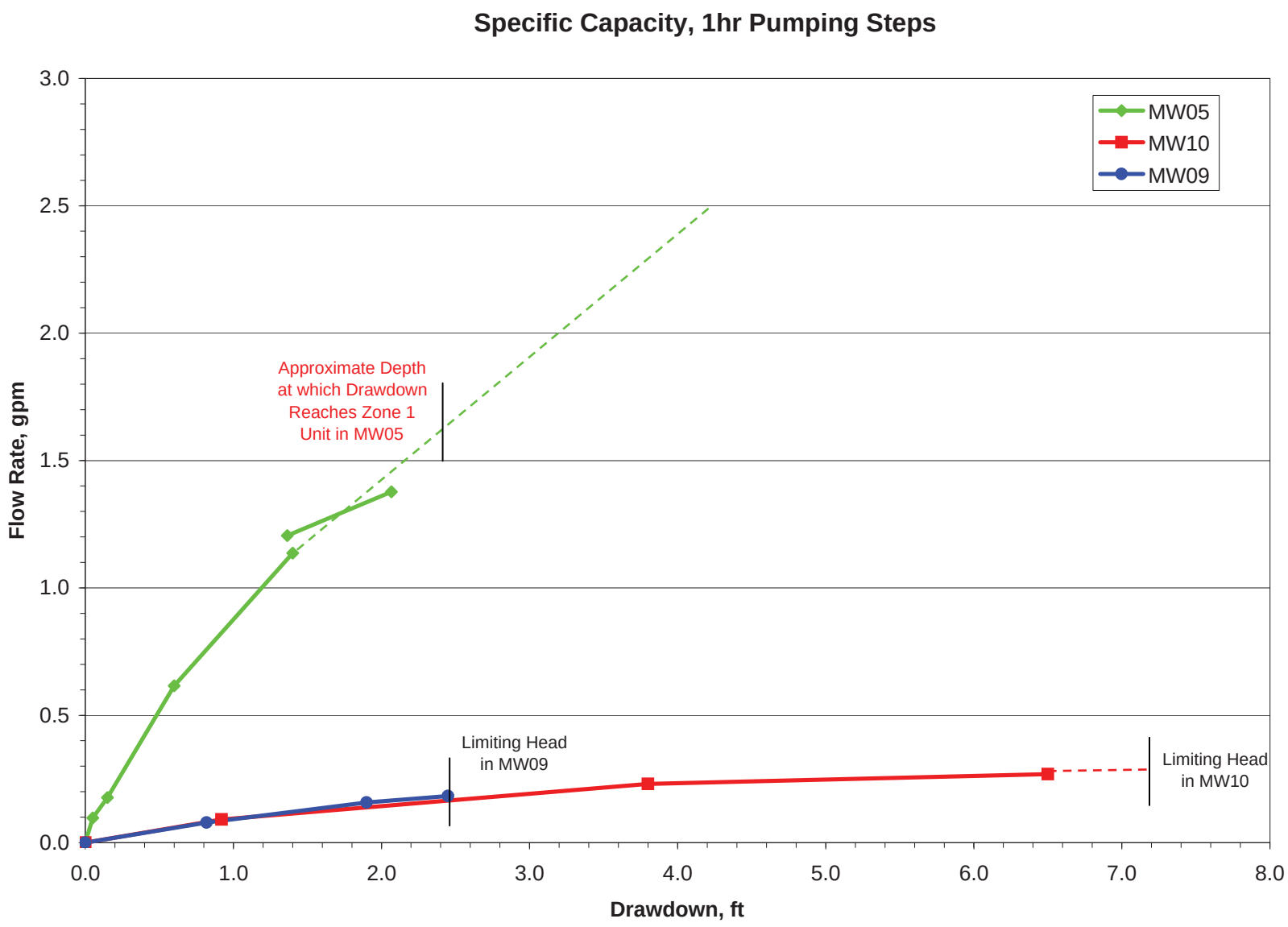

FIGURE 4.28 Drawdown and flow rate for well MW05 after 1 hr of pumping during pumping test 1 and pumping test 2, with the specific capacity estimates previously obtained for well MW05.

FIGURE 4.29 Groundwater flow pattern and estimated average groundwater velocities in Zone 1. Source of photograph: NAIP (2008).

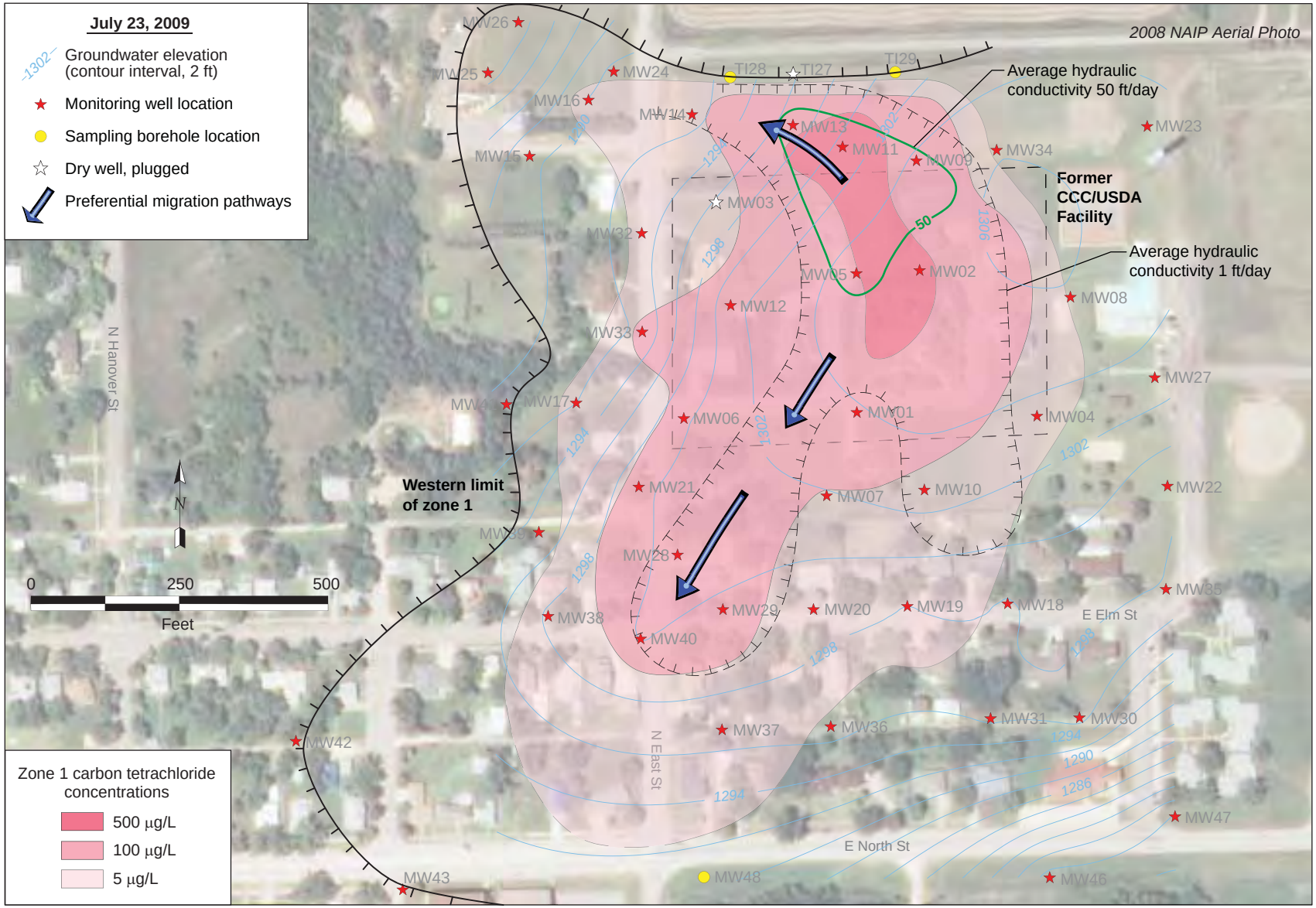

FIGURE 4.30 Interpreted lateral extent of carbon tetrachloride contamination, potentiometric surface, hydraulic conductivity, and preferred migration pathways in groundwater Zone 1. Source of photograph: NAIP (2008).

