

In cooperation with the
U.S. Army Garrison, Aberdeen Proving Ground
Environmental Conservation and Restoration Division
Aberdeen Proving Ground, Maryland

Changes in Ground-Water Quality in the Canal Creek Aquifer Between 1995 and 2000-2001, West Branch Canal Creek Area, Aberdeen Proving Ground, Maryland

Water-Resources Investigations Report 02-4076

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by Daniel J. Phelan, William B. Fleck, Michelle M. Lorah, and Lisa D. Olsen

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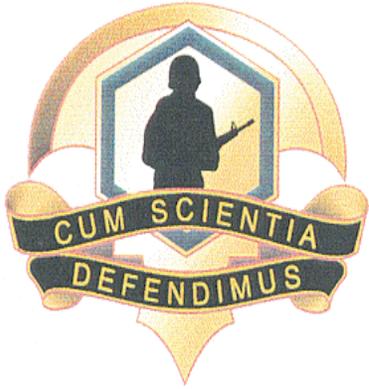
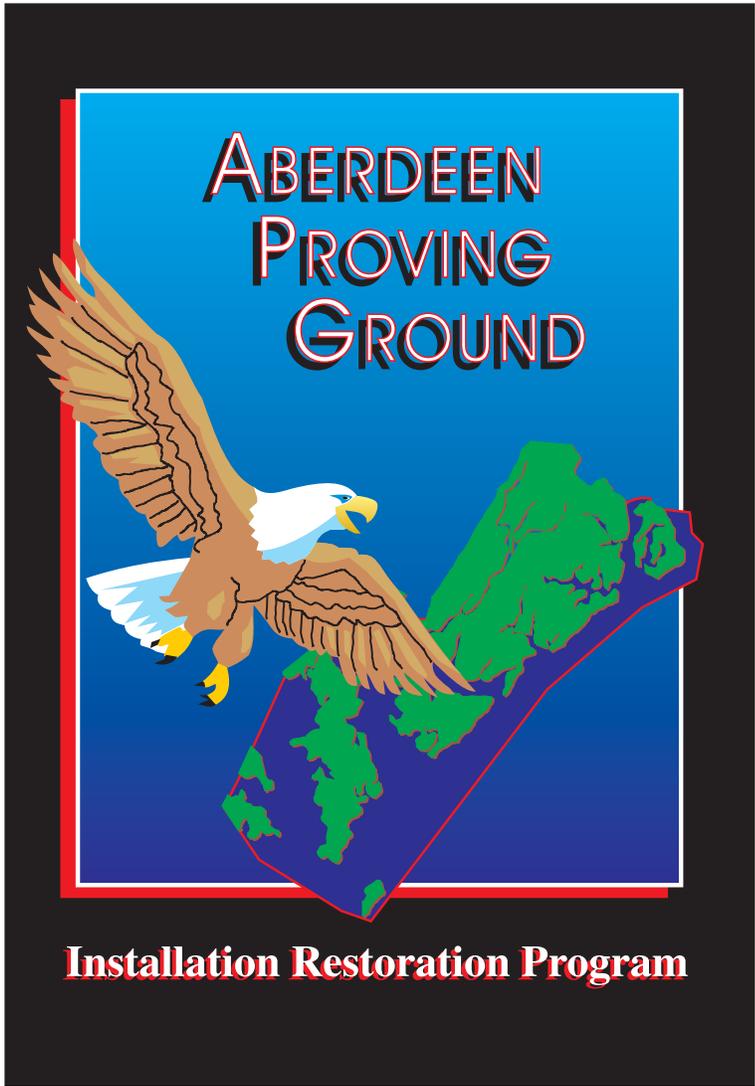
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2002
Aberdeen Proving Ground, Edgewood Area

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Conversion Factors and Vertical Datum

	Multiply	By	To obtain
	inch (in.)	2.54	centimeter
	foot (ft)	0.3048	meter
	foot per year (ft/yr)	0.3048	meter per year
	gallon (gal)	3.785	liter

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

Other abbreviated units of measure: Water temperature, chemical concentration, and other chemical and physical properties of constituents are given in metric units. Water temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by use of the following equation:

$$^{\circ}\text{F} = 1.8 (^{\circ}\text{C}) + 32$$

Chemical concentration in water is expressed in milligrams per liter (mg/L) and micrograms per liter (µg/L).

Abbreviations

The following terms are abbreviated in this report:

Aberdeen Proving Ground	(APG)	below land surface	(bls)
1,2-Dichloroethene	(1,2-DCE)	Carbon tetrachloride	(CT)
Chloroform	(CF)	Hexachloroethane	(HCA)
1,1,2,2-Tetrachloroethane	(TeCA)	Trichloroethene	(TCE)
Vinyl chloride	(VC)	volatile organic compounds	(VOCs)

Changes in Ground-Water Quality in the Canal Creek Aquifer Between 1995 and 2000–2001, West Branch Canal Creek Area, Aberdeen Proving Ground, Maryland

By Daniel J. Phelan, William B. Fleck, Michelle M. Lorah, and Lisa D. Olsen

Abstract

Since 1917, Aberdeen Proving Ground, Maryland has been the primary chemical-warfare research and development center for the U.S. Army. Ground-water contamination has been documented in the Canal Creek aquifer because of past disposal of chemical and ordnance manufacturing waste. Comprehensive sampling for volatile organic compounds in ground water by the U.S. Geological Survey in the West Branch Canal Creek area was done in June–October 1995 and June–August 2000. The purpose of this report is (1) to compare volatile organic compound concentrations and determine changes in the ground-water contaminant plumes along two cross sections between 1995 and 2000, and (2) to incorporate data from new piezometers sampled in spring 2001 into the plume descriptions.

Along the southern cross section, total concentrations of volatile organic compounds in 1995 were determined to be highest in the landfill area east of the wetland (5,200 micrograms per liter), and concentrations were next highest deep in the aquifer near the center of the wetland (3,300 micrograms per liter at 35 feet below land surface). When new piezometers were sampled in 2001, higher carbon tetrachloride and chloroform concentrations (2,000 and 2,900 micrograms per liter) were detected deep in the aquifer 38 feet below land surface, west of the 1995 sampling. A deep area in the aquifer close to the eastern edge of the wetland and a shallow area just east of the creek channel showed declines in total volatile organic compound concentrations of more than 25 percent, whereas between those two areas, concentrations generally showed an increase of greater than 25 percent between 1995 and 2000.

Along the northern cross section, total concentrations of volatile organic compounds in ground water in both 1995 and 2000 were determined to be highest (greater than 2,000 micrograms per liter) in piezometers located on the east side of the section, farthest from the creek channel, and concentrations were progressively lower at piezometer locations closer to the creek channel. Total volatile organic compound concentrations increased more than 25 percent in some areas in the middle depths of the aquifer; however, it could not be determined if a defined plume was moving farther downgradient along ground-water flow paths toward the creek channel, or vertically downward because of density differences within the aquifer.

Introduction

Since 1917, Aberdeen Proving Ground (APG), Maryland (fig. 1) has been the primary chemical-warfare research and development center for the U.S. Army. In 1990, APG was placed on the National Priorities List established under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980, and the Army and the U.S. Environmental Protection Agency, Region III, signed an Interagency Agreement for investigation and remediation of the Canal Creek area and other areas at APG.

The U.S. Geological Survey (USGS), in cooperation with the U.S. Army Environmental Conservation and Restoration Division, began a study in 1992 to determine the distribution, fate, and transport of chlorinated volatile organic compounds (VOCs) in ground water in an area of the wetland along the West Branch Canal Creek, APG, Maryland (fig. 1). The study area is a contaminated site that is part of, and downgradient from, known contaminant disposal areas.

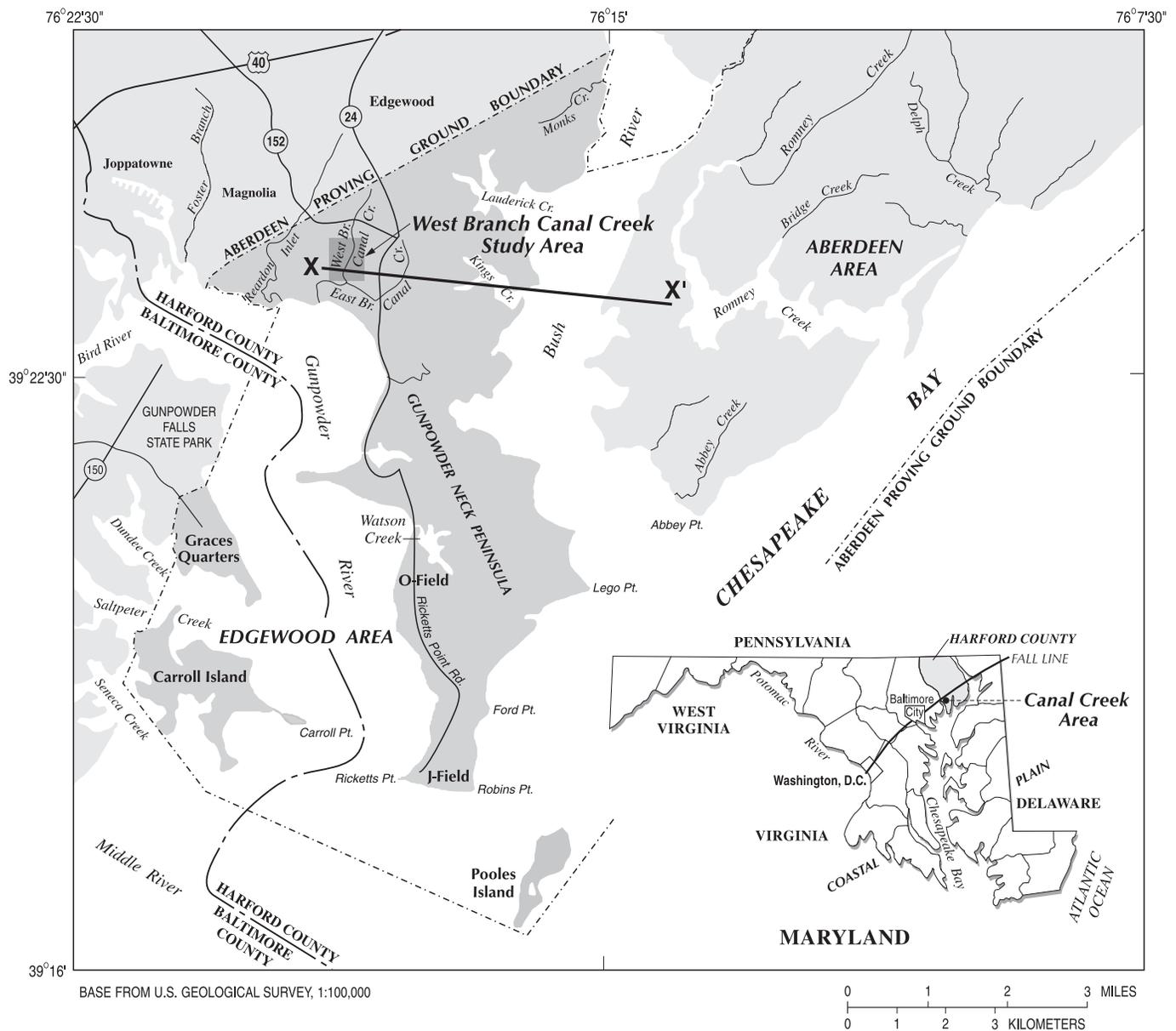


Figure 1. Location of the West Branch Canal Creek study area, Aberdeen Proving Ground, Maryland, and hydrogeologic section X-X' (shown in fig. 3).

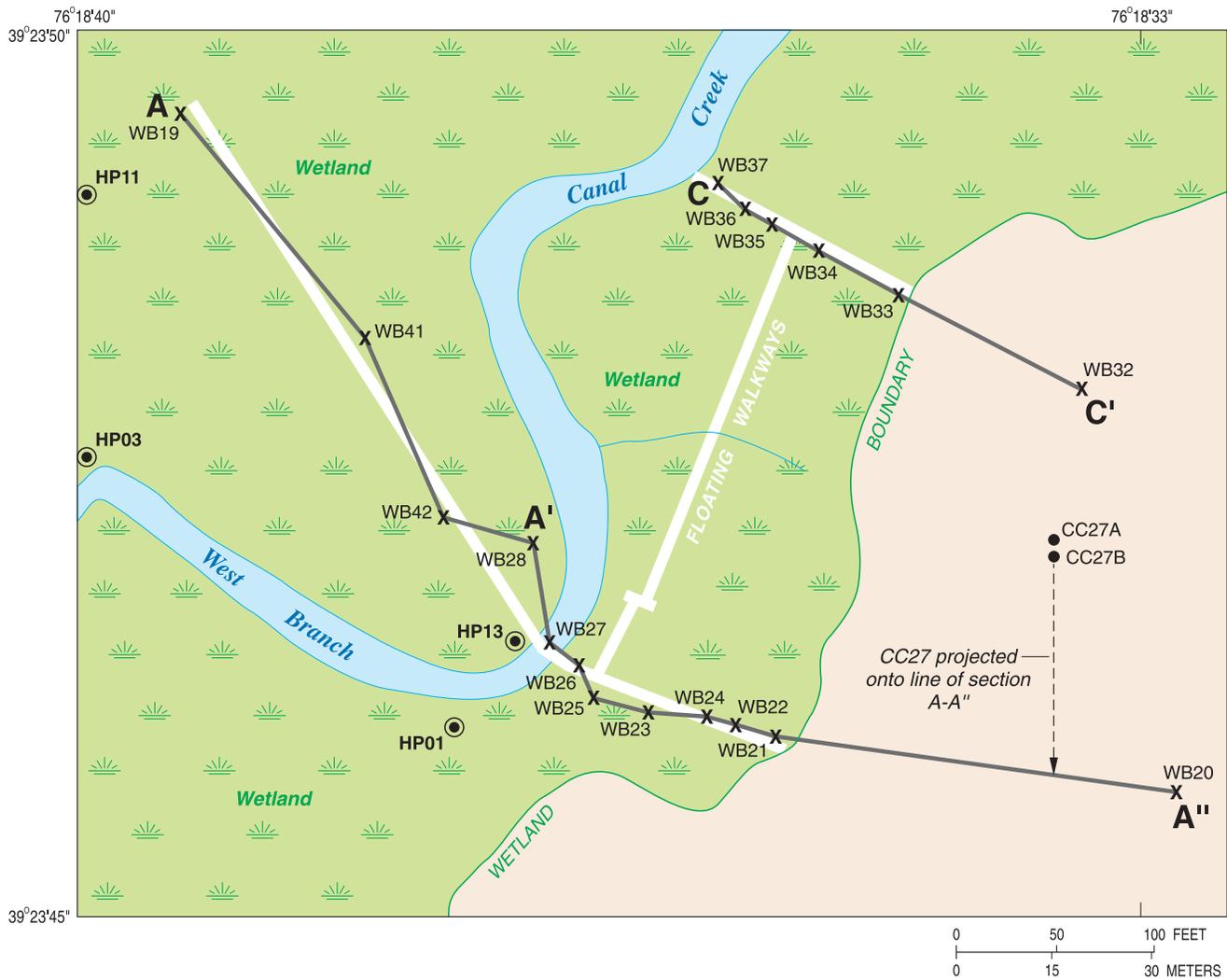
Purpose and Scope

The purpose of this report is (1) to compare VOC concentrations and determine changes in the ground-water contaminant plumes along two cross sections between June–October 1995 (Lorah and others, 1997) and June–August 2000, and (2) to incorporate data from new piezometers sampled in spring 2001 into the plume descriptions. Two cross sections through the wetland area showing the distribution of total VOCs, 1,1,2,2-tetrachloroethane (TeCA), trichloroethene (TCE), carbon tetrachloride (CT), and chloroform (CF) in 1995 and in 2000–2001 are presented. Cross sections showing concentrations of CT were

not included in Lorah and others (1997), but are presented in this report for both 1995 and 2000–2001.

Description of Study Area

The West Branch Canal Creek study area is in the north-west section of the Edgewood area of APG (fig. 1). The area is a mix of wooded and tidal wetland areas, some open fields, abandoned buildings, office buildings, and warehouses. When precipitation is heavy, water collects in wooded areas where drainage is poor because of the low soil permeability. Land-surface altitudes range from a maximum of 150 ft (feet) above sea level at the northern edge of



EXPLANATION

- CC27A ● 4-INCH WELL AND IDENTIFICATION NUMBER
- WB22 X PIEZOMETER SITE AND IDENTIFICATION NUMBER
- HP01 ● HOVERPROBE SAMPLING SITE AND IDENTIFICATION NUMBER
- A—A'' LINE OF SECTION

Figure 2. Location of sampling sites and sections A-A'' and C-C' in the wetland study area along West Branch Canal Creek, Aberdeen Proving Ground, Maryland. (Modified from Lorah and others, 1997.)

the drainage basin in Edgewood (fig. 1), to sea level in the tidal part of the stream.

The climate is temperate and moderately humid. Because of the proximity of APG to the Chesapeake Bay and the Atlantic Ocean, winters are milder and humidity is higher than farther inland. Average annual precipitation ranges from 39 to 45 in. (inches) (Durda and others, 1991, p. 2–7). The mean daily temperature is 33.8 °F (degrees Fahrenheit) in the winter and 75.2 °F in the summer (Durda and others, 1991, p. 2–7; Lorah and others, 1996).

Floating walkways were installed in 1994 along the two sections to allow access to part of the wetland along the West Branch Canal Creek (fig. 2). Access to the wetland beyond the walkway area is limited by tall, dense marsh vegetation (primarily *Phragmites*), and soft mud that is typically more than 8 ft deep. Surface-water depths can range from 0 to about 5 ft, depending on location, tides, and winds.