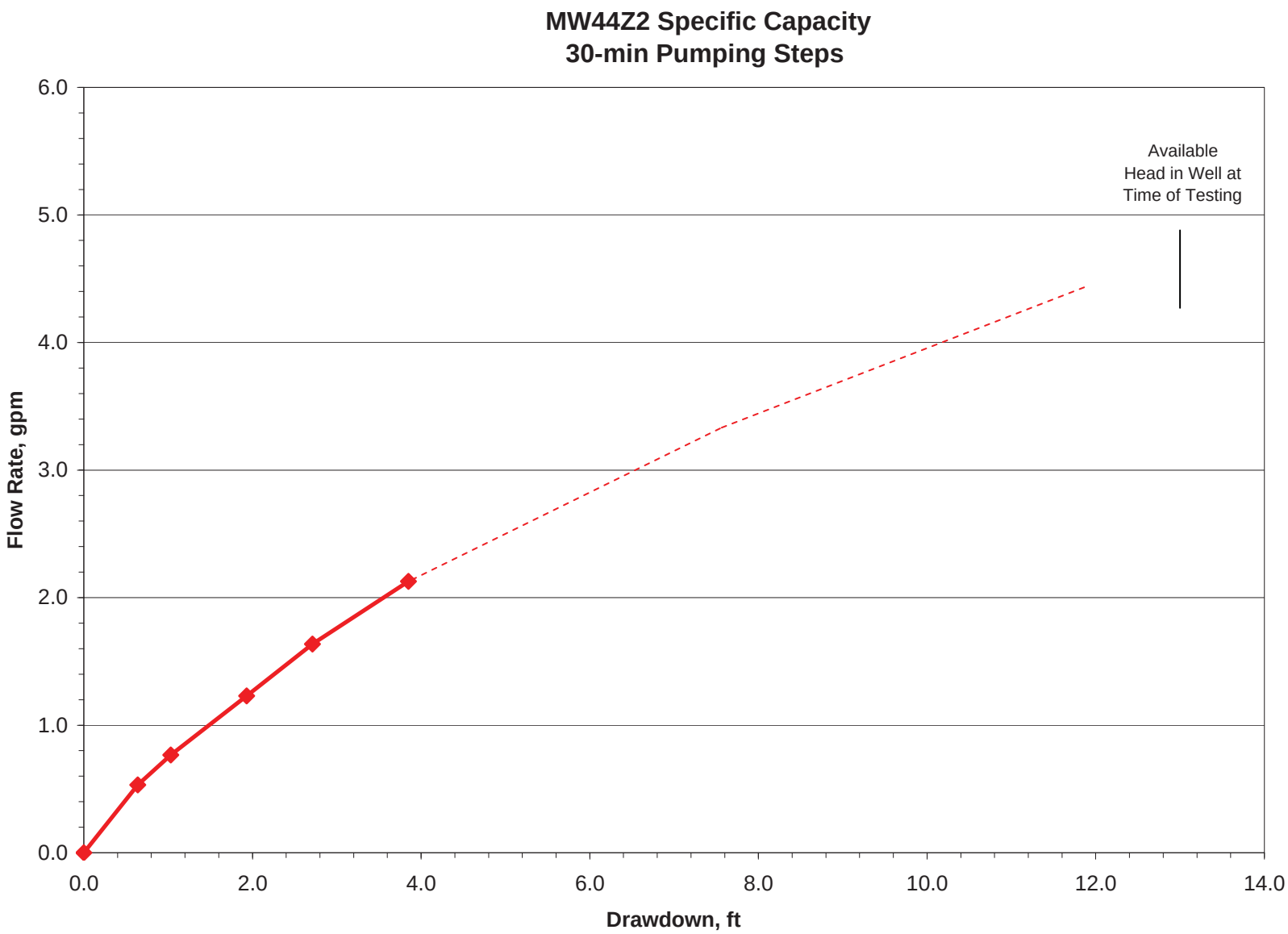

FIGURE 4.31 Specific capacity estimates for Zone 2 well MW44Z2, calculated on the basis of 30-min pumping steps.

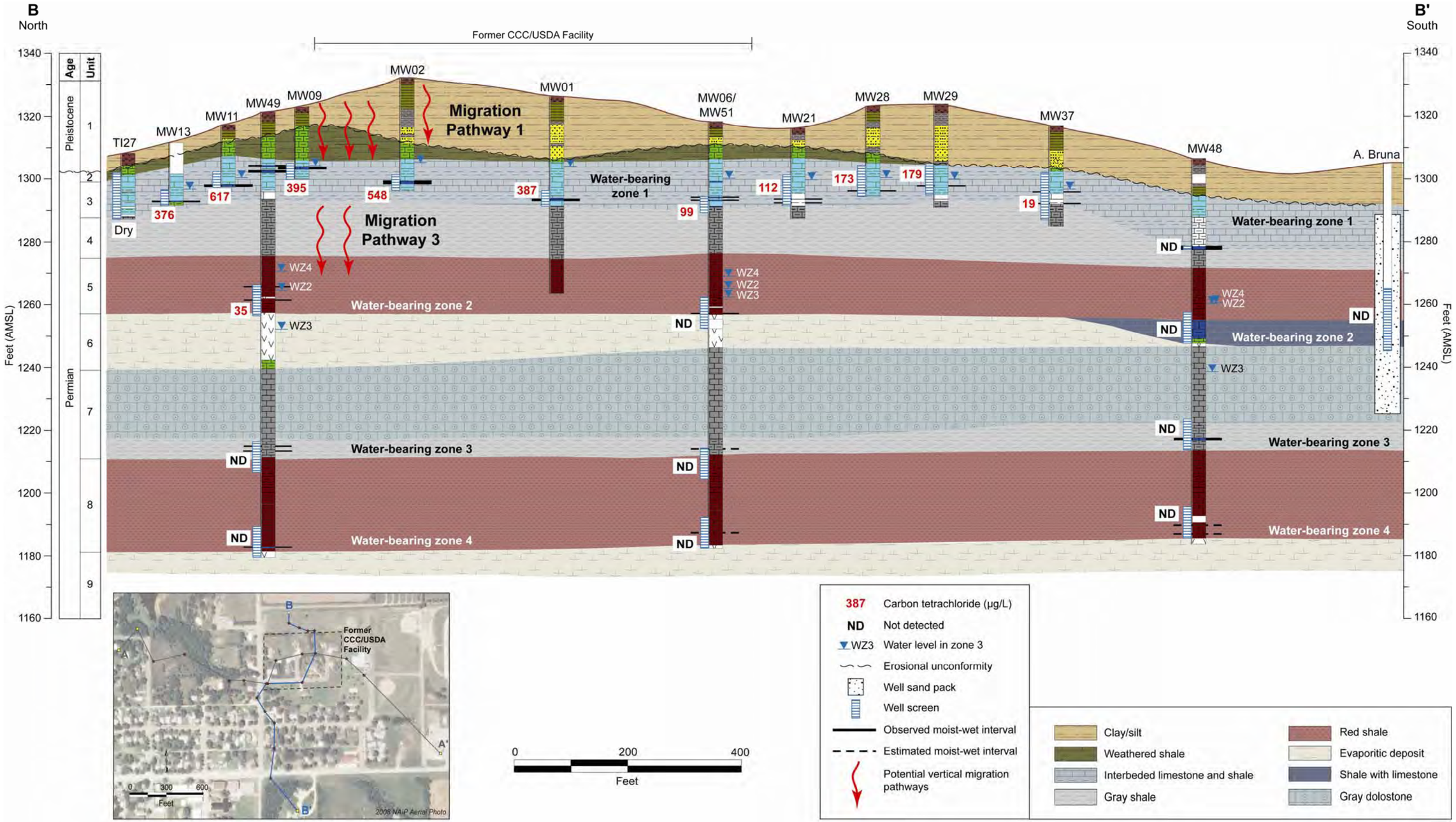

FIGURE 4.32 Interpreted vertical migration pathways 1 and 3 along hydrogeologic cross section B-B'. Source of photograph: NAIP (2008).

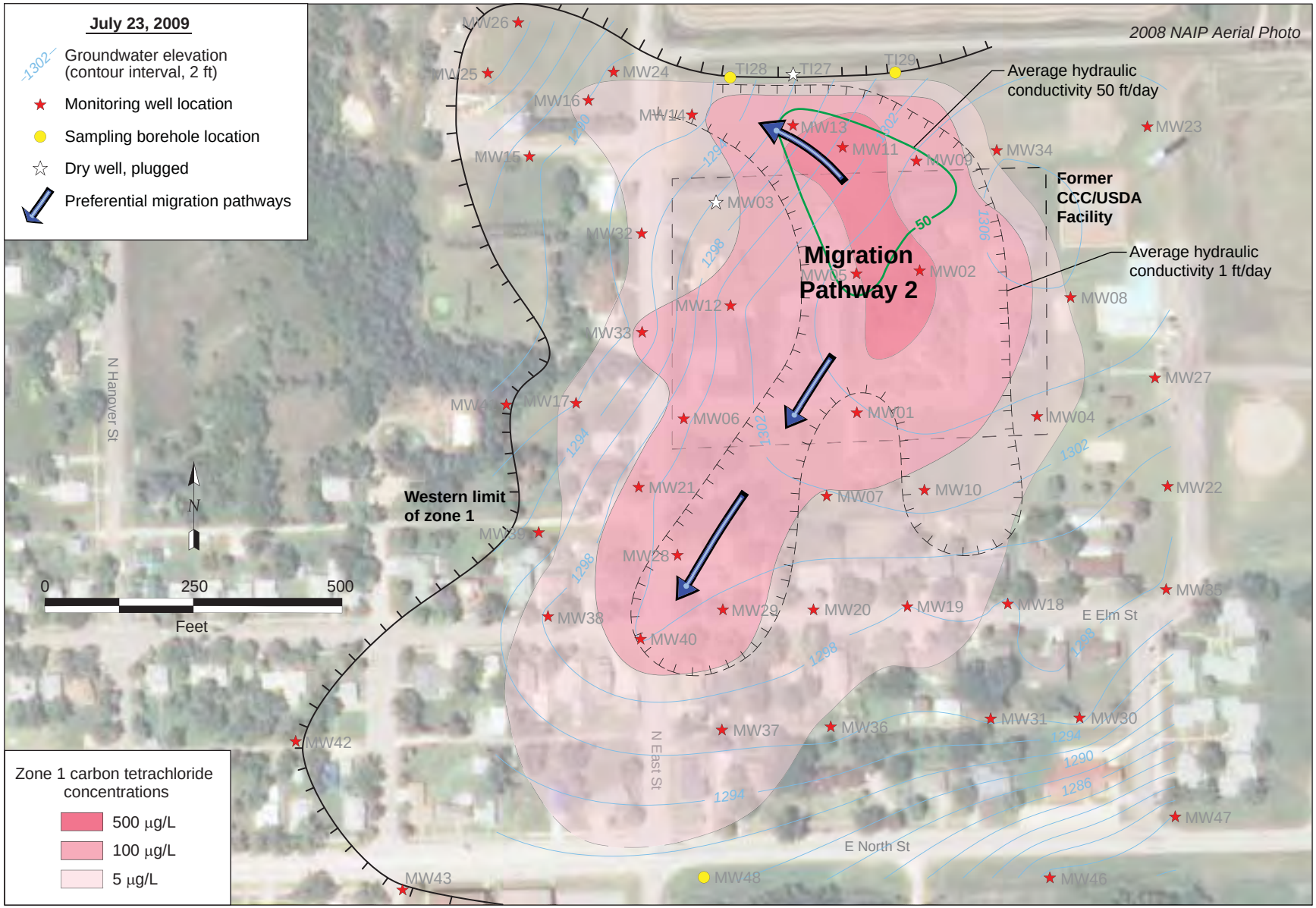

FIGURE 4.33 Interpreted lateral migration pathway 2 in groundwater Zone 1. Source of photograph: NAIP (2008).

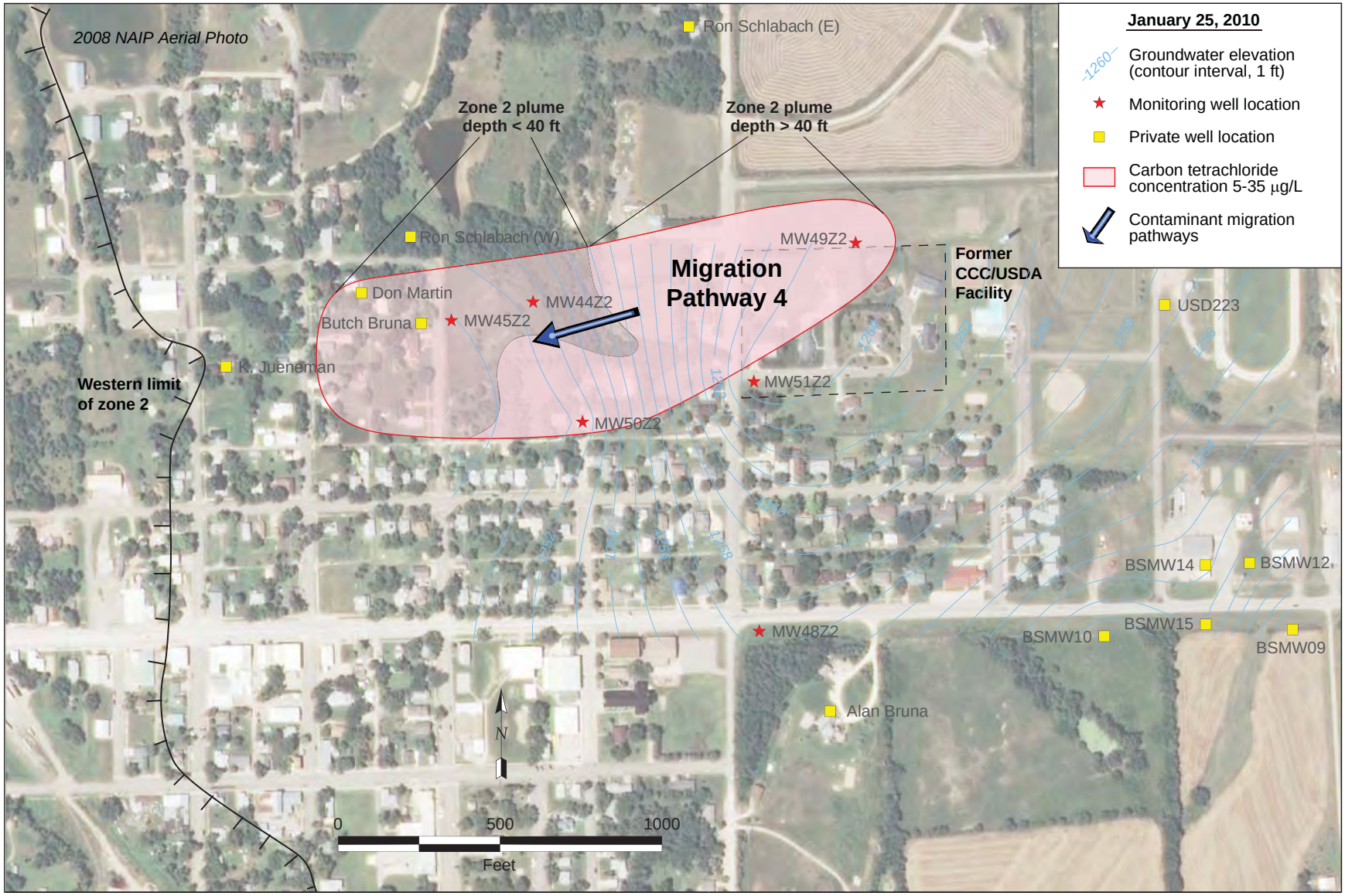

FIGURE 4.34 Interpreted lateral migration pathway 4 in groundwater Zone 2. Source of photograph: NAIP (2008).