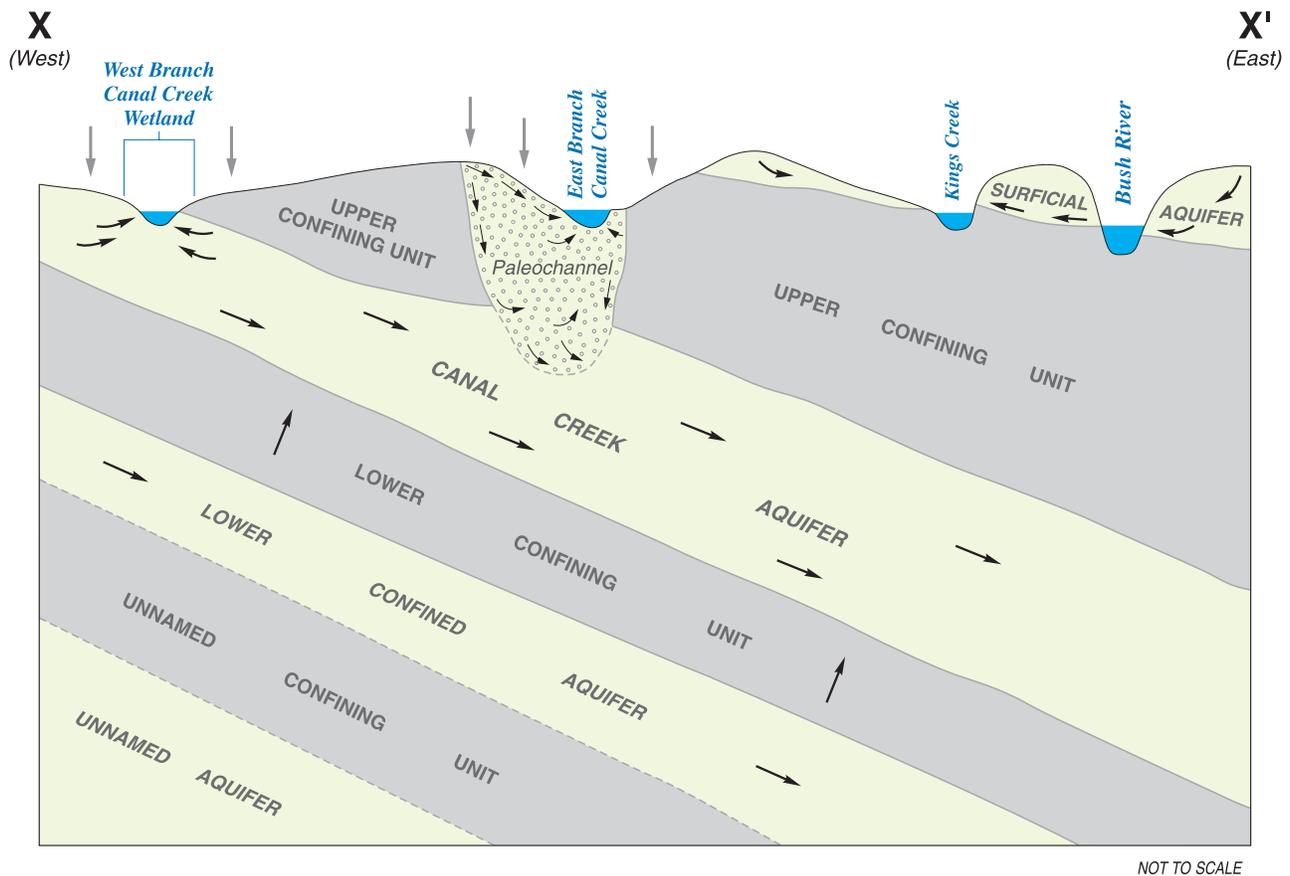


Figure 3. Generalized hydrogeologic section X-X' showing directions of ground-water flow in the Canal Creek area, Aberdeen Proving Ground, Maryland (modified from Lorah and others, 1997, p. 10). [Location of section shown in fig. 1.]

Hydrogeologic Setting

The geology of the Canal Creek area is characterized by thick, wedge-shaped deposits of unconsolidated Coastal Plain sediments that dip southeastward (fig. 3). The Canal Creek aquifer ranges from 30 to 70 ft thick in this area and is unconfined in the wetland area (Lorah and Clark, 1996). The lower confined aquifer, which underlies the approximately 60-ft-thick confining unit beneath the Canal Creek aquifer, is not known to be contaminated (Lorah and Vroblesky, 1989; Lorah and Clark, 1996; Oliveros and Vroblesky, 1989). The 60-ft-thick confining unit appears to prevent contamination in the Canal Creek aquifer from migrating downward into deeper aquifers.

Within the West Branch Canal Creek study area, the Canal Creek aquifer sediments consist of medium- to coarse-grained sand and gravel, interfingering with thin layers, or lenses, of clay and silt. East of the wetland, the aquifer is overlain by landfill material and the sediments of the upper confining unit. Within the West Branch Canal Creek wetland area, the aquifer is overlain by fine-grained organic-rich wetland sediments, which range from about 6 to 25 ft thick. The wetland sediments consist of peat, clay, silt, sandy clay, and clayey sand (Olsen and others, 1997).

Two hydrogeologic cross sections in the West Branch Canal Creek area are described in this report. The piezometers shown in the sections were installed during different drilling phases between 1993 and 2000. The southern section is designated as A–A'', and includes data from new piezometer nests installed west of the creek channel in 2000 (fig. 2). On the basis of data collected from these new piezometers, the A–A'' section described in this report extends farther west than in previous reports describing the contamination in the wetland.

The northern section is designated as C–C', and no additional piezometer nests were installed in this area since previous reports describing the hydrogeology were published. The locations of these sections are shown in figure 2, and the hydrogeology of the two sections, and the depths of the piezometer screens used for measuring water levels and water quality along the sections are presented in figures 4 and 5.

Ground water in the Canal Creek aquifer generally flows laterally and upward from both sides of the creek toward the center of the wetland. Discharge of ground water from the Canal Creek aquifer occurs through the wetland sediments into the creek and surrounding wetland areas (Lorah and Clark, 1996). Anaerobic biodegradation of the VOCs from the Canal Creek aquifer occurs in these wetland sediments (Lorah and Clark, 1996).

The head distributions and generalized ground-water flow directions for the A–A'' section in the Canal Creek aquifer and the overlying wetland sediments at high tide on December 3, 2001 are shown in figure 6. Head differences, calculated from measurements in piezometers between high and low tide on December 3, 2001 along the section were negligible; therefore, only high tide data are shown in figure 6. The ground-water divide representing the convergence of ground-water flow from the east and west sides of the wetland is located near the center of the wetland, in the general vicinity of piezometer nests WB41 and WB42 (fig. 6). Ground-water flow in the wetland area is primarily vertical toward the wetland surface. The creek channel meanders cross the wetland area (figs. 1 and 2); however, the center of the wetland and not the location of the creek channel appears to be the center point of ground-water discharge (fig. 6).

Site History

Most of APG's chemical-manufacturing and munitions-filling plants were concentrated in the area of the West Branch and East Branch Canal Creek. After World War II, large-scale production and filling operations declined sharply, and many of the manufacturing plants have been demolished or abandoned.

Chlorinated organic solvents, which were used as decontaminating agents and degreasers, were common waste products from the manufacturing and filling plants in the Canal Creek area. Wastes from many of these activities were discharged into Canal Creek directly through overland runoff or through sewer discharges until the late 1970s (Lorah and Clark, 1996). The various disposal activities also resulted in ground-water contamination in the Canal Creek aquifer

along the West Branch Canal Creek. Some of these wastes remain in the Canal Creek aquifer and continue to reach the wetland indirectly through the discharge of contaminated ground water. In the late 1960s, potentially contaminated construction materials from the demolition of some of these manufacturing plants were pushed out into the Canal Creek wetland, creating landfills where there originally had been natural wetland sediments (Lorah and Vroblesky, 1989; Lorah and Clark, 1996). No known wastes have been discharged to the wetland or creek from the manufacturing plants or sewer systems within at least the last two decades.

CT, CF, TeCA, TCE, and Hexachloroethane (HCA) are the major contaminants found in the Canal Creek aquifer in the West Branch Canal Creek wetland. Organic solvents, such as CT, TeCA, and TCE probably were the most common wastes produced in large quantities from manufacturing, filling, and other miscellaneous activities in the Canal Creek area. The chemical agent chloracetophenone (CN, a tear gas) was manufactured in two different buildings east of the West Branch Canal Creek wetland between 1921 and 1944. Several million pounds of CF, CT, and benzene were handled at both CN plants during the manufacturing process. HCA was a constituent used in the manufacturing of smoke mixtures in the vicinity, and CT was used in the reduction process. The history of the manufacturing and disposal activities in the Edgewood area of APG is described in detail in Nemeth (1989).

Description of Contaminant Plumes and Potential Source Areas

The sewer lines and landfill areas that likely are the sources of contamination along the East and West Branch Canal Creek previously were described by Nemeth (1989) and Lorah and Clark (1996). Sewer lines that reportedly were used to discharge wastes from the various chemical manufacturing facilities in the study area discharged to the West Branch Canal Creek wetland in the general vicinity of the floating walkways (fig. 2). Some of the sewer lines leaked organic solvents directly into the aquifer before discharging to the wetland (Nemeth, 1989). The ends of the sewer lines now are buried and have not been located. One sewer line (identified as part of sewer line number 6, Nemeth, 1989, p. 169) carried wastes from the World War II chlorine plant and discharged to the east side of the wetland in the general vicinity of well nest CC27 (fig. 2). The chlorine plant was thought to be a large source of solvents; however, other chemical-agent manufacturing plants also could have discharged wastes to sewer line 6. Chemical wastes from the manufacturing activities also were transported in drums or other containers to the edges of the wetland and disposed of at various locations in the area (Nemeth, 1989).

Ground-water contamination in the West Branch Canal Creek study area appears to be present in two overlapping contaminant plumes, based on the locations of the centers of concentrations, and differences in relative proportions of the compounds in the plumes. TeCA and TCE are the compounds most associated with plume 1, and are located

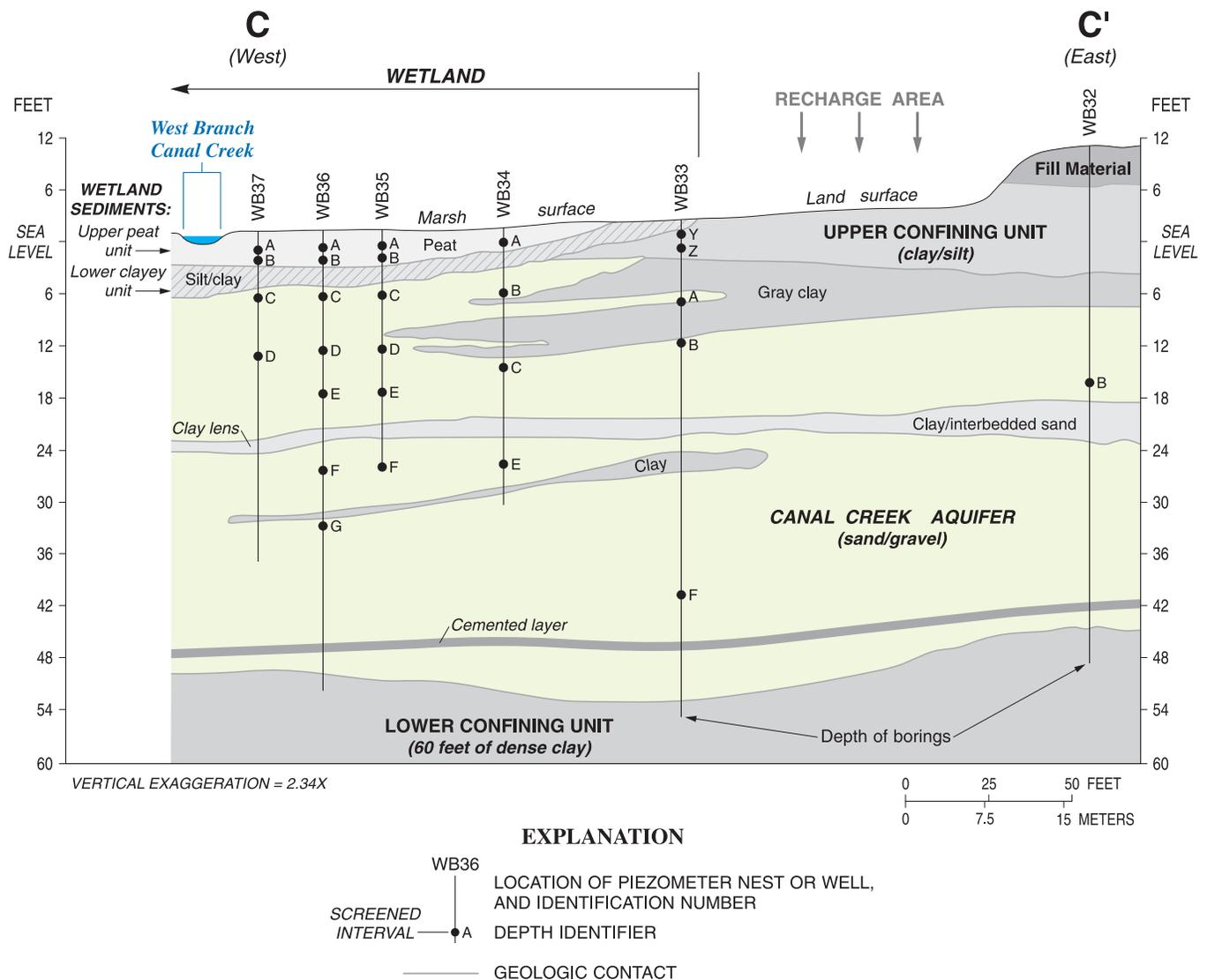


Figure 5. Section C-C' showing the hydrogeology and locations of piezometer nests and screen depths, West Branch Canal Creek, Aberdeen Proving Ground, Maryland (modified from Lorah and others, 1997).

predominantly along the C-C' section. CF and CT are the compounds most associated with plume 2, and are located predominantly along section A-A'' and other sites south of the section. Samples from well nest CC27, which originally were included along the A-A'' section, are more indicative of concentrations in plume 1.

In 1995, the highest concentrations of VOCs in plume 2 along the A-A'' section (fig. 4) were located near the center of the wetland near piezometer WB28F (screened at 34.5–35 ft below land surface, or bls), and on land at well CC27A (screened at 18–23 ft bls). Along the C-C' section, the highest concentrations of VOCs (primarily TeCA and TCE) in plume 1 were located near the eastern edge of the wetland near piezometer WB32B (screened at 14.5 ft bls) (fig. 5). The VOCs with the highest concentrations in ground water at WB28F were CT and CF. The VOCs with

the highest concentrations in ground water at well CC27A were TeCA and TCE (the same compounds detected primarily along section C-C' in plume 1). Section A-A'' intersects plume 2; however, the highest concentrations of CT and CF found to date were measured south of the A-A'' section at sites HP01 and HP13 (fig. 2; Phelan, Senus, and Olsen, 2001).

The differences in concentrations and relative proportions of TeCA, TCE, CT, and CF between piezometers representing plume 1 and plume 2 in both 1995 and 2000 are shown in figure 7. The highest concentrations in each of the two plumes are from different compounds. The plumes likely originated from two different sources (Lorah and others, 1997); however, ground-water samples indicate different degrees of intermixing caused by decades of transport by ground-water flow into the wetland areas.

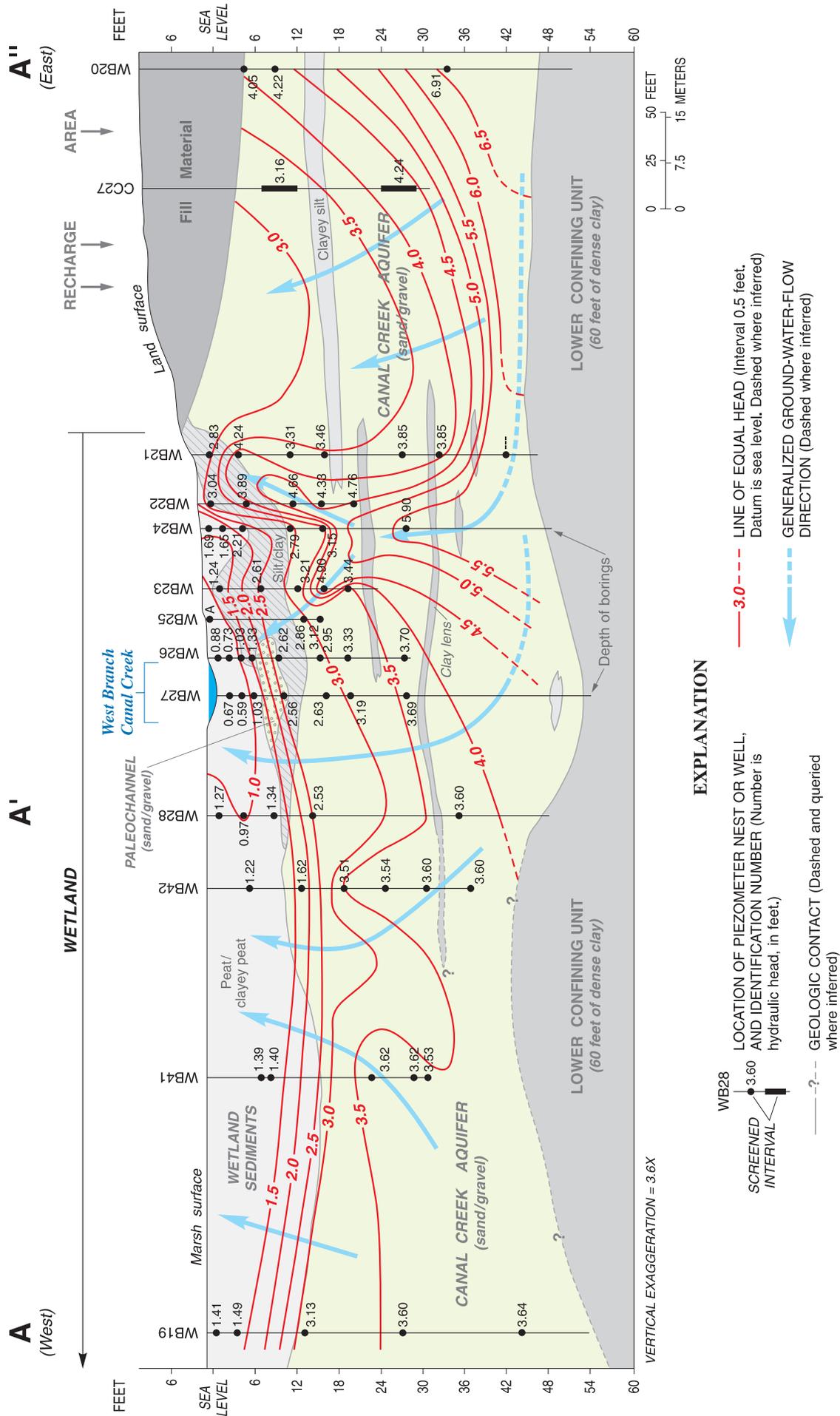


Figure 6. Section A-A' showing head distribution and generalized ground-water-flow directions at high tide, December 3, 2001, West Branch Canal Creek study area, Aberdeen Proving Ground, Maryland.

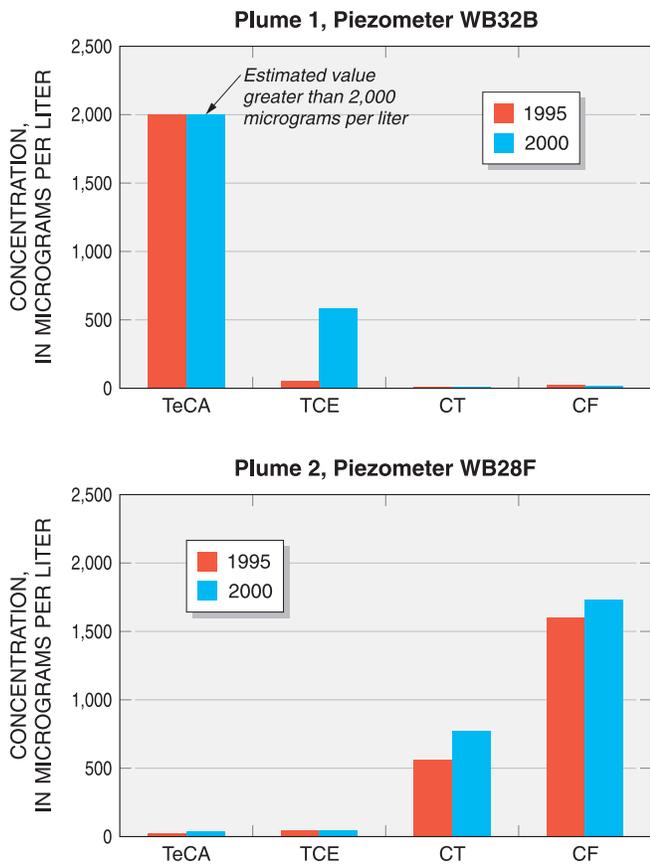


Figure 7. Chemical differences between contaminant plumes 1 and 2 in 1995 and 2000 in piezometers WB32B (C-C' transect) and WB28F (A-A" transect), Canal Creek aquifer, West Branch Canal Creek study area, Aberdeen Proving Ground, Maryland. [TeCA, 1,1,2,2-tetrachloroethane; TCE, trichloroethene; CT, carbon tetrachloride; CF, chloroform; maximum concentrations from duplicate samples reported]

The sites where the highest concentrations of contaminants were found in the ground water were at HP01 and HP13 (fig. 2), just south of the A-A" section (Phelan, Senus, and Olsen, 2001). HCA (a waxy solid used as a component of smoke agents), CF, and CT were the compounds with the highest concentrations. Waste HCA likely was codisposed with waste CF and CT because these two solvents were used in the local manufacturing processes and would have aided in dissolving the HCA prior to disposal into sewer lines. Contaminants that were present in lower concentrations in that vicinity were TCE and TeCA, which could have been disposed of in the area or produced by degradation of HCA, or both. Phelan, Senus, and Olsen (2001) measured high concentrations of HCA (up to 10,000 µg/L, or micrograms per liter), CT (up to 29,000 µg/L), and CF (up to 23,000 µg/L) in the Canal Creek aquifer at site HP01 at depths of 12–27 ft bls.