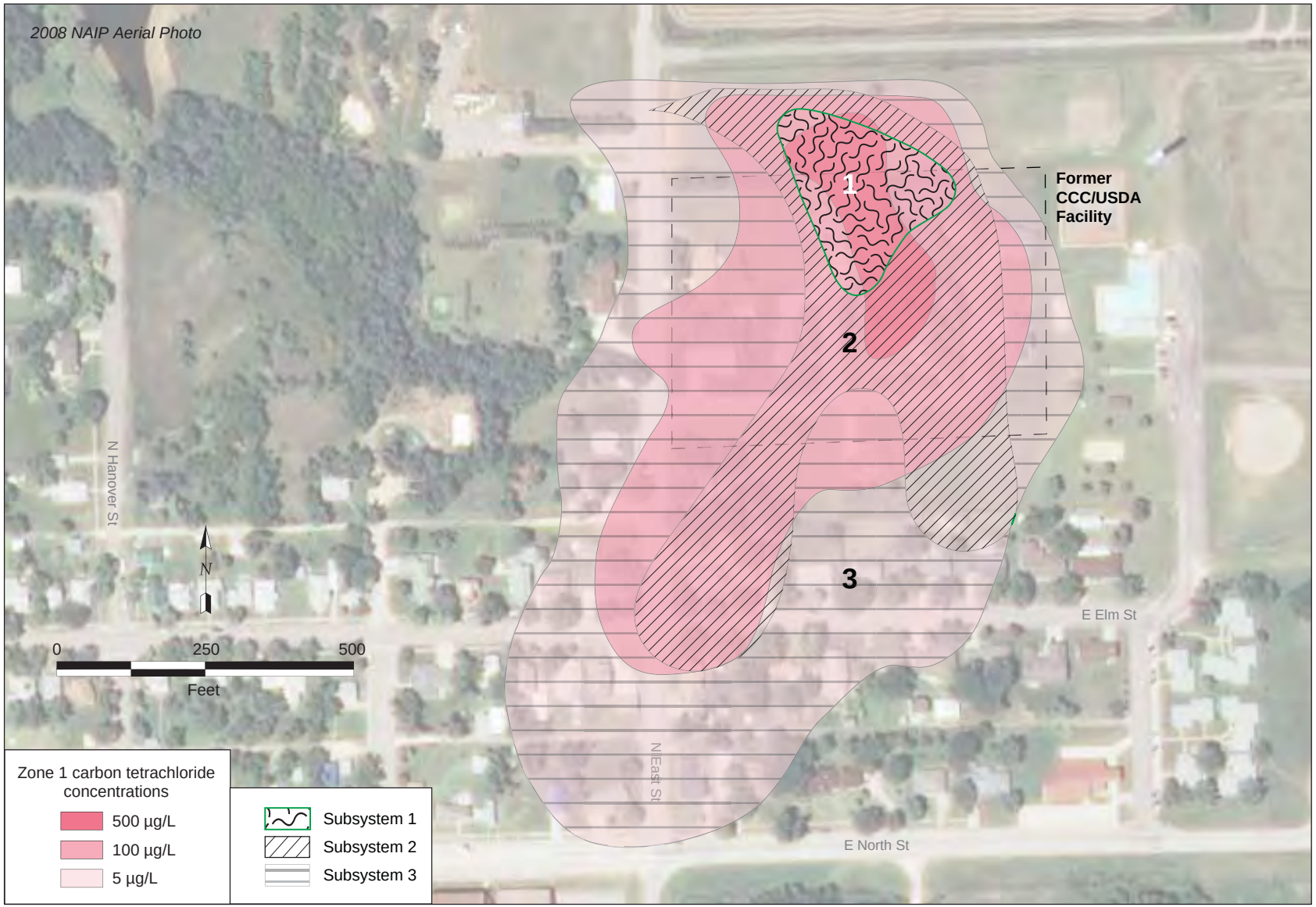

FIGURE 4.35 Interpreted spatial configurations of Subsystems 1, 2, and 3 within the carbon tetrachloride distribution in groundwater Zone 1. The characteristics of the subsystems are summarized in Table 4.6. Source of photograph: NAIP (2008).

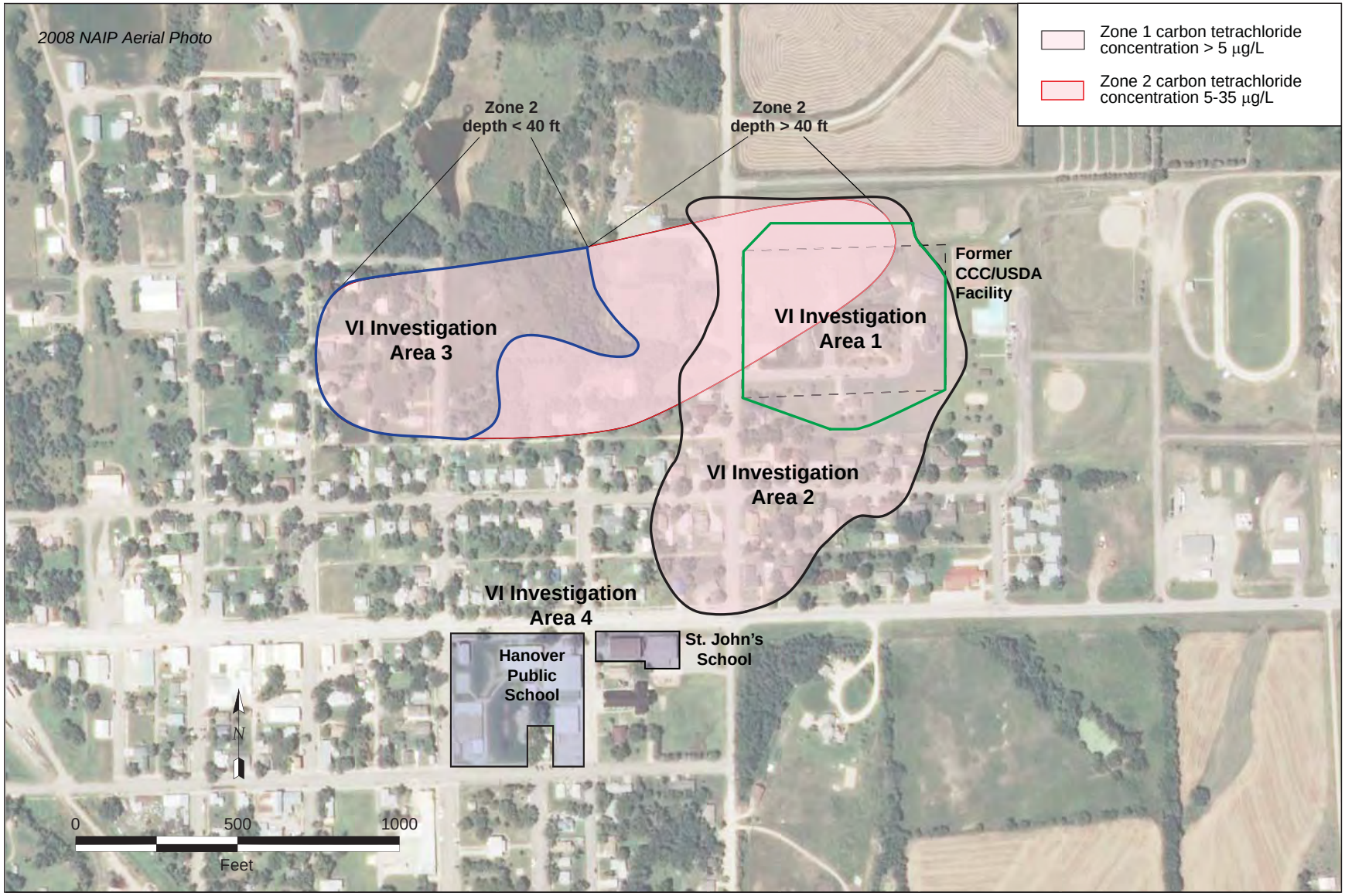

FIGURE 4.36 Vapor intrusion investigation Areas 1 and 2 (groundwater Zone 1), Area 3 (groundwater Zone 2), and Area 4 (schools). Source of photogaph: NAIP (2008).

FIGURE 4.37 Results of on-site screening analysis for carbon tetrachloride in soil gas samples collected in March 2009 within the potentially contaminated areas of groundwater Zone 1 and Zone 2. Source of photograph: NAIP (2008).

FIGURE 4.38 Results of laboratory analysis for carbon tetrachloride, chloroform, and radon in sub-slab vapor and indoor air samples collected in February-March 2009 at nine residences on and near the former CCC/USDA facility. Source of photograph: NAIP (2008).

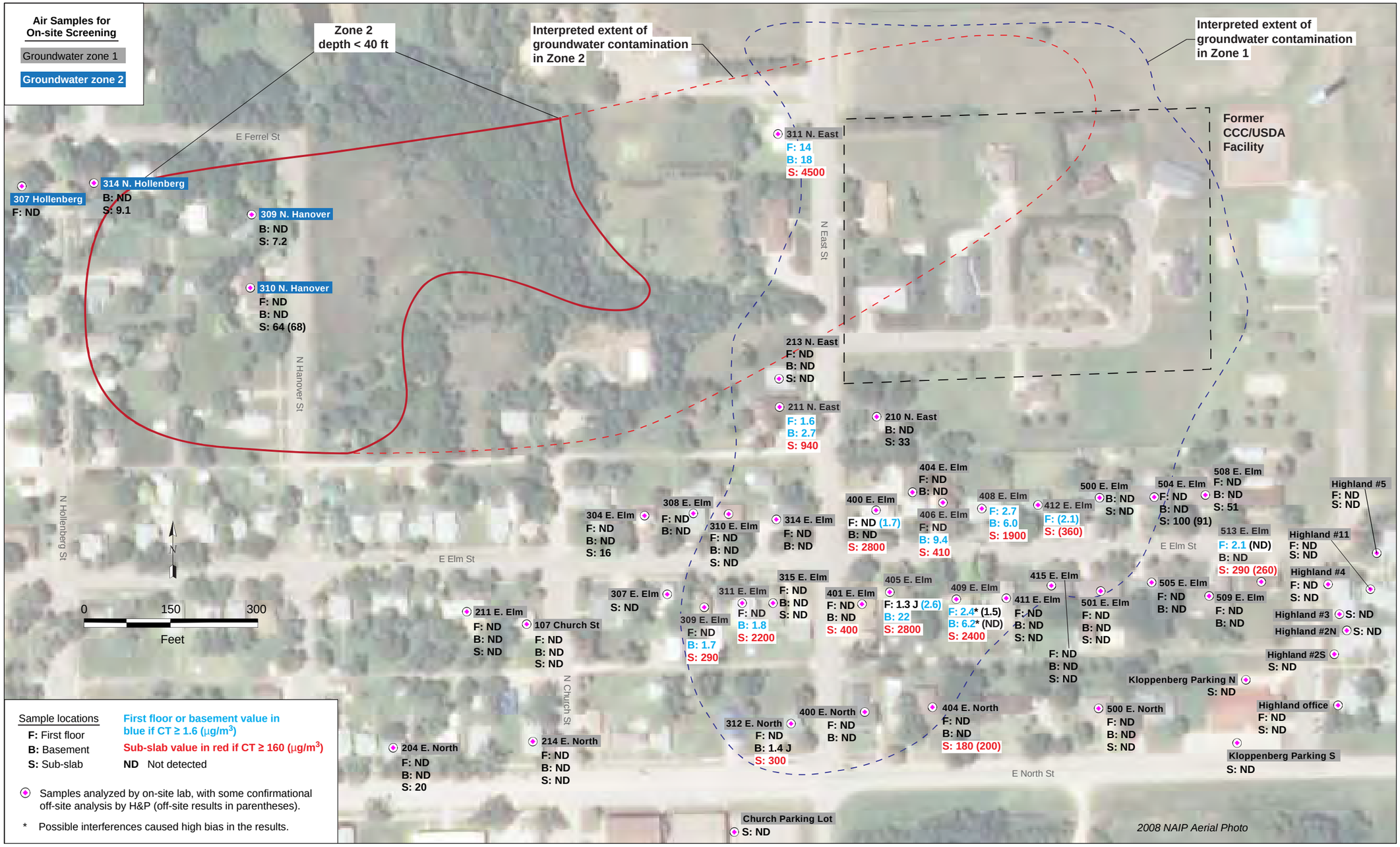

FIGURE 4.39 Results of on-site screening analysis for carbon tetrachloride for indoor air and sub-slab vapor samples collected in March-April 2009 at residences within and near the contaminated areas of groundwater Zone 1 and Zone 2. Source of photograph: NAIP (2008).

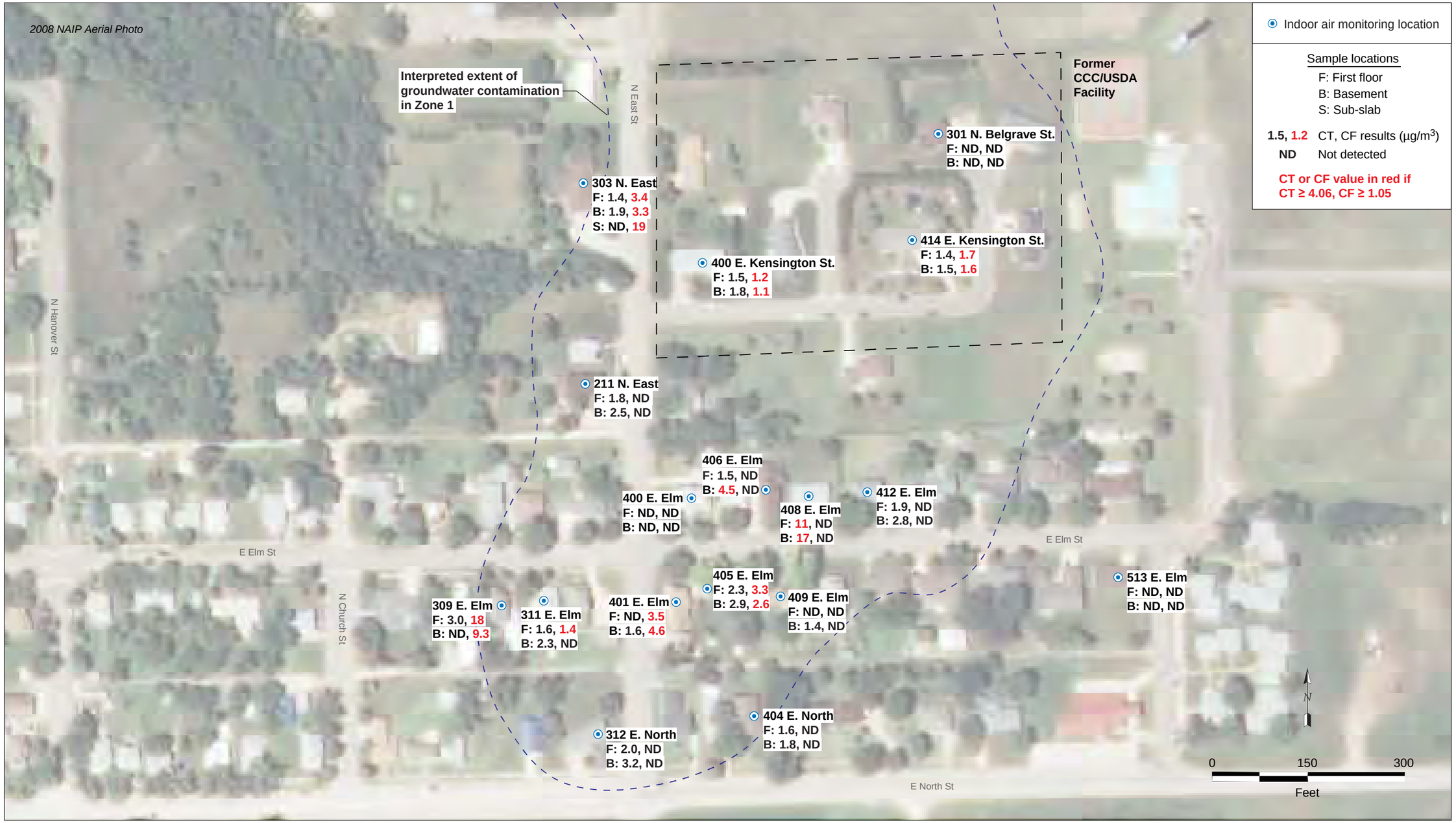

FIGURE 4.40 Results of laboratory analysis for carbon tetrachloride and chloroform in indoor air and sub-slab vapor samples collected in August 2009 at selected homes potentially affected by contamination in groundwater Zone 1. Source of photograph: NAIP (2008).