Previous Investigations

During 1977–78, the U.S. Army Toxic and Hazardous Materials Agency performed the first survey of the soil, sediment, ground water, and surface water of the Edgewood area of APG (Nemeth and others, 1983). An entire facility assessment was conducted by Nemeth (1989), in which he documented site history, ordnance and chemical manufacturing, filling, and support activities. Nemeth (1989) also identified the approximate locations of sewer lines in the Canal Creek area that were shown in historical APG facility drawings. These leaky sewer lines were the origin of much of the ground-water contamination in the study area.

A study conducted by the USGS during 1985–92 described the hydrogeology of the Canal Creek area, and determined that a large ground-water contaminant plume was present in the Canal Creek aquifer along the West Branch Canal Creek. The study also showed that the contaminated ground water probably was discharging to the creek and the surrounding freshwater wetlands (Lorah and Clark, 1996, fig. 2). Major contaminants included the chlorinated VOCs TeCA, TCE, and CT, which are common industrial solvents used in the area.

The effects of natural attenuation on VOCs in ground water discharging through the fine-grained wetland sediments were determined by the USGS in an investigation conducted from 1992 to 1996 (Lorah and others, 1997). Biodegradation and sorption were shown to be important mechanisms for natural attenuation of VOCs in the wetland sediments. Lorah and others (1997) also discussed ground-water flow and distribution of VOCs in 1995 along what is referred to in this report as the A-A" and C-C' sections. Those data are the basis for the comparisons to 1995 conditions presented here.

The relatively thin layers of wetland sediments (ranging from 6 to 25 ft) are critical in reducing contaminant concentrations and the toxicity of ground water before it discharges to the wetland surface and the creek. Hydrogeologic, water-quality, and sediment-quality data collected by the USGS between 1992 and 1996 in the West Branch Canal Creek area are presented in Olsen and others (1997). Reports by Olsen and others (1997) and Spencer and others (in press) present the ground-water quality data, and describe methods for the collection, interpretation, and quality assurance of the water-quality data collected in the West Branch Canal Creek area from 1992 to 2001.

Continuous cores and ground-water samples from the Canal Creek aquifer were collected in remote locations in the Canal Creek wetland during 2000 using a hovercraft-mounted vibracore drill rig called a "Hoverprobe." The lithologic data collected from the 5 coreholes and the 12 ground-water profiling sites are presented in Phelan, Senus, and Olsen (2001). Total VOCs in water from the upper part of the aquifer at two sites ranged from about 15,000 to greater than 50,000 µg/L, whereas samples from other sites showed no ground-water contamination (Phelan, Senus, and Olsen, 2001).

The distribution and occurrence of VOCs in surface water in the Canal Creek area were described by Olsen and Spencer (2000), and Phelan, Olsen, and others (2001). As many as 13 different VOCs were detected in surface-water samples collected in 1999 and 2000. Concentrations of individual VOCs in surface-water samples ranged from below the reporting limit of 0.5 µg/L to a maximum of 50.2 µg/L for chloroform.

Cross sections with VOC concentrations for the 1995 ground-water data presented in this report are from Lorah and others (1997). Tables of the 1995 VOC data, in addition to the inorganic constituents and physical parameters, are presented in Olsen and others (1997). Tables of ground-water VOC data from 2000–2001 used in this report are included in Spencer and others (in press).

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Methods of Investigation

Ground-water samples were collected from a variety of 4-in. wells, 2-in. wells, 1-in. piezometers, 0.75-in. drive-point piezometers, and 0.25-in. piezometers, with depths ranging from 1 ft to 45.5 ft bls, along two cross sections within the study area. Descriptions of the wells and piezometers used in this study are listed in the Appendix.

The 0.75-in. drive-point piezometers were installed in nests of 5 to 10 piezometers along the A–A' and C–C' sections (fig. 2), which generally are aligned parallel to the ground-water flow paths. In piezometer and well numbers, the prefix "WB" denotes West Branch, "CC" denotes Canal Creek, and "HP" denotes hoverprobe sampling sites. The relative depth intervals are identified by letter codes at the end of the numbers. The letter "A" corresponds to the shallowest, the letter "B" corresponds to the next shallowest, and so forth, except for piezometers WB33Y and WB33Z, which are 0.25-in. diameter piezometers installed in 1999 that were screened shallower than piezometer WB33A. Piezometer nests WB19 to WB37 are composed of 0.75-in. diameter piezometers, and were installed between July 1994 and February 1995. Piezometer nests WB41 and WB42 are 1-in. diameter piezometers that were installed in November 2000 to further define the extent of the contamination along the A–A' section west of the creek channel.

The A–A' section presented in Lorah and others (1997), extended from piezometer nests WB28 on the west to WB20 on the east. In this report, the original A–A' section has been expanded to the west to piezometer nest WB19 (fig. 2). The west end of the section at WB19 has been renamed as A, the nest at WB28 has been renamed A', and the east end at WB20 has been renamed A''. The previous A–A' section is referred to in this report as A'–A'', and the new longer cross section is now A–A'' (fig. 2).

The C–C' section is upstream of section A–A'', and includes an area east of the creek channel. Piezometers WB33Y and WB33Z are the only piezometers in that section that were added between 1995 and 2000 and used in this report. The hydrogeology of the A–A'' and C–C' sections, and the locations and depths of piezometer nests from which the ground-water samples were collected, are shown in figures 4 and 5, respectively.

Ground-water samples collected for organic constituents were analyzed at the USGS on-site laboratory at West Branch Canal Creek. VOC samples were analyzed using purge-and-trap gas chromatography with a mass-selective detector. Descriptions of the sampling methods and results of the quality-assurance methods for the data presented in this report are described in detail in Lorah and Clark (1996), Olsen and others (1997), Spencer and others (in press), Phelan, Senus, and Olsen (2001) and Phelan, Olsen, and others (2001). Olsen and others (1997) reported that the mean relative percent differences (RPDs) between duplicate organic compound concentrations were less than 15 percent for samples analyzed at the on-site laboratory. Samples with the highest RPDs tended to be samples in which analyte concentrations were less than 10 µg/L. Spencer and others (in press) found that for the 2000–2001 data, bromomethane and toluene analyzed at the on-site laboratory both had relatively high median RPDs (58 percent and 39 percent, respectively), compared to the other organic compounds. All other organic compound median RPDs for the 2000 data were below 12.2 percent.

Changes in Ground-Water Quality Between 1995 and 2000–2001

The following sections present comparisons showing the changes in the ground-water contaminant plumes along sections A–A'' and C–C' between 1995 (Lorah and others, 1997) and 2000–2001 (Spencer and others, in press). The general ground-water flow patterns described by Lorah and others (1997) reflect steady-state flow conditions with only slight seasonal variations because there has been no appreciable pumping or changes in hydrologic stresses on the Canal Creek aquifer in the study area since about 1968. Therefore, no changes in the overall direction and rate of the movement of the ground water affecting the contaminant plumes were anticipated for the period 1995–2001. The present steady-state flow conditions do not mean that plumes 1 and 2 have not moved, however, as contamination will tend to move from the source areas along the ground-water flow paths in the dissolved aqueous phase to discharge areas, and more dense non-aqueous phase liquid (DNAPL) can move downward in the aquifer contrary to the direction of ground-water flow. The rate of average linear velocity of ground-water flow in the Canal Creek aquifer in this area was calculated to be 3 ft/yr (feet per year) by Lorah and others (1997). The compounds HCA, TeCA, TCE, CT, and CF each have specific gravities that range from 1.46 to 2.09, which means that these compounds in the pure product state would tend to sink in the aquifer. Lorah and others (1997) documented seasonal changes in VOC concentrations in ground water. This report compares the concentrations of VOCs in ground water measured during the summers of 1995 and 2000 (and May 2001 for new piezometer nests WB41 and WB42) to exclude the possible effects of seasonal changes.

Comparison of Maximum Concentrations

The maximum concentrations of the major VOCs detected at each piezometer nest along sections A–A'' and C–C' that were sampled in both 1995 and 2000 are compared in figure 8. Ground-water samples collected from piezometer nests WB41 and WB42 and piezometers WB33Y and WB33Z that were installed after 1995 were not included in this comparison. Maximum concentrations in each piezometer nest are used for comparison, regardless of variability with depth, in order to compare the magnitude of the contamination problem and to compare overall trends in contaminant concentrations over time and distance.

Along section A–A'', the maximum concentrations of CT and CF (identified previously as the two major VOCs found in plume 2) were fairly consistent east of the creek channel (with the exception of well CC27, which is located farther north in the landfill area east of the wetland). At piezometer WB28F (screened from 34.5 to 35 ft bls), west of the creek channel, maximum concentrations of CT and CF generally were five to six times greater than the concentrations from piezometers east of the creek (WB27 through WB20) in both 1995 and 2000 (fig. 8). Maximum CT and CF concentrations for piezometer WB28F in 2000 were 770 and

1,730 µg/L, respectively. Ground-water samples collected by Phelan, Senus, and Olsen (2001) at hoverprobe site HP01 had CT and CF concentrations of 29,000 (at 17 ft bls) and 23,100 µg/L (at 37 ft bls) respectively, indicating that these sites are closer to the source of the contaminants associated with plume 2.

Along section C–C', maximum concentrations of TeCA and TCE (identified previously as the two major VOCs in plume 1) and total VOCs in ground water generally declined progressing westward toward the creek channel in both 1995 and 2000. The concentrations of CT and CF along section C–C', primarily associated with plume 2, generally did not decrease westward toward the creek channel in either 1995 or 2000 (fig. 8).

Distribution of Volatile Organic Compounds

Cross sections showing the distribution of total VOCs, TeCA, TCE, CT, and CF concentrations in ground water in 1995 and 2000–2001 illustrate changes in the extent of the contaminant plumes. Data collected from piezometers installed after 1995 are included in the cross sections for 2000–2001. Two 0.25-in. diameter piezometers (WB33Y and WB33Z) were installed in 1999 along the C–C' section to measure VOC concentrations in shallow ground water (2 ft and 4.5 ft bls, respectively) at the edge of the wetland where wetland sediments are thin, and daily flooding by high tides typically does not occur. Two additional piezometer nests (WB41 and WB42) installed on the west side of the creek along section A–A'' were sampled in spring 2001 to further define the extent of the contaminant plume between piezometer nests WB19 and WB28 (fig. 4).

Section A–A'' Along section A–A'', piezometer nests WB19, WB21–WB25, WB28, WB41, and WB42 are in an area that is flooded by high tides, where the land surface typically is exposed at low tide. Sites WB26 and WB27 are in the creek channel and land surface is almost always below the creek level. Well nest CC27 and piezometer nest WB20 are located east of the wetland at a higher elevation and were drilled through the fill material (fig. 4).

Total Volatile Organic Compounds (VOCs)—In 1995, total concentrations of VOCs along section A–A'' were highest in the landfill area east of the wetland (5,200 µg/L in well CC27A at 23 ft bls), and concentrations were next highest deep in the aquifer (3,300 µg/L at 35 ft bls) immediately west of the creek channel at WB28F (figs. 8 and 9a). When additional piezometers were installed in 2000 and sampled in 2001 west of piezometer nest WB28, VOC concentrations along the A–A'' section deep in the aquifer near the center of the wetland were higher than the concentrations at CC27A (fig. 9b). In 2000, Phelan, Senus, and Olsen (2001) detected even higher concentrations of total VOCs in ground water directly south of the A–A'' section (50,700 µg/L at a depth of 12 ft bls) at site HP13 next to the creek channel about 75 ft south of piezometer nest WB28, and at site HP01 (50,100 µg/L at a depth of 17 ft bls), about 120 ft south of piezometer nest WB26 (fig. 2). The total VOC concentration of greater than 50,000 µg/L indicates the probable presence of DNAPL in the Canal Creek aquifer south of the

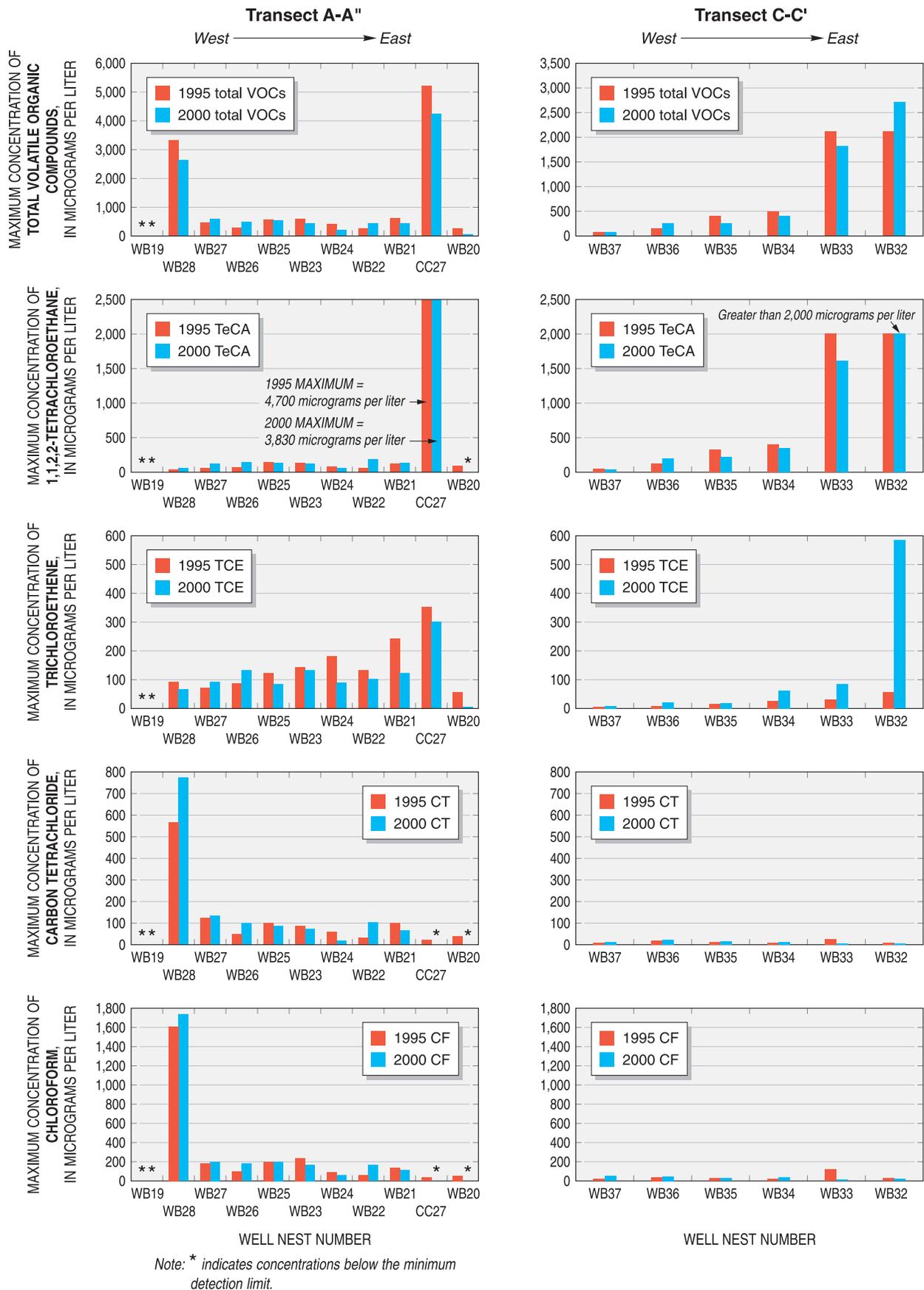
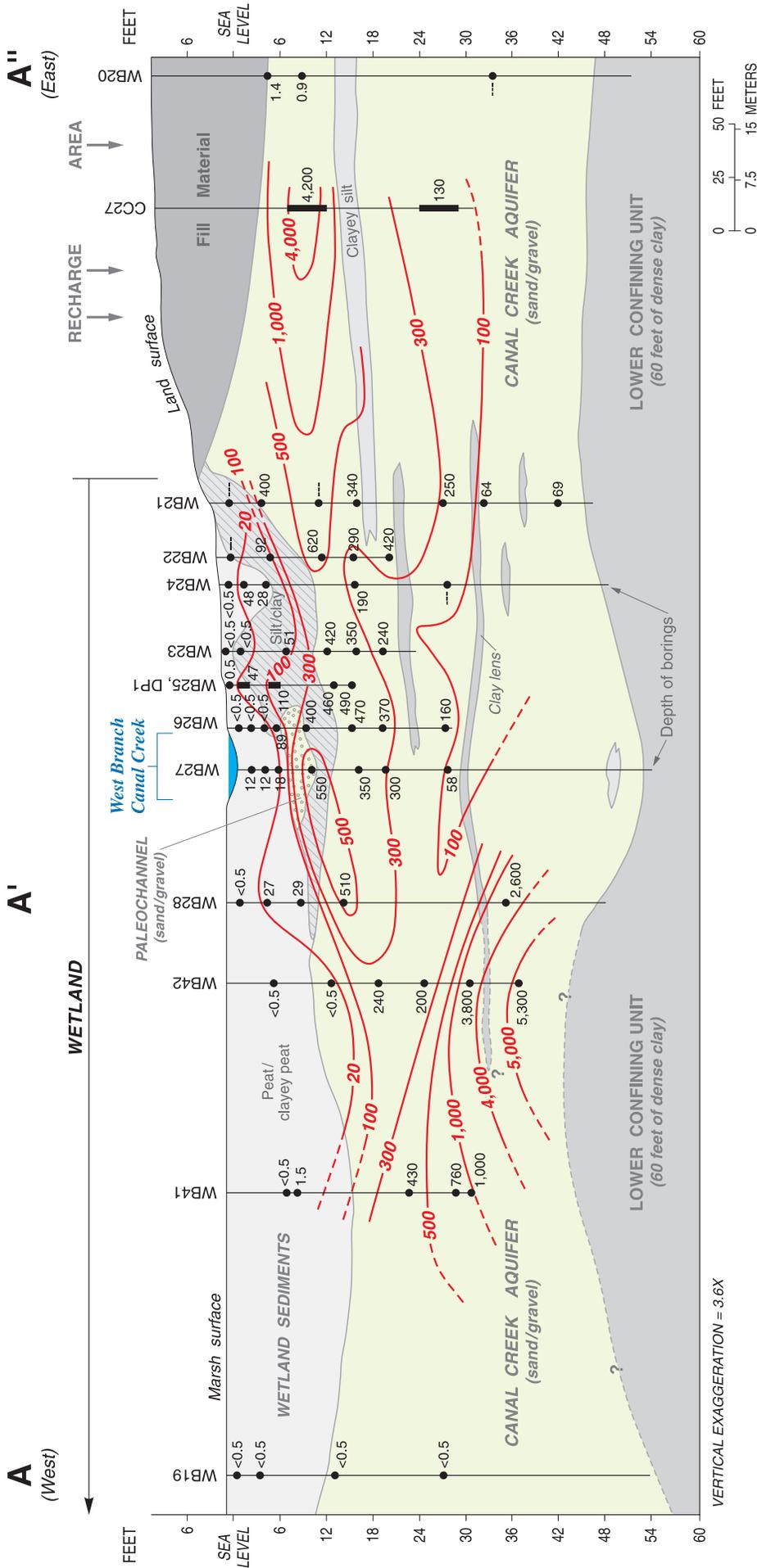


Figure 8. Changes in maximum volatile organic compound concentrations in sections A-A' and C-C' between 1995 and 2000, West Branch Canal Creek study area, Aberdeen Proving Ground, Maryland. (Refer to figure 2 for location of transects A-A' and C-C'.) [VOCs, volatile organic compounds; TeCA, 1,1,2,2-tetrachloroethane; TCE, trichloroethene; CT, carbon tetrachloride; CF, chloroform]



EXPLANATION

— 20 — LINE OF EQUAL CONCENTRATION OF TOTAL VOLATILE ORGANIC COMPOUNDS, IN MICROGRAMS PER LITER (Interval variable. Dashed where inferred.)

● LOCATION OF PIEZOMETER NEST OR WELL, AND IDENTIFICATION NUMBER (Number is concentration of total volatile organic compounds, in micrograms per liter. "—" indicates no data; "<" less than)

— ? — GEOLOGIC CONTACT (Dashed and queried where inferred)

WB28

SCREENED INTERVAL

VERTICAL EXAGGERATION = 3.6X

Figure 9b. Distribution of total volatile organic compounds in ground water in section A-A'', 2000-2001, West Branch Canal Creek study area, Aberdeen Proving Ground, Maryland.

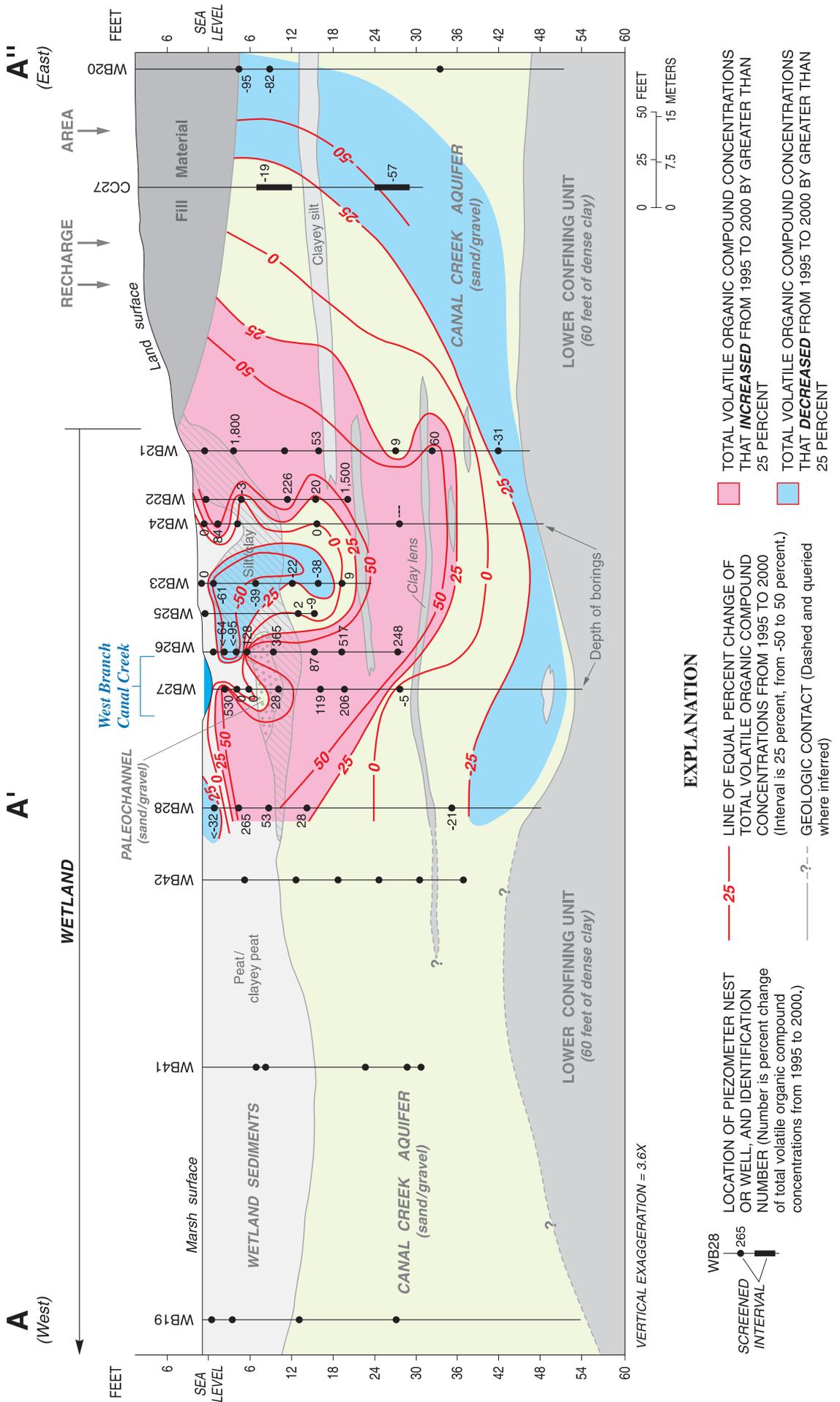


Figure 9c. Areas along section A-A'' where total volatile organic compound concentrations in ground water increased or decreased between 1995 and 2000, West Branch Canal Creek study area, Aberdeen Proving Ground, Maryland.

A–A'' section and close to site HP01.

Data from piezometer nests WB41 and WB42 show that the mapped extent of the VOC plume stretches west beyond the creek channel and piezometer nest WB28 (fig. 9b), described by Lorah and others (1997). The contaminant plume does not appear to reach piezometer nest WB19, which has consistently shown no evidence of contamination in samples collected between 1995 and 2000. Lorah and others (1997) found that 1995 concentrations of VOCs in samples from site WB19 were all less than 4 µg/L. In 2000, concentrations of VOCs in all samples from site WB19 were less than 1 µg/L (Spencer and others, in press). Two of the hoverprobe ground-water sampling sites located south and west of WB19 (sites HP03 and HP11, fig. 2) also had VOC concentrations in the Canal Creek aquifer that were below detection levels in ground water west of the A–A'' section in April 2000 (fig. 2).

The areas where total VOC concentrations changed by more than 25 and 50 percent between 1995 and 2000 along the A'–A'' section are shown in figure 9C. Declines in total VOC concentrations of more than 25 percent were found (1) in an area deep in the aquifer, extending from near piezometer nest WB28 to close to the eastern edge of the wetland (east of WB21G), (2) in a shallow area of wetland sediments just east of the creek channel (between WB23 and WB26), and (3) in 3 of 4 sample pairs in the aquifer at the east end of the section at sites CC27 and WB20. Total VOCs in the paleochannel deposits under the creek in the vicinity of WB27 and WB26 increased by more than 25 percent, as did concentrations in some middle and upper parts of the Canal Creek aquifer between the creek and the eastern edge of the wetland (fig. 9c).

1,1,2,2-Tetrachloroethane (TeCA)—The distribution of TeCA in ground water along section A–A'' in 1995 and 2000–2001 is shown in figures 10a and 10b. Contoured sections of the TeCA concentrations from the A–A'' section for both 1995 and 2000–2001 indicate a plume in the top half of the aquifer spreading horizontally from below the fill material, past the eastern edge of the wetland toward the base of the wetland sediments at about 10 to 12 ft bls near the creek channel. Data from 2001 indicate that the plume extends west past WB41, but not as far as WB19 (fig. 10b). The highest concentration of TeCA along the A–A'' section is located in the landfill area at well CC27A (figs. 4, 10a–b). The highest concentrations of TeCA detected along the A–A'' section in the wetland were under the general area of the creek channel (fig. 10b). Much of the TeCA plume could have been impeded from moving farther downward into the aquifer by the clayey silt layer located below the screen in well CC27A (fig. 10a).

Trichloroethene (TCE)—The distribution of TCE in ground water along the A–A'' section is shown in figures 11a and 11b. As with TeCA, the highest concentrations of TCE were found primarily in the upper half of the Canal Creek aquifer, below the fill material. Lorah and others (1997) showed that the TCE plume extended westward beyond the creek channel (fig. 11a). Data from the new piezometer nests installed in 2000 shows that the TCE plume extends westward beyond site WB41 and deeper (fig. 11b), and is found at concentrations as high as those found below the fill material east of the wetland, even though the plume does not extend to site WB19. Based on the data from samples collected from well CC27, and from shallow and deep samples collected from the aquifer under the creek channel, there were no major changes in the TCE plume along the A'–A'' section between 1995 and 2000.

Carbon tetrachloride (CT)—The distribution of CT in ground water along the A–A'' section is shown in figures 12a and 12b. The CT plume along the A'–A'' section as mapped in 1995 (fig. 12a) showed a plume centered along the upper part of the Canal Creek aquifer in the wetland area, with a single likely unrelated high concentration (560 µg/L) deep in the aquifer at a depth of 35 ft in WB28 (fig. 12a). Based on the CT concentrations in samples from the same piezometers in 2000, the CT plume showed no substantial change in magnitude or location between 1995 and 2000. With the additional data from sites WB41 and WB42 in 2001, however, there appears to be a more concentrated part of the CT plume located near the bottom of the Canal Creek aquifer at the center of the wetland at WB42F at a depth of 38 ft (figs. 4 and 12b). This plume may have resulted from the dissolution of DNAPL that may have settled at or near the bottom of the Canal Creek aquifer. The CT measured in the deep plume (2,000 µg/L in WB42F) likely is associated with the high concentrations of CT (up to 29,000 and 30,900 µg/L) discovered at the top of the Canal Creek aquifer (17 to 16 ft bls) by Phelan, Senus, and Olsen (2001) at hoverprobe sites HP01 and HP13, respectively.

Chloroform (CF)—The distribution of CF in ground water along the A–A'' section is shown in figures 13a and 13b. There appear to be only minor differences in the extent and magnitude of CF concentrations between 1995 and 2000 in ground water along the original section A'–A''. In 1995, maximum CF concentrations in three piezometers screened in the upper part of the aquifer east of the creek channel were between 200 and 230 µg/L (fig. 13a); however, in 2000–2001, no concentrations in that part of the aquifer were greater than 190 µg/L (fig. 13b).

As with CT, the additional 2001 data from the new piezometers indicate a concentrated CF plume near the bottom of the Canal Creek aquifer west of the creek channel at piezometer WB42F. CF concentrations in ground water along the A–A'' section are nearly twice as high as the CT concentrations in the respective ground-water samples (figs. 12b and 13b). A graph comparing molar concentrations of CF to CT in ground water along section A–A'' in 2000–2001 is shown in figure 14a. The slope of the linear-regression line comparing CF to CT in ground water is 1.8. Both CF and CT were detected at lower concentrations in surface water at Canal Creek, but in the same proportions as were detected in ground water in the aquifer. A graph comparing the molar concentrations of CF to CT in surface water in the West Branch Canal Creek area in 1999–2000 is shown in figure 14b (Phelan, Olsen, and others, 2001). These compounds may have been disposed of together as solvents from the manufacturing of the chemical-filled ordnance known to have been used in the area (Lorah and others, 1997).

In addition, CT can degrade to CF, and then to methylene chloride and carbon dioxide in a sequential hydrogenolysis reaction under anaerobic conditions (Bouwer, 1994). The ground water in the Canal Creek aquifer generally is aerobic, whereas ground water in the wetland sediments is anaerobic. CT and CF concentrations were highest deep in the Canal Creek aquifer (2,000 and 2,900 µg/L respectively at 37–38 ft bls), west of the creek channel at piezometer WB42F (figs. 12b and 13b). In samples collected from sites where CT and CF concentrations were greater than 1,000 µg/L, methylene chloride was found at concentrations ranging from 43 to 91 µg/L (Spencer and others, in press). No CT, CF, or methylene chloride was detected in the two shallowest ground-water samples from sites WB41 and WB42. This lack of detection indicates that natural attenuation of CT and CF could be occurring as ground water is discharging vertically toward the surface water through the anaerobic wetland sediments; however, additional investigation is needed to confirm this hypothesis. If ground water from that part of the plume was discharging directly to surface water through any preferential flow paths, such as seeps at the edge of the wetland, without undergoing the sequential hydrogenolysis reaction under anaerobic conditions within the wetland sediments, then CT and CF would be expected to be found in the same proportions in surface-water samples reported by Phelan, Olsen, and others (2001) (fig. 14b).

Section C–C' Along section C–C', piezometer nests WB34–WB37 are in the area that is flooded by high tides, where land surface typically is exposed at low tide. Site WB33 is on dry land near the edge of the wetland sediments that may be flooded only once or twice a year, and site WB32 is east of the wetland in the fill material area (fig. 5).

Total Volatile Organic Compounds (VOCs)—Along section C–C', total concentrations of VOCs in ground water during 1995 and 2000 were highest in piezometers farthest east of the creek channel (WB32 and WB33), and concentrations progressively were lower at piezometer locations closer to the creek channel (figs. 8, 15a–b). VOC concentrations typically were higher above the clay lens that generally is located between 19 and 24 ft bls than concentrations deeper in the aquifer below the lens (figs. 15a–b).

Total VOC concentrations in piezometers WB33Y (2 ft bls) and WB33Z (4.5 ft bls) (installed in 1999, fig. 5) in March 2000 were 310 and 770 µg/L, respectively. In June 2000, piezometer WB33Y was dry, and total VOC concentrations in WB33Z were 870 µg/L (Spencer and others, in press). In both sampling rounds, TeCA and TCE were the primary contaminants at WB33Y and WB33Z; however, the degradation compounds *cis*-1,2-dichloroethene (1,2-DCE) and *trans*-1,2-DCE accounted for about one-third of the total VOCs in those samples (Spencer and others, in press), indicating at least some degradation of the parent compounds. The increase of total VOCs (from 770 to 870) in piezometer WB33Z is within the median RPD between duplicate samples, and the seasonal variability in the median concentrations of TeCA was reported by Lorah and others (1997) to be less than the variability expected from sampling and analytical precision. The interpretation of VOC contours along the C–C' section for 2000 incorporates the new data from WB33Y and WB33Z, causing a noticeable change in the contours close to the contact of the wetland sediments and land surface at the edge of the wetland between 1995 and 2000 (figs. 15a–b). In addition, piezometer WB34D was not sampled in 1995, but was sampled in 2000. The inclusion of these data, combined with new data from WB33Y and WB33Z, resulted in substantial changes in contour interpretations along the C–C' section.

The areas where total VOC concentrations changed by more than 25 percent between 1995 and 2000 along the C–C' section are shown in figure 15c. In general, total VOC concentrations decreased more than 25 percent between 1995 and 2000 in areas close to the creek channel at both the top and the bottom of the aquifer (fig. 15c). Total VOC concentrations increased more than 25 percent in some areas in the middle depths of the aquifer.

Although figures 15a and 15b show concentrations above detection levels in the shallow piezometers ("A" depth, fig. 5), Lorah and others (1997, p. 67) showed that hydrogenolysis of the 1,2 DCE (produced from dichloroelimination of TeCA) was occurring in the shallow wetland sediments and that degradation products decreased below detection levels within 6 in. of land surface.