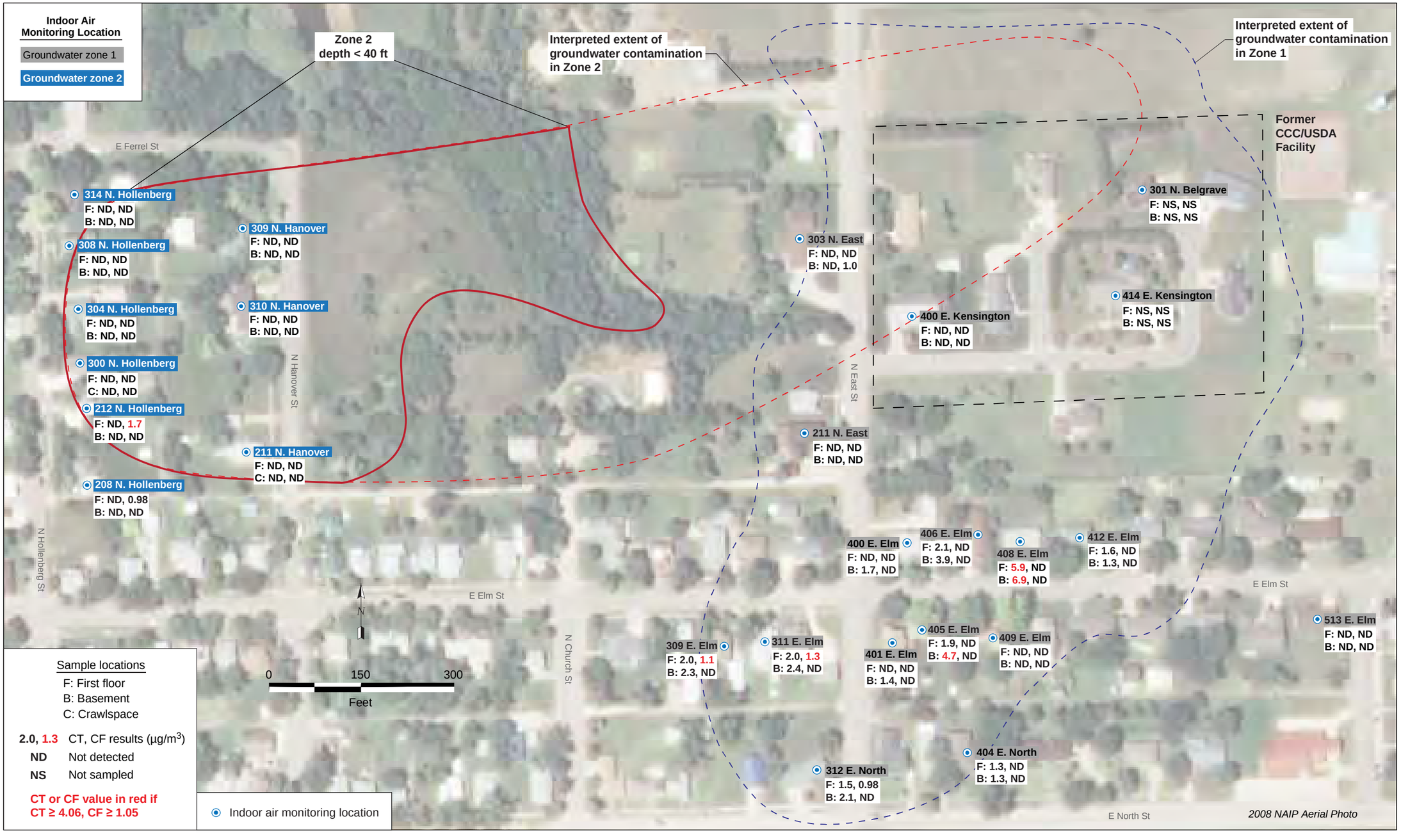

FIGURE 4.41 Results of laboratory analysis for carbon tetrachloride and chloroform in indoor air samples collected at homes potentially affected by contamination in groundwater Zone 1 in January 2010 and at homes potentially affected by contamination in groundwater Zone 2 in February 2010. Source of photograph: NAIP (2008).

FIGURE 4.42 Radon concentrations detected in indoor air of the schools and the tested homes. Source of photograph: NAIP (2008).

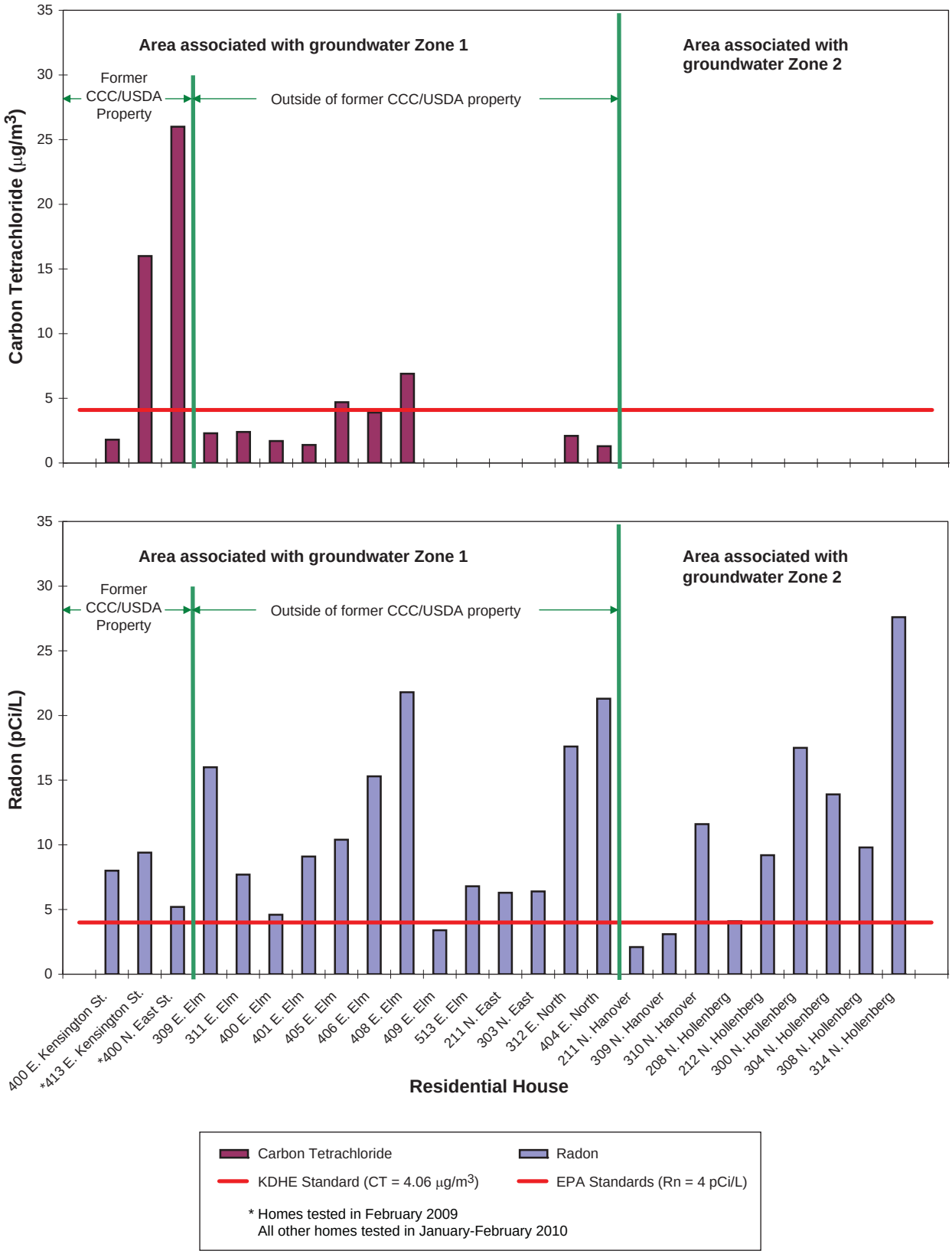

FIGURE 4.43 Qualitative correlation between radon and carbon tetrachloride in basement indoor air of homes tested.

FIGURE 4.44 Sampling locations in the vapor intrusion investigation, with concentrations of carbon tetrachloride and chloroform found in laboratory analysis of indoor air and sub-slab vapor samples collected at the five residences selected for mitigation. Source of photograph: NAIP (2008).

5 Summary of Key Findings

The key technical findings of the comprehensive geologic, hydrologic, and geochemical site characterization studies; the aquifer hydraulic testing; and the VI investigation programs conducted at the former CCC/USDA grain storage facility in Hanover are summarized below with regard to the physical setting, the extent of the contamination, and vapor intrusion.

5.1 Physical Setting

- The geologic sequence in the Hanover area generally consists of unconsolidated Pleistocene eolian deposits (on upland areas) and alluvial sediments (in floodplains areas) overlying Permian bedrock. In the study area, a vertical sequence of nine primary lithostratigraphic units was recognized. In order of increasing depth, these units consist of (1) silt and clay with a lower section of sand and sandy silt, (2) weathered shale, (3) interbedded limestone and shale, (4) gray shale, (5) an upper red shale, (6) an interval that varies laterally in facies from evaporitic deposits to soft gray shale with limestone, (7) gray dolostone and shale, (8) a lower red shale, and (9) a lower evaporitic deposit.

- A prominent erosional unconformity marks the top of the bedrock section. Together with more recent topographic downcutting, this erosional unconformity has influenced the lateral extent of the lithostratigraphic units at this site. The complete sequence of units outlined above is present beneath a local upland area that extends southwestward from the former CCC/USDA property. On the eastern and western flanks of the upland area, erosion has progressively cut into, or locally removed, the shallower lithostratigraphic units. On the western flank of the uplift, Units 1-4 are completely absent, and erosion has partially removed Unit 5.

- Four groundwater-bearing intervals were identified in the bedrock sequence. Groundwater Zone 1 — the uppermost water-bearing unit — consists of a few discrete, thin, saturated horizons (total combined thickness of 1-3 ft) developed along bedding planes and fractures within the interbedded

limestones and shales of Unit 3. The areal extent of groundwater Zone 1 is bounded by the erosional limits of Unit 3. Semi-radial groundwater movement was identified in Zone 1, with flows to the northwest, west, southwest, and south originating from a localized groundwater high (groundwater divide) beneath the upland area at the former CCC/USDA facility. Preferentially southwestward groundwater flow is evident along a narrow, relatively permeable zone, moving at an average velocity of approximately 14 ft/yr (greater by roughly one or two orders of magnitude than the rates of flow to the northwest, west, or south).

- Groundwater Zone 2 consists of relatively thick saturated intervals in the shale with limestone facies of Unit 6, or thin moist-wet intervals along bedding planes near the base of the upper red shale (Unit 5) where this interval overlies the evaporitic facies of Unit 6. Zone 2 is laterally more extensive than Zone 1, since it is located deeper in the stratigraphic sequence and hence has been less severely truncated by erosion. Semi-radial groundwater flow was also identified in groundwater-bearing Zone 2, originating from a localized high beneath the former CCC/USDA facility. Groundwater movement to the west, southwest, south, and southeast is indicated; however, the highest hydraulic gradients are observed in the westerly flow direction.