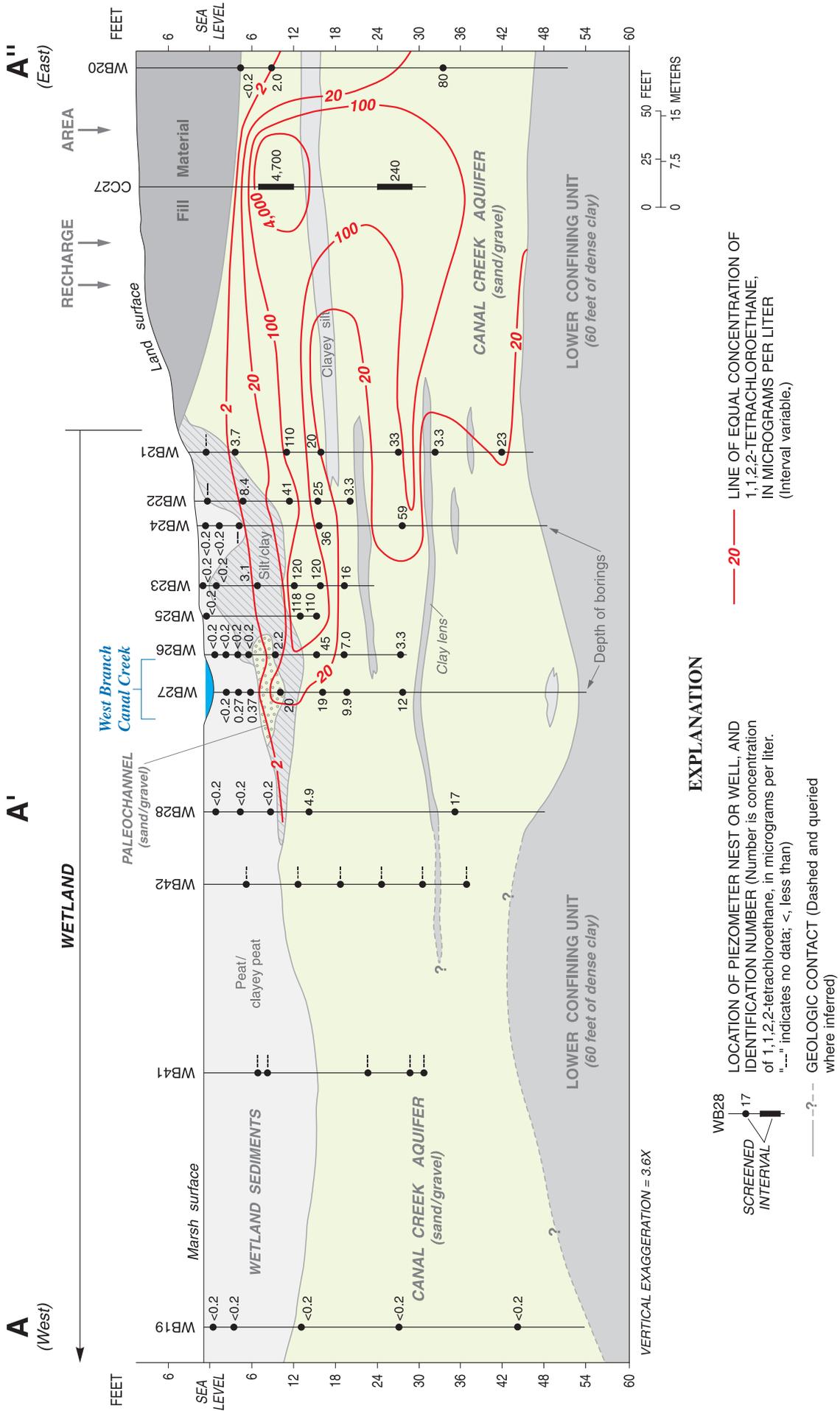
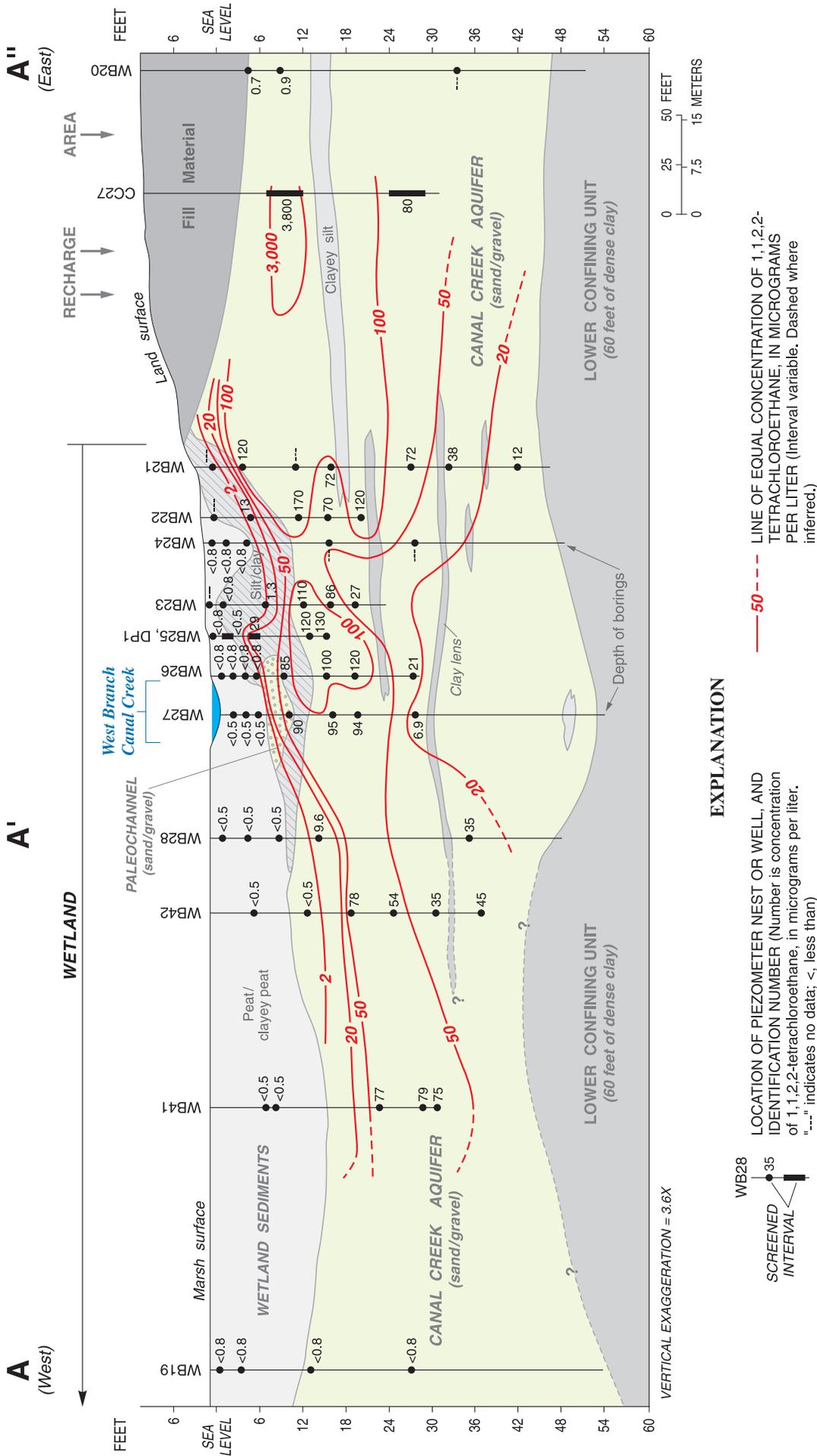


Figure 10a. Distribution of 1,1,2,2-tetrachloroethane (TeCA) in ground water in section A-A', June-October 1995, West Branch Canal Creek study area, Aberdeen Proving Ground, Maryland. (Data and contours from Lorah and others, 1997; contours modified to fit wider cross section.)



EXPLANATION

- SCREENED INTERVAL
- LOCATION OF PIEZOMETER NEST OR WELL, AND IDENTIFICATION NUMBER (Number is concentration of 1,1,2,2-tetrachloroethane, in micrograms per liter. "<" indicates no data; "<," less than)
- ?—?— GEOLOGIC CONTACT (Dashed and queried where inferred)
- 50—50— LINE OF EQUAL CONCENTRATION OF 1,1,2,2-TETRACHLOROETHANE, IN MICROGRAMS PER LITER (Interval variable. Dashed where inferred.)

Figure 10b. Distribution of 1,1,2,2-tetrachloroethane (TeCA) in ground water in section A-A', 2000-2001, West Branch Canal Creek study area, Aberdeen Proving Ground, Maryland.

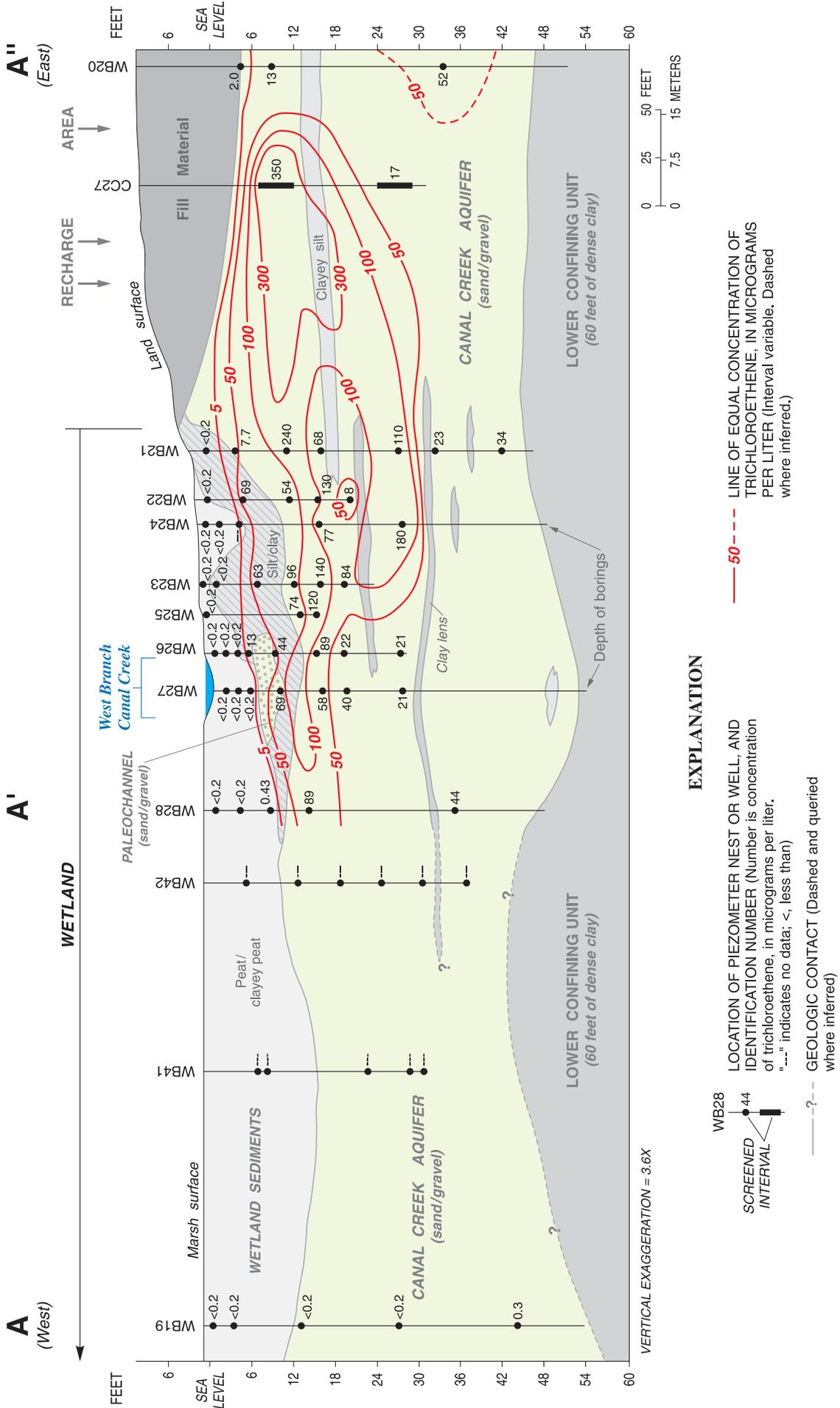


Figure 11a. Distribution of trichloroethene (TCE) in ground water in section A-A', June-October 1995, West Branch Canal Creek study area, Aberdeen Proving Ground, Maryland. (Data and contours from Lorah and others, 1997; contours modified to fit wider cross section.)

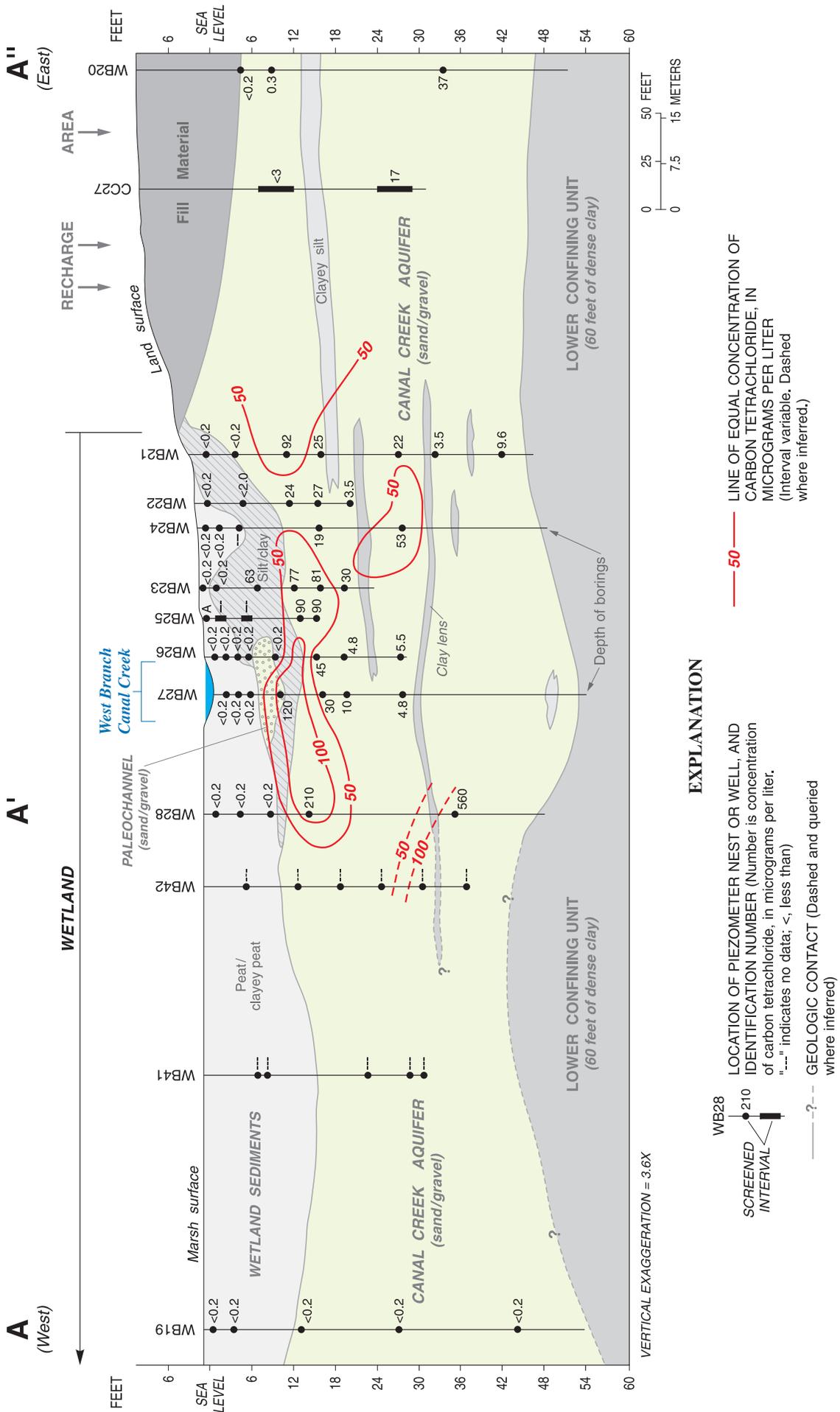


Figure 12a. Distribution of carbon tetrachloride (CT) in ground water in section A-A', June-October 1995, West Branch Canal Creek study area, Aberdeen Proving Ground, Maryland. (Data from Olsen and others, 1997.)

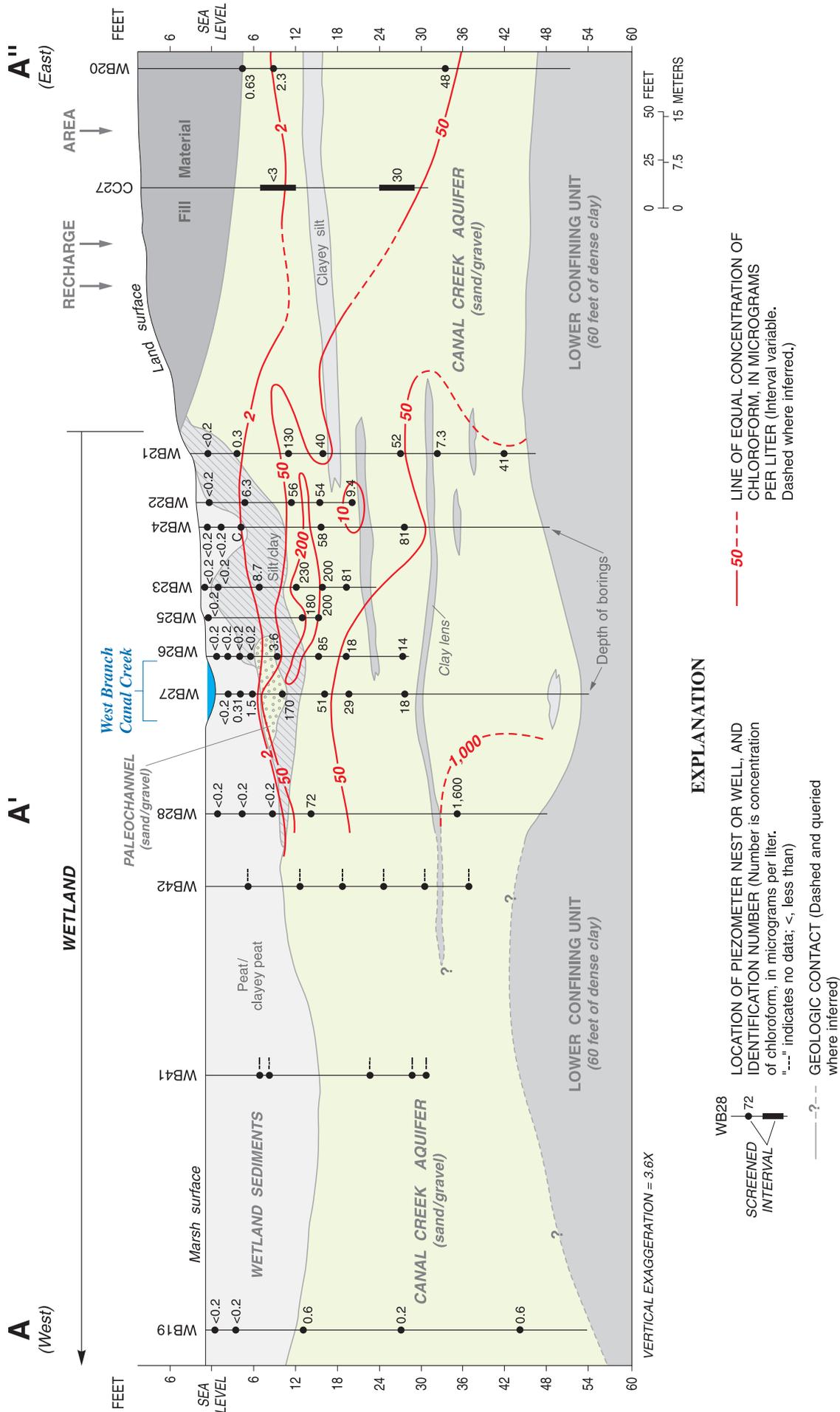


Figure 13a. Distribution of chloroform (CF) in ground water in section A-A', June-October 1995, West Branch Canal Creek study area, Aberdeen Proving Ground, Maryland. (Data and contours from Lora and others, 1997; contours modified to fit wider cross section.)

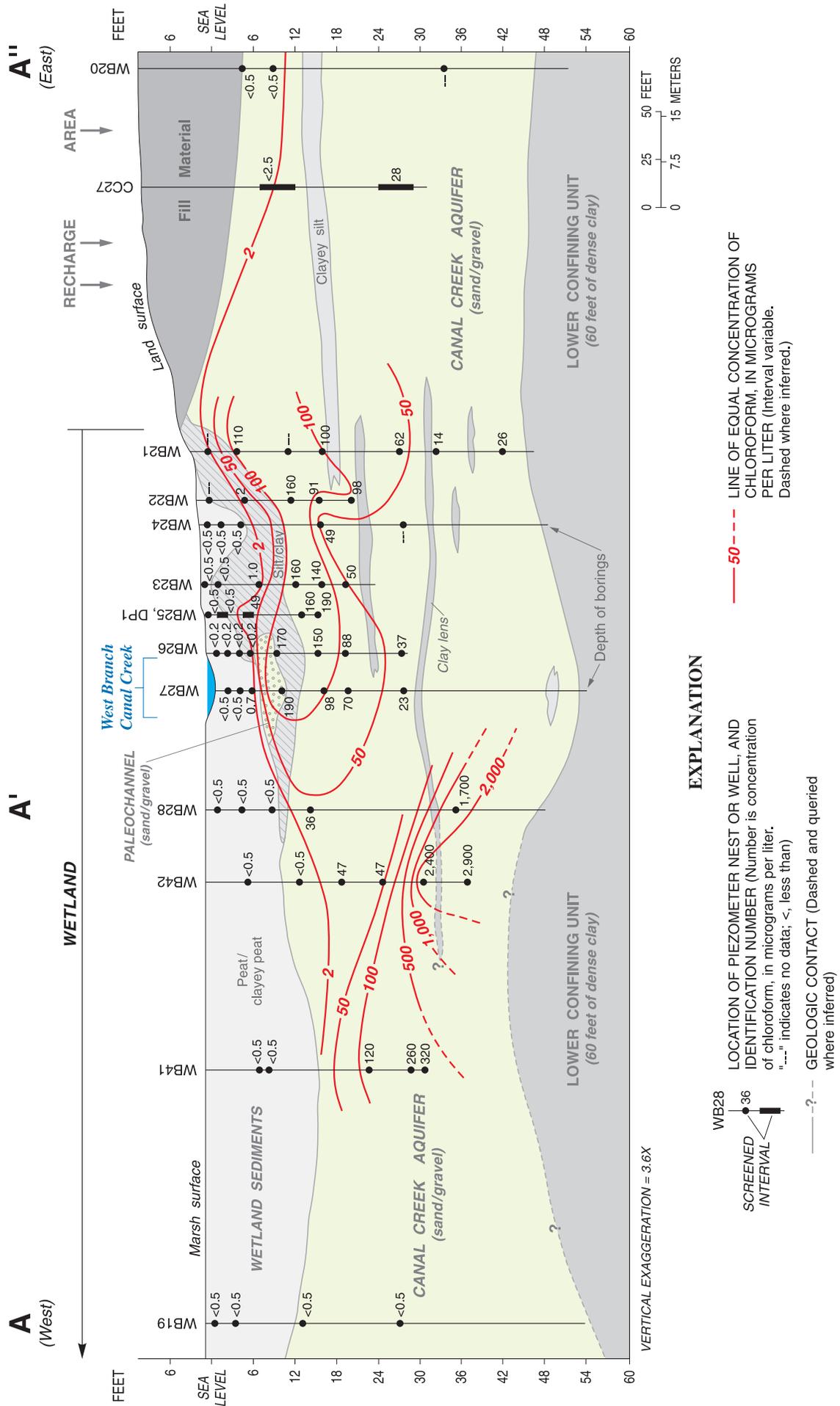


Figure 13b. Distribution of chloroform (CF) in ground water in section A-A', 2000-2001, West Branch Canal Creek study area, Aberdeen Proving Ground, Maryland.

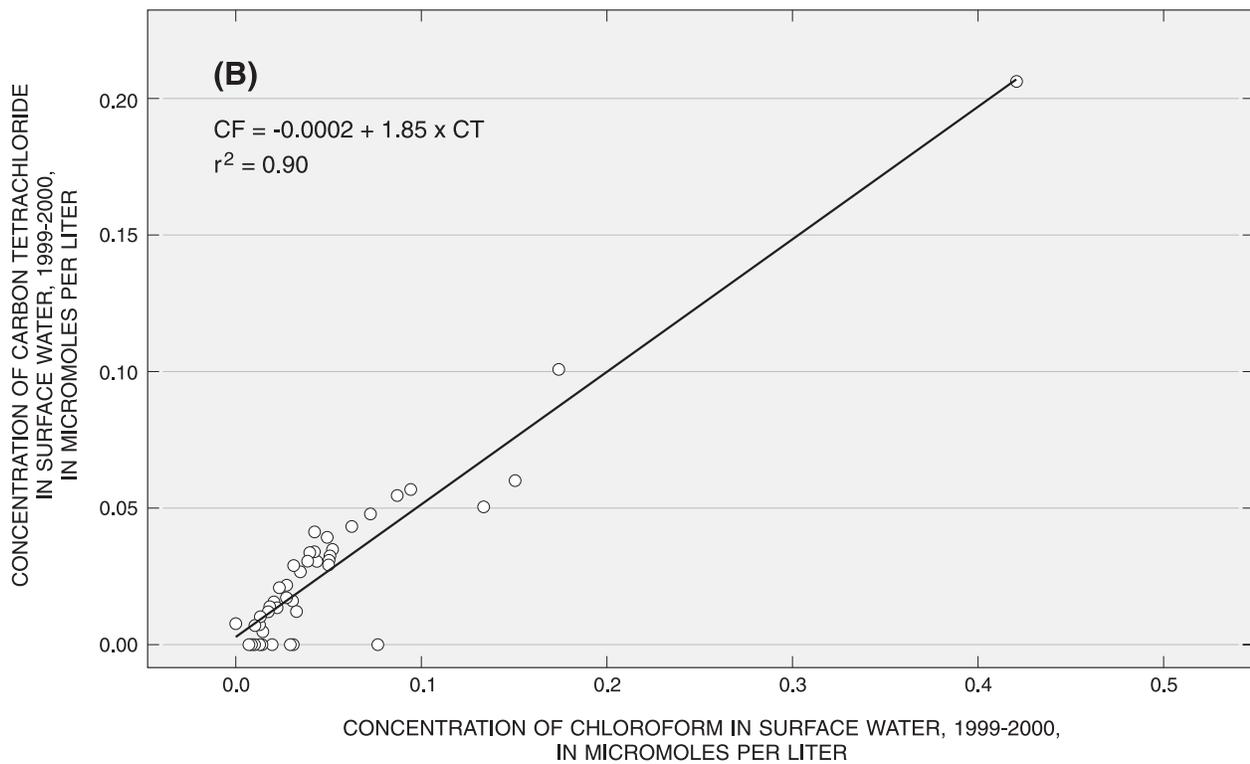
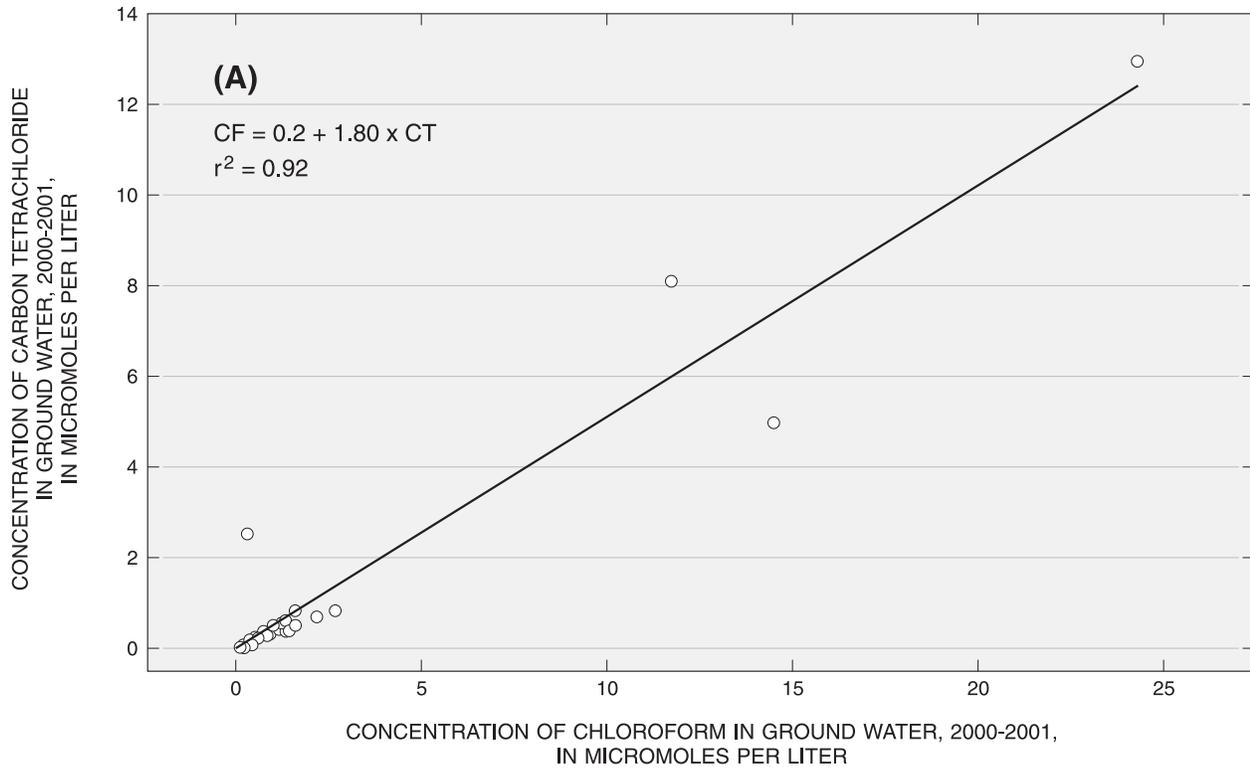


Figure 14. Comparison of molar concentrations of carbon tetrachloride (CT) to chloroform (CF) in (A) ground water, 2000-2001 and (B) surface water, 1999-2000, West Branch Canal Creek study area, Aberdeen Proving Ground, Maryland.

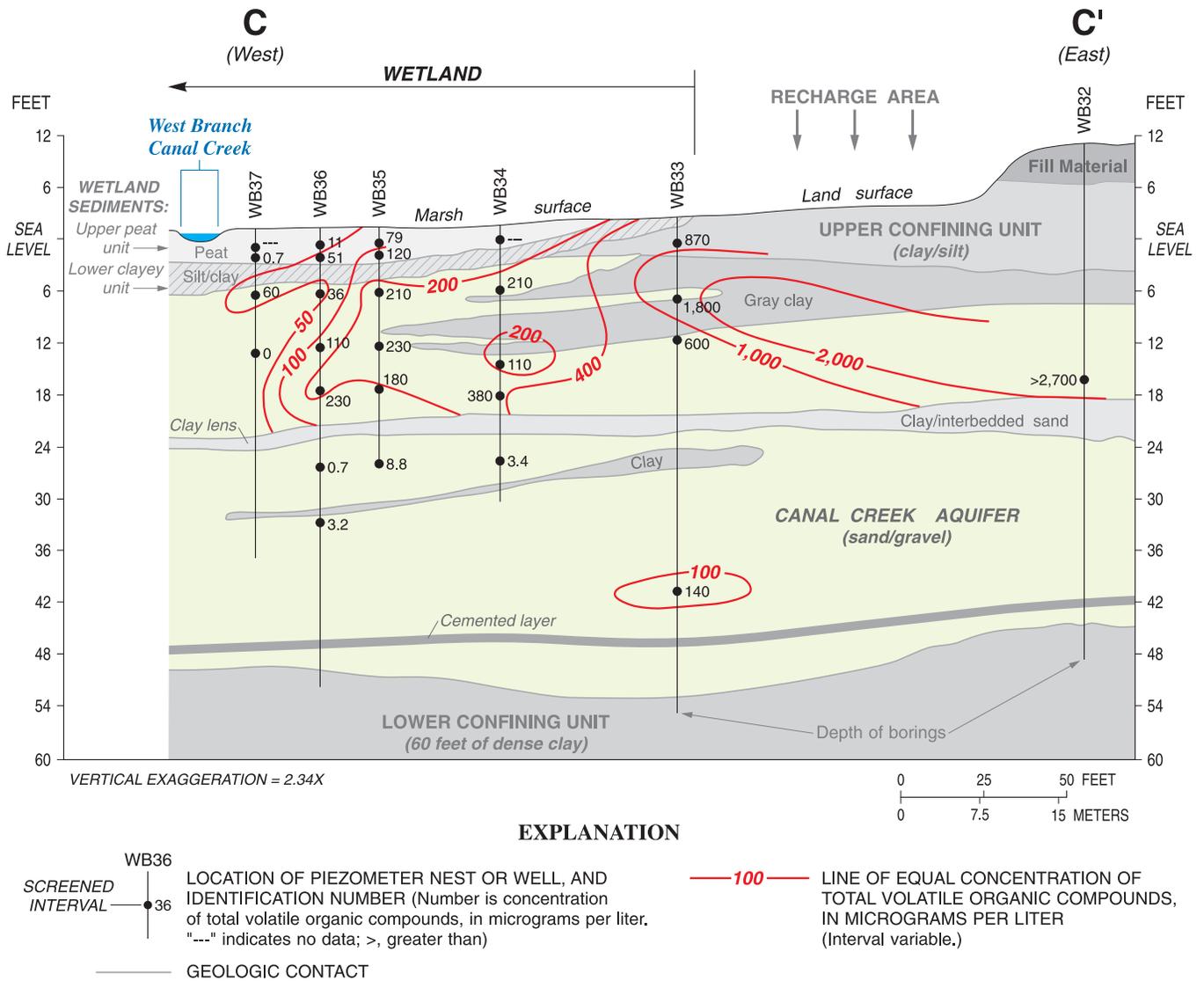
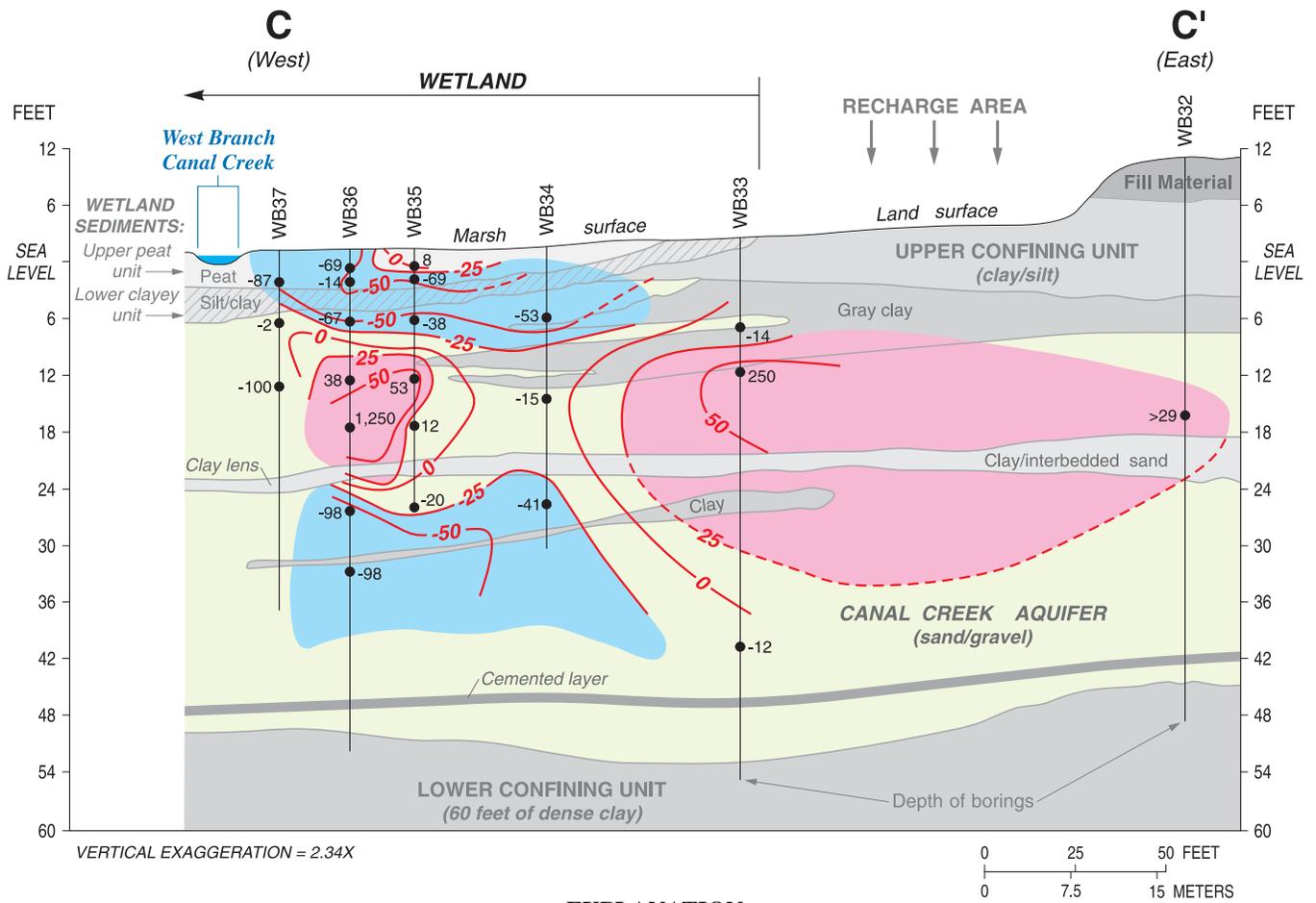


Figure 15b. Distribution of total volatile organic compounds in ground water in section C-C', June-August 2000, West Branch Canal Creek, Aberdeen Proving Ground, Maryland.



- EXPLANATION**
- WB36
 LOCATION OF PIEZOMETER NEST OR WELL, AND IDENTIFICATION NUMBER (Number is percent change of total volatile organic compound concentrations from 1995 to 2000, in micrograms per liter; >, greater than)
 - SCREENED INTERVAL
 - 25- - LINE OF EQUAL PERCENT CHANGE OF TOTAL VOLATILE ORGANIC COMPOUND CONCENTRATIONS FROM 1995 TO 2000 (Interval is 25 percent, from -50 to 50 percent. Dashed where inferred.)
 - GEOLOGIC CONTACT
 - TOTAL VOLATILE ORGANIC COMPOUND CONCENTRATIONS THAT **INCREASED** FROM 1995 TO 2000 BY GREATER THAN 25 PERCENT
 - TOTAL VOLATILE ORGANIC COMPOUND CONCENTRATIONS THAT **DECREASED** FROM 1995 TO 2000 BY GREATER THAN 25 PERCENT

Figure 15c. Areas along section C-C' where total volatile organic compound concentrations in ground water increased or decreased between 1995 and 2000, West Branch Canal Creek study area, Aberdeen Proving Ground, Maryland.

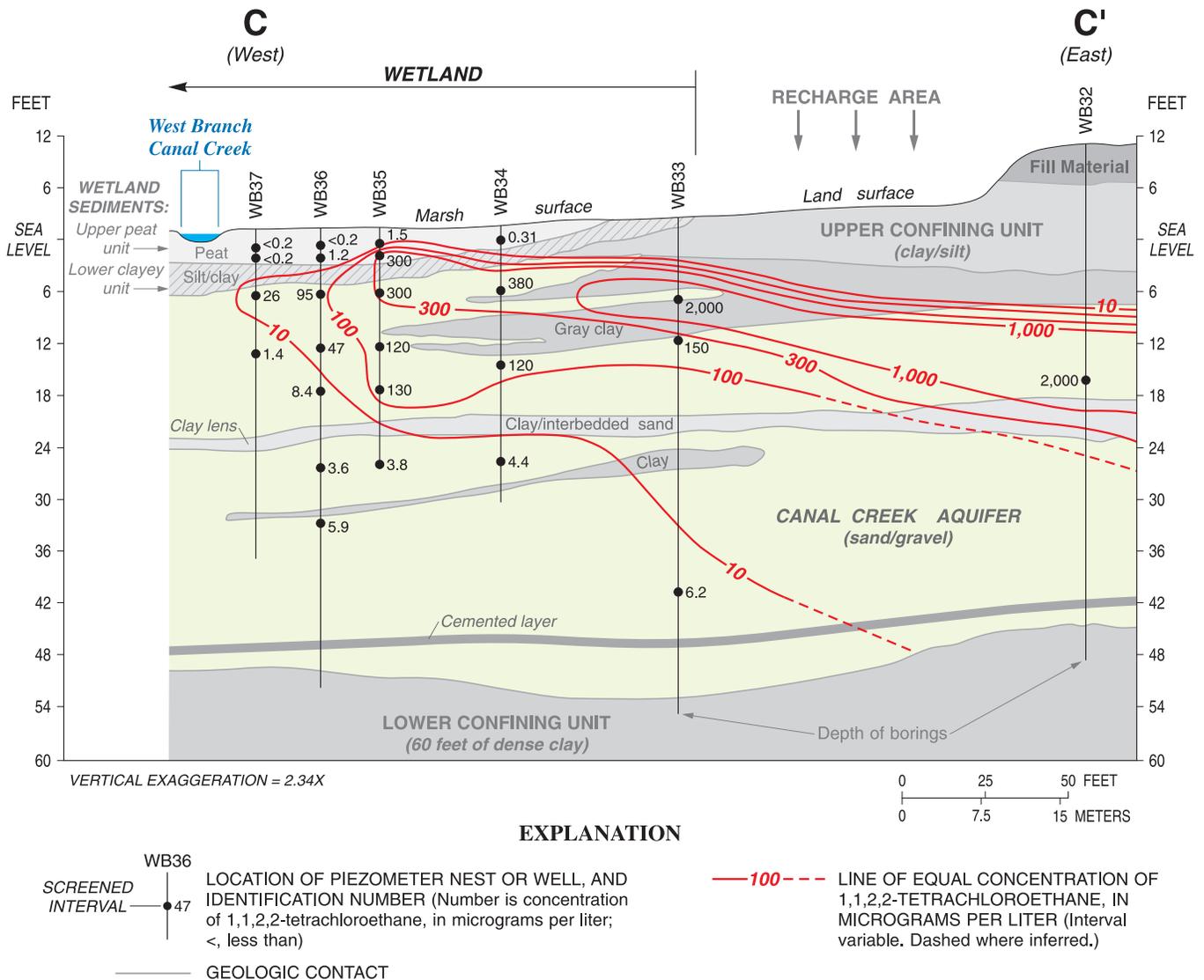


Figure 16a. Distribution of 1,1,2,2-tetrachloroethane (TeCA) in ground water in section C-C', June-October 1995, West Branch Canal Creek, Aberdeen Proving Ground, Maryland (modified from Lorah and others, 1997).