- Groundwater Zone 3 is hosted by the gray dolomitic shale near the base of Unit 7. The thin moist-wet intervals in this unit, which are difficult to identify, have a combined thickness of less than 2 ft. Groundwater Zone 4 is developed at the base of the lower red shale (Unit 8). The multiple thin, moist-wet intervals that form Zone 4 also have a total thickness of less than 2 ft. Continuous monitoring indicates that the groundwater levels in monitoring wells installed in Zone 3 and Zone 4 have yet to equilibrate with the ambient levels in the surrounding lithologies; therefore, the detailed patterns of groundwater flow in these units cannot be determined from available data. The existing observations for these wells suggest, however, that the capacity of Zone 3 and Zone 4 to transmit groundwater to wells is very limited.

- Groundwater leakage from Zone 1 to Zone 2 is indicated in the area beneath the upland where groundwater mounding is observed in both Zone 1 and

Zone 2. This vertical leakage, however, is minimal, as indicated by the much lower concentrations of carbon tetrachloride and nitrate in Zone 2. The apparent mixing ratio of Zone 1 groundwater flowing into Zone 2 is estimated at 10% or less, on the basis of concentration data for both carbon tetrachloride and nitrate in the upland area.

- Although equilibrium groundwater levels have not been achieved in Zone 3 or Zone 4, recent groundwater level measurements in Zones 1-4 indicate an upward hydraulic gradient from Zone 4 to Zone 3 (and also from Zone 4 to Zone 2). These observations suggest that a natural hydraulic barrier exists to downward migration of Zone 2 groundwater into the deeper parts of the flow system beneath the upland area.

5.2 Extent of the Contamination

- The residual concentrations of carbon tetrachloride and chloroform identified in soil were well below the KDHE Tier 2 standards for these contaminants (200 μg/kg and 960 μg/kg, respectively), indicating that the soils pose no unacceptable health or environmental risks and do not represent a potential continuing source of contamination to groundwater. Vertical-profile sampling (for VOCs analyses) of the vadose zone soils beneath the former CCC/USDA facility was conducted at 38 locations. Carbon tetrachloride was detected at 8 locations only, at a maximum concentration of 35 μg/kg. Low levels of chloroform (≤ 44 μg/kg) were also detected at 2 locations.

- Carbon tetrachloride contamination was identified in the groundwater in Zone 1 at concentrations up to 617 μg/L. The highest concentrations of carbon tetrachloride (> 500 μg/L) were detected beneath the north central portion of the former CCC/USDA facility. Concentrations exceeding 100 μg/L generally underlie the topographic upland that extends to the south and southwest of the former facility, along the preferred groundwater flow pathway identified in this direction.

- The lateral variations in carbon tetrachloride concentrations observed in Zone 1 (as a result of contaminant migration) show relatively close correlation to the spatial variations in the hydraulic conductivity of the Zone 1 unit that were identified through extensive hydraulic testing. Specifically, carbon tetrachloride concentrations > 100 μg/L are generally associated with the regions of highest K_h values in the unit (beneath the upland area), while progressively lower concentrations and K_h values are generally observed toward the margins of the upland.

- The elevated ratios of chloroform to carbon tetrachloride observed suggest that some degradation of carbon tetrachloride (by reductive dechlorination under anaerobic conditions) is occurring in the Zone 1 groundwater along the leading, downgradient margins of the contaminant distribution, as well as in groundwater Zone 2. Chloroform was found in groundwater Zone 1 at a maximum concentration of 18 μg/L. In the northern part of the former CCC/USDA facility, the relative abundance of chloroform to carbon tetrachloride was generally less than 2%. However, near the margins of the carbon tetrachloride distribution, the ratios of chloroform to carbon tetrachloride in Zone 1 increased locally to values of 13% to 64% or more. A similar increase (to values of 9% to 22%) is also evident in Zone 2.

- Carbon tetrachloride was identified in Zone 2 along a relatively narrow pathway extending to the west and downgradient from the former CCC/USDA facility. The observed carbon tetrachloride concentrations ranged from 35 μg/L at the northern edge of the former facility to 11-28 μg/L near the downgradient toe of the distribution. Lower levels of carbon tetrachloride (1.5-7.8 μg/L) were also found in four private wells near the apparent western edge of this distribution. The private wells extend into the deeper groundwater zones but are believed to be continuously gravel packed across Zone 2.

- No carbon tetrachloride was detected in groundwater Zone 3 or Zone 4 at monitoring wells completed exclusively in one of these zones. This observation is consistent with the interpretation that Zone 3 and Zone 4 receive little or no natural recharge via vertical infiltration from contaminated Zone 2. Carbon tetrachloride was, however, identified in the four private wells

noted above, suggesting that the well gravel packs might provide a conduit for contaminant migration to the deeper zones near the western, downgradient toe of the Zone 2 contaminant distribution.

- No unacceptable health risks are associated with potential human exposure to the contaminated groundwater in Zone 1 or Zone 2, if current conditions continue. No active private (or public) wells are known to be present within the area of Zone 1 contamination or to be completed in this unit. The four identified private wells that penetrate the contaminated portion of Zone 2 are used only for lawn and garden purposes. Field reconnaissance along the projected erosional limits of the Zone 1 and Zone 2 units (in the identified directions of contaminant migration) revealed no springs or seepage to suggest direct drainage from these intervals to the surface.

- The results of extensive hydraulic characterization studies (slug tests, step-drawdown pumping tests, and constant-rate pump testing) conducted for groundwater-bearing Zone 1 strongly suggest that the production capacity of this unit is restricted by the total effective thickness (1-3 ft) of the few discrete, thin horizons that form the interval; the heterogeneous hydraulic conductivity of the interval (ranging from 0.001 ft/day to 75 ft/day); and the generally limited availability of groundwater in Zone 1. The results further indicate that groundwater pumping (or injection) through use of conventional wells does not represent a viable mechanism for hydraulic control or removal of the contaminated groundwater in Zone 1.

- The results of extensive hydraulic testing conducted for groundwater-bearing Zone 2 suggest that this unit has a greater capacity than Zone 1 for groundwater production, because of the relatively greater total thickness (up to 5 ft) and generally less discrete nature of the Zone 2 water-bearing intervals, as well as the generally higher estimated K_h values of Zone 2 (ranging from 7.9 ft/day to 43 ft/day). Pumping tests conducted near the western (downgradient) margin of the Zone 2 contaminant distribution demonstrated that groundwater extraction appears feasible as a potential response technology in this portion of the Zone 2 water-bearing unit.

5.3 Vapor Intrusion

- On the basis of KDHE (2007b) guidance, approximately 60 occupied residences were identified for the consideration of possible VI that might be linked to the carbon tetrachloride contamination identified in groundwater-bearing Zone 1 or in the western, more downgradient portion of Zone 2 (at depths ≤ 40 ft BGL). Comprehensive indoor air testing and periodic air monitoring were conducted in the summer and/or winter at all identified, accessible structures.

- No risk of upward VI could be demonstrated in association with the localized low residual levels of carbon tetrachloride detected in subsurface soils at the former CCC/USDA facility.

- Five homes overlying the documented contamination in groundwater-bearing Zone 1 were identified as impacted by carbon tetrachloride VI at levels greater than the KDHE Tier 2 standard of 4.055 $\mu g/m^3$ for this contaminant in indoor air. No carbon tetrachloride was detected at either the Hanover public school facility or St. John's School, which both lie outside the interpreted limits of the carbon tetrachloride distribution in groundwater Zone 1 and Zone 2.

- With the approval of the KDHE (2009f, 2010e), the CCC/USDA installed mitigation systems at each of the five homes determined to be impacted by VI. Performance testing of the installed systems has demonstrated that they are effectively reducing indoor air contaminant concentrations to acceptable levels. Therefore, no unacceptable health risks are currently associated with potential human exposure to indoor air contaminated with carbon tetrachloride and chloroform as a result of VI from contaminated groundwater in Zone 1 or Zone 2.

- Radon analysis, performed to use radon as a possible supplemental indicator of subsurface VI to indoor air, identified unacceptable levels of radon that exceed the EPA standard (up to 7 times the EPA action level of 4.0 pCi/L) in 22 of 25 homes tested for this contaminant, as well as at selected locations in the Hanover public school facility and St. John's School. These observations

demonstrate that the upward intrusion of radon to unacceptable health risk levels is a widespread phenomenon for the Hanover community. Radon is a naturally occurring substance that is unrelated to grain fumigation activities.