1,1,2,2-Tetrachloroethane (TeCA)—The overall extent of the TeCA plume along the C–C' section changed little between 1995 and 2000. The plume is located predominantly in the upper half of the Canal Creek aquifer, and is separated from the lower part of the aquifer by a clay layer roughly 19–23 ft below sea level (figs. 16a–b). The TeCA concentration in the deeper part of the aquifer at piezometer WB33F increased from 6 to 130 µg/L between 1995 and 2000, however (fig. 16b). Lorah and others (1997) showed that in the vicinity of piezometers WB35A and WB35B, concentrations of TeCA

decreased and concentrations of the anaerobic degradation compounds dichloroethane (DCE) and vinyl chloride (VC) increased in the wetland sediments between 3 ft and 0.5 ft bls. Between 0.5 ft bls and land surface, concentrations decreased to about the minimum detection levels for each compound. Results showed a significant variation in the total amount of degradation products, and this variation could be related to seasonal changes in temperature in the shallow sediments (Lorah and others, 1997).

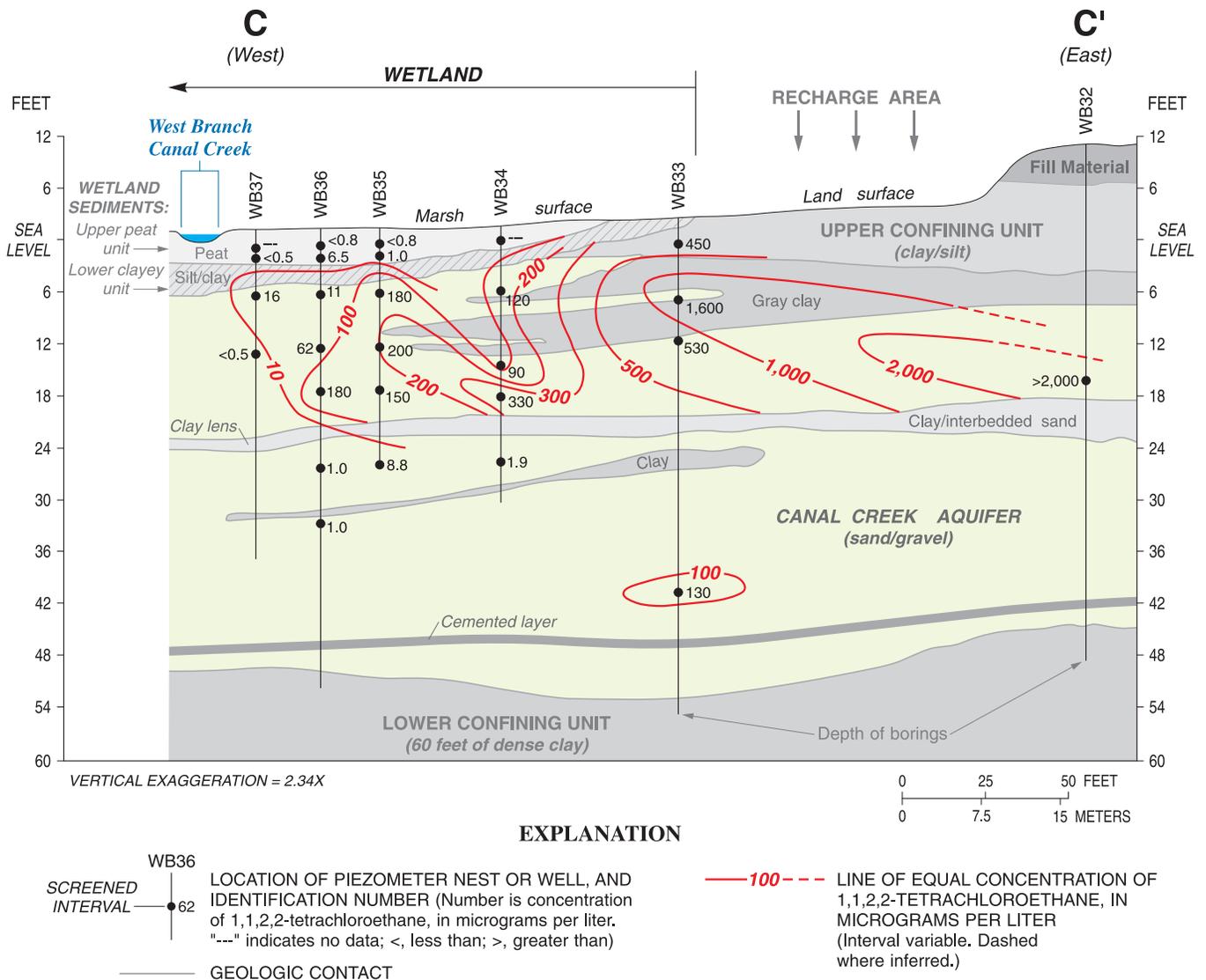


Figure 16b. Distribution of 1,1,2,2-tetrachloroethane (TeCA) in ground water in section C-C', June-August 2000, West Branch Canal Creek, Aberdeen Proving Ground, Maryland.

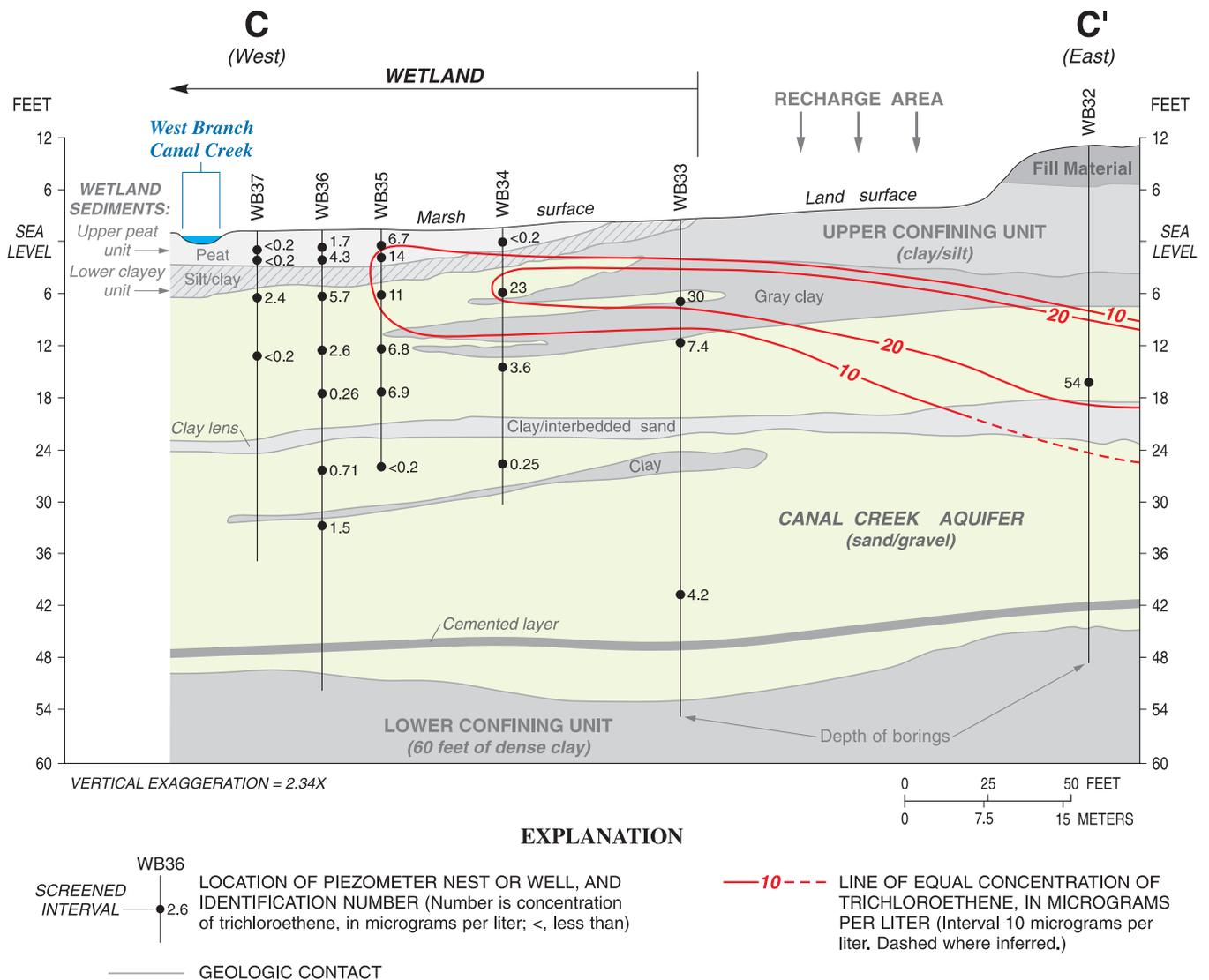


Figure 17a. Distribution of trichloroethene (TCE) in ground water in section C-C', June-October 1995, West Branch Canal Creek, Aberdeen Proving Ground, Maryland (modified from Lorah and others, 1997).

Trichloroethene (TCE)—As with the TeCA plume along the C-C' section, the extent of the TCE plume is primarily in the upper half of the Canal Creek aquifer (figs. 17a–b). The TCE concentrations east of WB34 along the C-C' section generally increased from two to ten times between 1995 and 2000; however, very few changes occurred within the wetland sediments above the aquifer, indicating that the

anaerobic natural attenuation of TCE as described by Lorah and others (1997) is continuing to occur and was not affected by the increased concentrations in the eastern region of the plume. In addition, there was essentially no change in the low TCE concentrations below the clay lens approximately 25 ft bls in the Canal Creek aquifer between 1995 and 2000.

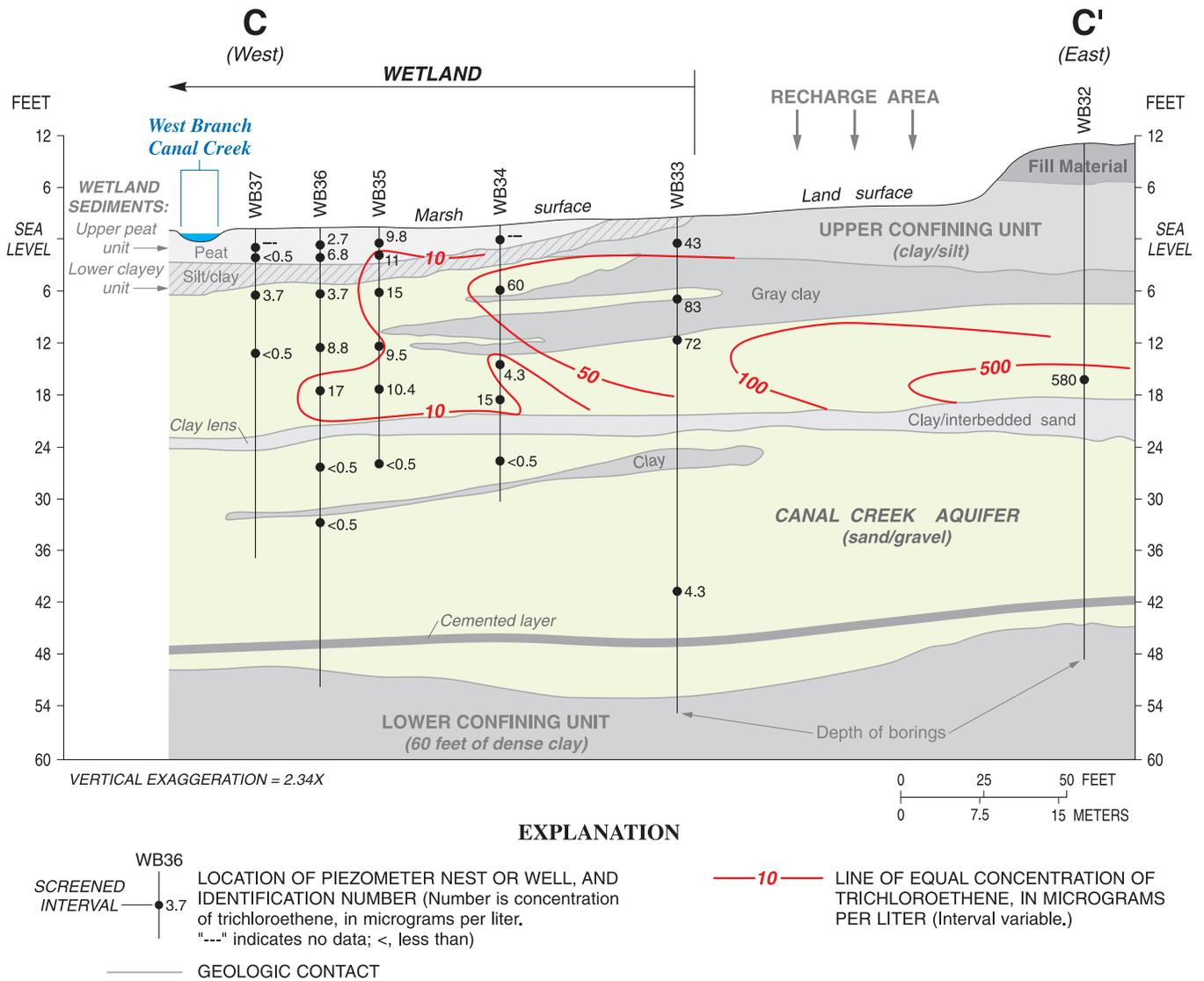


Figure 17b. Distribution of trichloroethene (TCE) in ground water in section C-C', June-August 2000, West Branch Canal Creek, Aberdeen Proving Ground, Maryland.

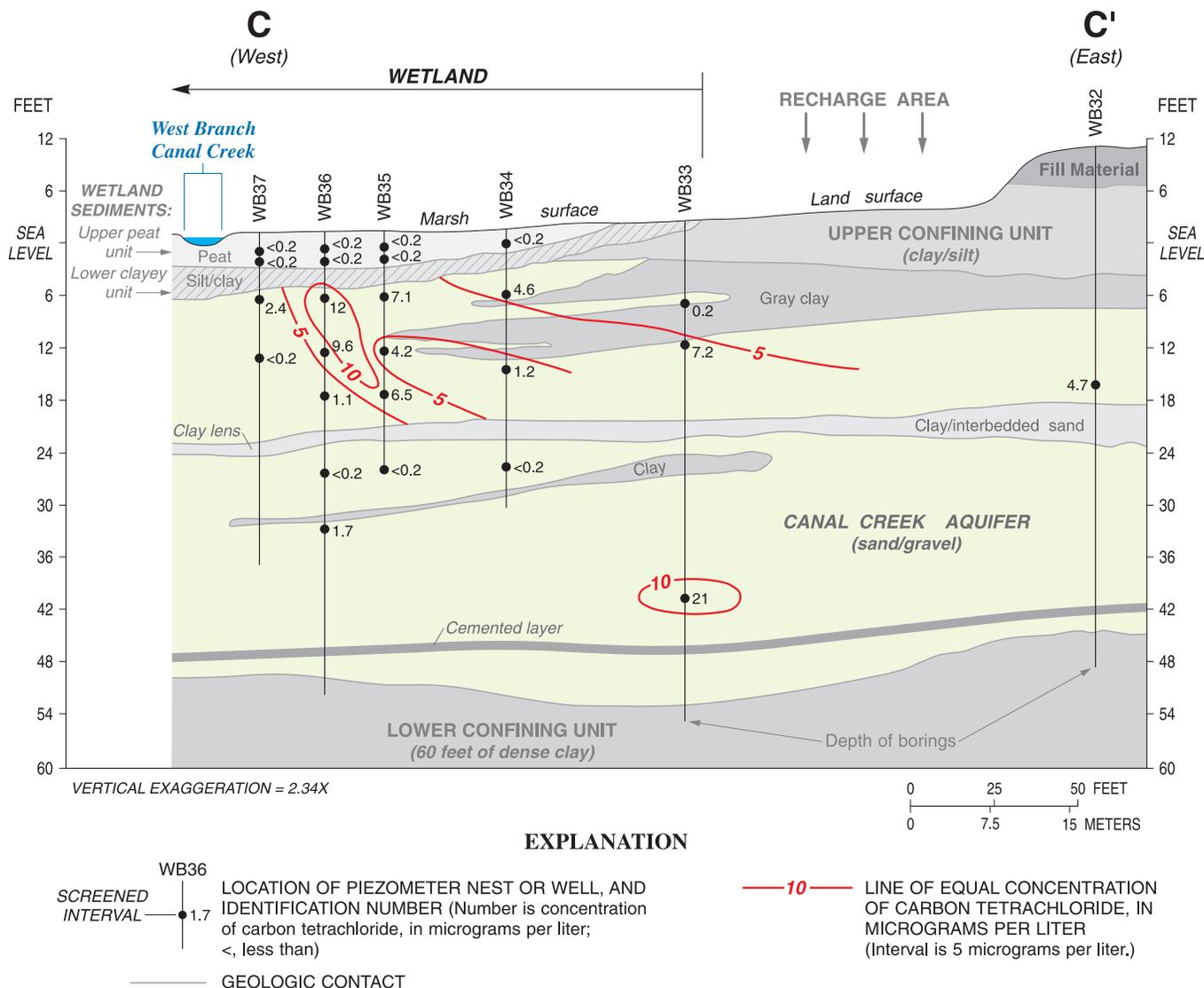


Figure 18a. Distribution of carbon tetrachloride (CT) in ground water in section C-C', June-October 1995, West Branch Canal Creek, Aberdeen Proving Ground, Maryland (data from Olsen and others, 1997).

Carbon tetrachloride (CT)—Contours of the 1995 and 2000 CT data along the C-C' section are shown in figures 18a and 18b, respectively. Below the upper confining unit in the top half of the Canal Creek aquifer in piezometer nests WB32 and WB33 east of much of the wetland, CT concentrations decreased from as high as 21 µg/L in 1995 to 3.1 µg/L or less in 2000 (figs. 18a-b). There were two detections of CT from piezometers screened in the deeper half of the aquifer

in 1995 (1.7 and 21 µg/L), and there were no detections in the deeper half of the aquifer in 2000 (at a detection limit of 0.5 µg/L) (fig. 18b). The CT plume along the C-C' section is located in the upper half of the Canal Creek aquifer, in the vicinity of piezometer nests WB34, WB35, and WB36, and the plume has changed little in area and overall concentration in the wetland area between 1995 and 2000 (figs. 18a-b).