- Additional information about radon, including options for radon testing and mitigation, is available from the following sources:

  - Toll free: 1-866-865-3233 — KDHE Bureau of Environmental Health

  - Toll free: 1-800-693-5343 — Kansas Radon Hotline

  - URL: http://www.epa.gov/radon/pubs/citguide.html — EPA publication, *A Citizen's Guide to Radon: The Guide to Protecting Yourself and Your Family from Radon*

  - URL: http://www.epa.gov/radon/pdfs/hmbuygud.pdf — EPA publication, *Home Buyer's and Seller's Guide to Radon*

  - URL: http://www.epa.gov/radon/rnxlines.html — EPA web page of radon hotlines and information

6 Recommendations

This section contains preliminary recommendations for corrective action objectives and corresponding potential corrective action alternatives and technologies, as required by the KDHE (2005a). In the development of these preliminary objectives and recommendations, the following key findings of the 2009-2010 Hanover site investigation were considered:

- Since 1974, drinking water has been supplied to the city of Hanover by the Washington County RWD #1 from a well field 6.5 mi north of Hanover. The city elected to abandon its existing public wells in favor of the RWD supply because of the hardness of the local groundwater.

- No unacceptable health risks are associated with potential human exposure to the contaminated groundwater in Zone 1 or Zone 2 under the current conditions. No active private (or public) wells are known to be present within the area of Zone 1 contamination or to be completed in this unit. The four identified private wells that penetrate the contaminated portion of Zone 2 are used only for lawn and garden purposes.

- Carbon tetrachloride contamination was identified in groundwater Zone 1 at concentrations up to 617 µg/L. This contamination is constrained laterally within a local, limited area by the erosion limit of Zone 1. The current investigation confirmed that most of the Zone 1 contaminant system (94% of the total area) is not amenable to extraction or injection technologies that could restore groundwater to carbon tetrachloride concentrations below the MCL and the KDHE Tier 2 standard value of 5 µg/L.

- Low levels of carbon tetrachloride (≤ 35 µg/L) were found in groundwater Zone 2 along a relatively narrow pathway extending from the former CCC/USDA facility to the west, where groundwater extraction as a potential response technology appears to be feasible. Private wells located in Zone 2 might provide conduits for contaminant migration to deeper Zones 3 and 4 via unrestricted gravel packs.

- No carbon tetrachloride was detected in groundwater Zone 3 or Zone 4 at monitoring wells completed exclusively in either of these discrete water-bearing zones.

- Five homes overlying the documented contamination in groundwater Zone 1 were identified as impacted by carbon tetrachloride VI at levels greater than the KDHE Tier 2 standard of 4.055 $\mu g/m^3$ in indoor air. Mitigation systems have been installed and tested.

- No unacceptable human health risks are currently associated with potential exposure to indoor air contaminated with carbon tetrachloride and chloroform from groundwater in Zone 1 or Zone 2 at Hanover.

Although no unacceptable health risks are associated with current human exposure to the contaminated groundwater and indoor air, the potential for future exposure cannot be ruled out. In order to reduce and/or manage any potential risks, preliminary potential corrective action objectives and alternatives are presented and discussed below.

6.1 Preliminary Corrective Action Objectives

Corrective actions for the carbon tetrachloride contamination at Hanover will encompass the following preliminary general objectives:

- Eliminate or otherwise manage the risk due to potential exposure to a domestic water supply containing carbon tetrachloride at a concentration above the KDHE Tier 2 standard.

- Eliminate or otherwise manage the risk due to potential exposure to indoor air containing carbon tetrachloride at a concentration above the KDHE Tier 2 standard.

- Reduce the mass and/or volume of carbon tetrachloride in groundwater in the isolated highly contaminated area where available corrective action technologies could possibly be implemented as a viable mechanism for removal or treatment of the contaminants of concern.

With regard to risks due to exposure to contaminated indoor air, a comprehensive VI investigation was performed in 2009-2010, according to the methodologies discussed in Section 2. After evaluation of the VI results presented and discussed in Sections 3 and 4, five homes were identified for mitigation by the CCC/USDA and the KDHE. The KDHE (2009g, 2010e) approved installation of a VI mitigation system at each home. The monitoring results for the mitigation systems (Sections 3.9 and 4.8) demonstrate the elimination of risk due to exposure to carbon tetrachloride in indoor air in the affected homes at concentrations above the KDHE Tier 2 standard.

This section focuses on objectives for corrective actions associated with groundwater contamination. In accordance with KDHE (2005b) guidance, the CCC/USDA will proceed to a CAS. To meet the general objectives above, the corrective action alternatives and individual components described below — and combinations of the individual components — are being considered for evaluation in the CAS for the site.

6.2 Potential Corrective Action Alternatives and Components

Three corrective action alternatives and three component technologies are proposed for evaluation in the CAS for the Hanover site. The component technologies could be implemented individually or in combination. Briefly, the alternatives and component technologies are as follows:

1. *No action alternative.* A no action alternative is required by the KDHE. Under this alternative, no active treatment of groundwater would be performed. However, operation of the existing VI mitigation systems would continue.

2. *Groundwater monitoring alternative.* Under this alternative, no active treatment of groundwater would be performed; however, selected existing wells would be monitored for carbon tetrachloride and chloroform concentrations to track the status of the contamination in groundwater Zone 1 and Zone 2. In addition, operation of the VI mitigation systems would continue. Five-year reviews would be performed to summarize the results of the groundwater monitoring effort. Elements of this alternative are common to

all of the alternatives described below and are referred to hereafter as the *common elements*.

3. *Environmental use controls alternative.* In addition to the common elements, this alternative would implement environmental use controls to protect human health and the environment, though no active treatment of groundwater would be performed. Environmental use controls might include the creation and implementation of a city ordinance that would prohibit drilling of a domestic drinking water well within the inferred areal extent of the contamination and/or establishment of vapor barrier requirements for all habitable new construction located within 100 ft laterally of the identified contamination. This alternative will help to eliminate the risks of potential exposure to carbon tetrachloride in groundwater.

4. *Groundwater extraction by a trenched horizontal well in groundwater Zone 1, with surface treatment.* This component technology would involve active treatment to reduce the volume and/or mass of carbon tetrachloride in groundwater Zone 1 at an area of high contamination identified as a location of less restricted permeability in the generally low-permeability formation that hosts Zone 1. (See subsystem 1 in Figure 4.35 and Section 4.7.2.) Trenched horizontal well technology could be implemented in Zone 1 in combination with the common elements. As discussed in Section 4, multiple hydraulic tests have demonstrated that groundwater extraction from Zone 1 by a conventional vertical well is not feasible. Even where maximum hydraulic conductivity and specific capacity values have been identified within the Zone 1 unit, a conventional vertical well could be dewatered at the lowest feasible pumping rate. To overcome this difficulty, trenched horizontal well technology could be implemented as follows:

   - A trenched horizontal well system (resembling a French drain system) would be emplaced at a shallow depth (~ 25 ft BGL) along groundwater Zone 1 within the area of high contamination to maximize extraction of contaminated groundwater from Zone 1 and to attenuate existing contamination in Zone 1.

- Extracted groundwater would be treated to remove carbon tetrachloride and chloroform by using a technology similar to a low-energy cascade aerator. Treated groundwater would be discharged to surface water.

5. *Groundwater extraction by a vertical interception well in groundwater Zone 2, with surface treatment.* This technology could be implemented in combination with the common elements. Conventional groundwater extraction technology would be used to intercept the contaminant in the more permeable groundwater Zone 2. The desired effects would include the removal of contaminated groundwater, prevention of further downgradient contaminant migration, and elimination of the source of contaminants entering private lawn and garden wells through unrestricted gravel packs. The groundwater extraction would be implemented as follows:

   - A single vertical well would be installed in Zone 2 near well MW44Z2 to extract groundwater, creating a hydraulic barrier that intercepts the contamination and prevents its further migration.

   - Extracted groundwater would be treated to remove carbon tetrachloride and chloroform by using a technology similar to a low-energy cascade aerator. Treated groundwater would be discharged to surface water. If a groundwater extraction system was installed in both Zone 1 and Zone 2, extracted groundwater could be co-mingled for treatment and discharge via a single aerator system.

6. *Groundwater treatment by a deep-rooted phytoremediation system.* In combination with the common elements and perhaps other component technologies, a system of deep-rooted green plants could be installed to assist in preventing contaminated groundwater from infiltrating the low-permeability Zone 1 by means of evapotranspiration and root microbial activities. The system would be installed across the preferential migration pathways for carbon tetrachloride in groundwater Zone 1, as identified in Section 4.7. The goal of this alternative would be containment and limited extraction of the contaminated groundwater identified in water-bearing Zone 1.

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