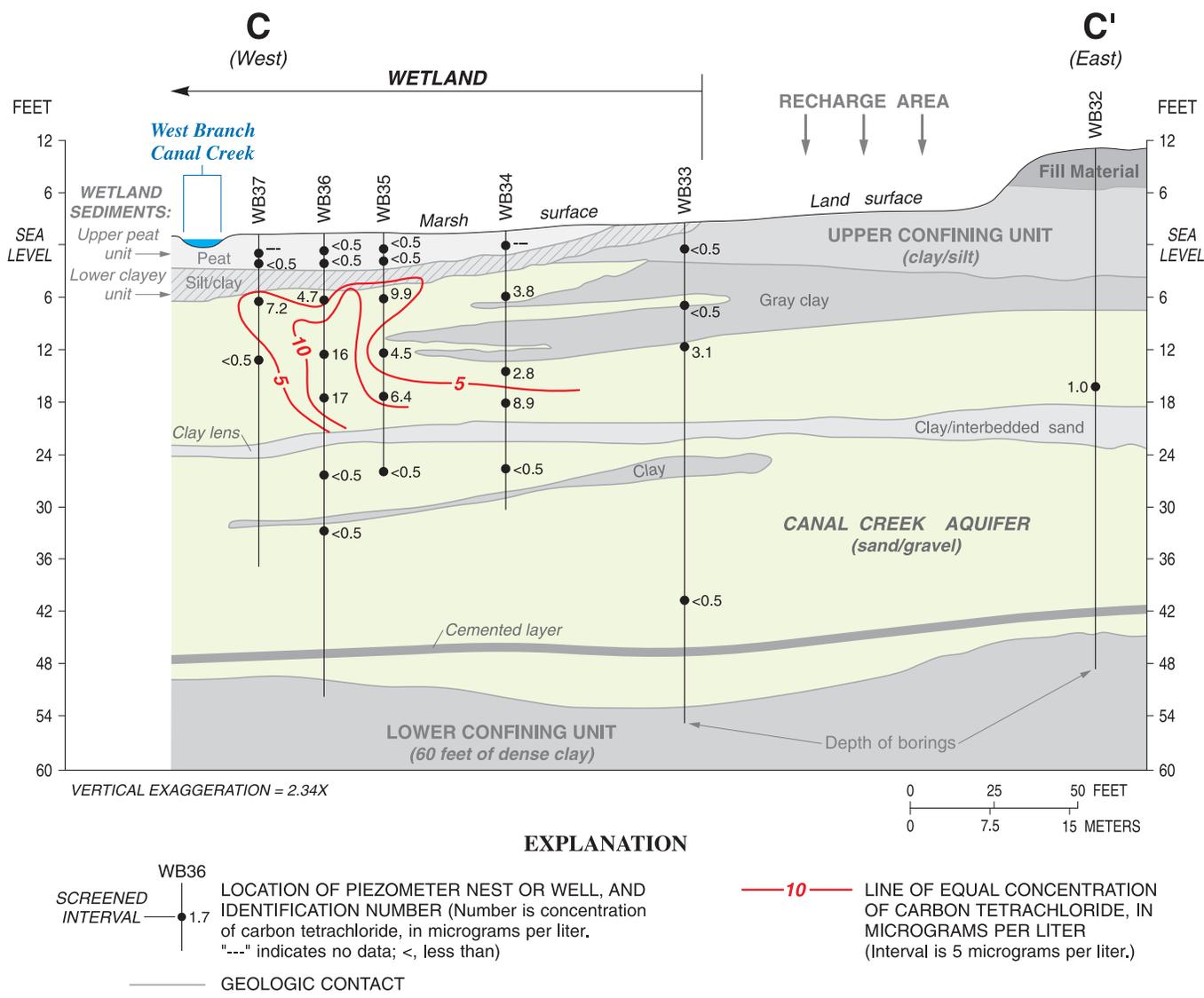


Figure 18b. Distribution of carbon tetrachloride (CT) in ground water in section C-C', June-August 2000, West Branch Canal Creek, Aberdeen Proving Ground, Maryland.

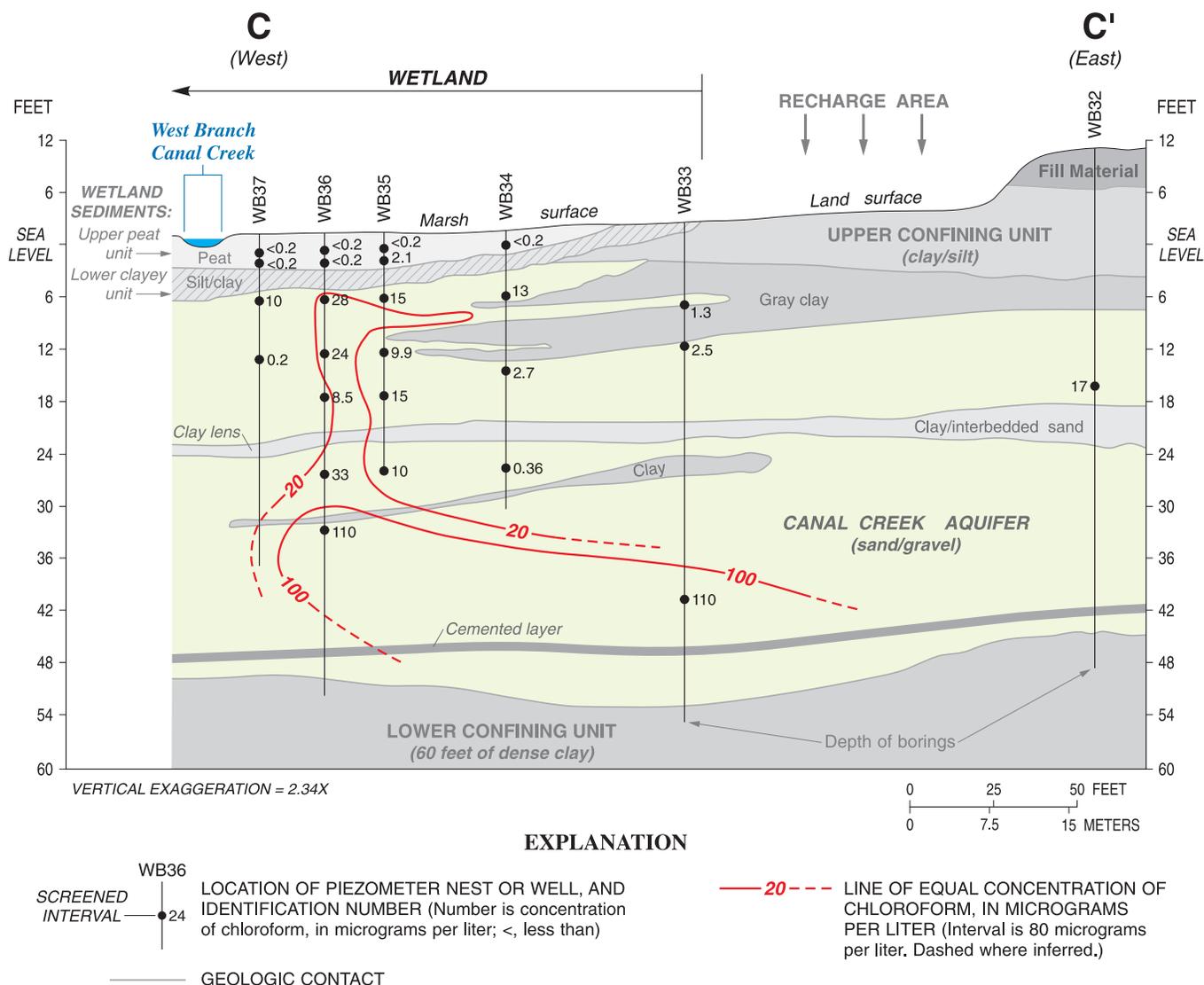


Figure 19a. Distribution of chloroform (CF) in ground water in section C-C', June-October 1995, West Branch Canal Creek, Aberdeen Proving Ground, Maryland (modified from Lorah and others, 1997).

Chloroform (CF)—Contours of the 1995 and 2000 CF data along the C–C' section are shown in figures 19a and 19b. CF concentrations in the lower half of the Canal Creek aquifer ranged from 0.36 to 110 µg/L in 1995; however, samples from the same piezometers in 2000 showed concentrations ranging from below the detection limit to only

1 µg/L. CF concentrations in the upper half of the aquifer ranged from below the detection limit of 0.5 µg/L to 28 µg/L in 1995, and 35 µg/L in 2000. The location and range of concentrations in the CF plume in the upper half of the Canal Creek aquifer along the C–C' section did not change measurably between 1995 and 2000.

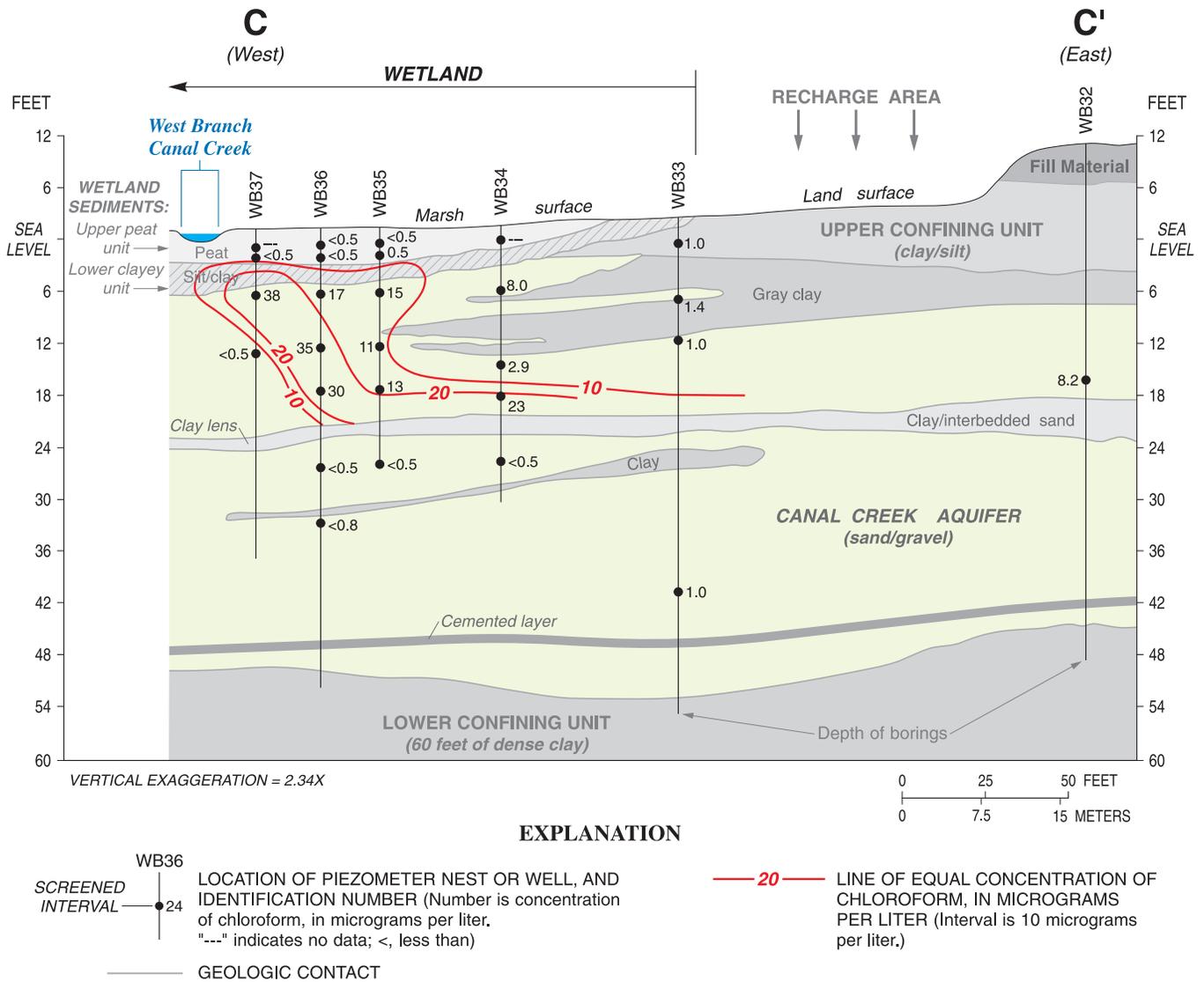


Figure 19b. Distribution of chloroform (CF) in ground water in section C-C', June-August 2000, West Branch Canal Creek, Aberdeen Proving Ground, Maryland.

Summary and Conclusions

Since 1917, Aberdeen Proving Ground, Maryland, has been the primary chemical-warfare research and development center for the U.S. Army. Most of the chemical-manufacturing and munitions-filling plants were concentrated in the area of the West Branch and East Branch Canal Creek. The U.S. Geological Survey, in cooperation with the U.S. Army Environmental Conservation and Restoration Division, began a study in 1992 to determine the distribution, fate, and transport of chlorinated volatile organic compounds in ground water from an area of the wetland along the West Branch Canal Creek.

The purpose of this report is to (1) compare volatile organic compound concentrations and determine changes in the ground-water contaminant plumes along two cross sections between June–October 1995 and June–August 2000, and (2) incorporate data from new piezometers sampled in spring 2001 into the plume descriptions. These two cross sections, A–A'' and C–C', generally are aligned parallel to ground-water flow paths in the wetland, with the possible exception of the well site CC27 in section A–A''.

Notable differences in the identities and concentrations of the predominant volatile organic compounds were observed between sections A–A'' and C–C' in both 1995 and 2000. Data from sections A–A'' and C–C' and nearby sampling sites indicate that there are two overlapping contaminant plumes in the wetland, and that these plumes differ in chemical composition. Section C–C' is more representative of Plume 1, which is in the northern part of the study area, and section A–A'' is more representative of Plume 2, which is in the southern part of the study area. In section C–C', 1,1,2,2-tetrachloroethane and trichloroethene had the highest concentrations of detected volatile organic compounds. In section A–A'', carbon tetrachloride and chloroform had the highest concentrations of detected volatile organic compounds, with the exception of 1,1,2,2-tetrachloroethane in well CC27A.

Along section A–A'', total concentrations of volatile organic compounds in 1995 were highest in the landfill area east of the wetland (5,200 micrograms per liter at 23 feet below land surface in well CC27A) and concentrations were next highest deep in the aquifer (3,300 micrograms per liter at 35 feet below land surface) near the creek channel at piezometer WB28F. When additional piezometers were sampled in 2001 west of piezometer nest WB28, carbon tetrachloride and chloroform concentrations (2,000 and 2,900 micrograms per liter, respectively) were higher deep in the aquifer (37–38 feet below land surface) at WB42 near the center of the wetland, than concentrations found at WB28F or well CC27A. An area deep in the aquifer close to the eastern edge of the wetland (east of piezometer WB21G), and a shallow area just east of the creek channel (between piezometers WB23 and WB26), showed decreases in total volatile organic compound concentrations of greater than 25 percent while the area between those two zones generally showed an increase of more than 25 percent. The areas with

the highest known concentrations of carbon tetrachloride (30,900 micrograms per liter at site HP13) and chloroform (21,500 micrograms per liter at site HP01) were measured in 2000 along the creek channel and near the top of the Canal Creek aquifer, just south of the A–A'' section.

Along section C–C', total concentrations of volatile organic compounds in ground water in both 1995 and 2000 were highest in piezometers located farthest east of the creek channel (WB32 and WB33), and concentrations progressively decreased at piezometer locations closer to the creek channel. Volatile organic compound concentrations typically are higher above the clay lens that generally is located between 19 and 24 feet below land surface, than concentrations deeper in the aquifer below the lens. In general, total volatile organic compound concentrations decreased more than 25 percent between 1995 and 2000 in areas close to the creek channel at both the top and bottom of the aquifer (less than 8 feet and greater than 30 feet below land surface). Total volatile organic compound concentrations increased more than 25 percent in some areas in the middle depths of the aquifer; however, it could not be determined if a defined plume was moving farther downgradient along flow lines toward the creek channel, or vertically downward because of the density differences within the aquifer.

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Appendix. Sampling locations for wells and piezometers in the West Branch Canal Creek study area, Aberdeen Proving Ground, Maryland

[Site identification number represents the latitude, longitude, and sequence number within the cluster and is used for tracking water-quality samples; -, no data]

Well number	Site identification number	Hydrogeologic unit	Well diameter (inches)	Screened interval (feet below land surface)	Land surface elevation (feet above sea level)
CC27A	392343076183301	Canal Creek aquifer	4.0	18.0–23.0	11.2
CC27B	392343076183302	Canal Creek aquifer	4.0	35.0–40.0	11.4
DPI-A	392346076183501	Wetland sediments, upper peat unit	2.0	1.9–2.9	1.20
DPI-B	392346076183502	Wetland sediments, lower peat unit	2.0	6.5–7.5	1.23
WB19A	392354076183701	Wetland sediments, upper peat unit	.75	1.3–1.8	1.52
WB19B	392354076183702	Wetland sediments, upper peat unit	.75	4.2–4.7	1.50
WB19D	392354076183704	Canal Creek aquifer	.75	13.5–14.0	1.51
WB19E	392354076183705	Canal Creek aquifer	.75	28.5–29.0	1.46
WB19F	392354076183706	Canal Creek aquifer	.75	45.0–45.5	1.33
WB20A	392345076183101	Canal Creek aquifer	.75	15.1–16.0	12.18
WB20B	392345076183102	Canal Creek aquifer	.75	21.0–21.5	12.32
WB20E	392345076183105	Canal Creek aquifer	.76	21.0–21.6	13.32
WB21A	392346076183301	Wetland sediments, lower clayey unit	.75	1.5–2.0	3.00
WB21B	392346076183302	Canal Creek aquifer	.75	6.5–7.0	3.10
WB21C	392346076183303	Canal Creek aquifer	.75	13.5–14.0	2.74
WB21D	392346076183304	Canal Creek aquifer	.75	17.5–18.0	3.14
WB21E	392346076183305	Canal Creek aquifer	.75	29.5–30.0	3.10
WB21F	392346076183306	Canal Creek aquifer	.75	36.0–36.5	3.10
WB21G	392346076183307	Canal Creek aquifer	.75	45.0–45.5	3.25
WB22A	392342076183401	Wetland sediments upper peat unit	.75	1.5–2.0	2.52
WB22B	392342076183402	Wetland sediments upper peat unit	.75	7.0–7.5	2.62
WB22C	392342076183403	Canal Creek aquifer	.75	13.0–13.5	2.52
WB22D	392342076183404	Canal Creek aquifer	.75	17.0–17.5	2.47
WB22E	392342076183405	Canal Creek aquifer	.75	22.0–22.5	2.53
WB23A	392341076183401	Wetland sediments, upper peat unit	.75	0.5–1.0	1.05
WB23B	392341076183402	Wetland sediments, lower clayey unit	.75	2.2–2.7	.77
WB23C	392341076183403	Wetland sediments, lower clayey unit	.75	8.5–9.0	1.06
WB23D	392341076183404	Canal Creek aquifer	.75	12.5–13.0	1.01
WB23E	392341076183405	Canal Creek aquifer	.75	16.0–16.5	.92
WB23F	392341076183406	Canal Creek aquifer	.75	21.0–21.5	1.00
WB24A	392343076183401	Wetland sediments, upper peat unit	.75	0.9–1.4	1.85
WB24B	392343076183402	Wetland sediments, upper peat unit	.75	3.0–3.5	1.77
WB24C	392343076183403	Wetland sediments, upper peat unit	.75	5.5–6.0	1.75
WB24D	392343076183404	Canal Creek aquifer	.75	12.5–13	1.64
WB24E	392343076183405	Canal Creek aquifer	.75	16.5–17.0	1.85
WB24F	392343076183406	Canal Creek aquifer	.75	28.0–28.5	1.80

Appendix. *Sampling locations for wells and piezometers in the West Branch Canal Creek study area, Aberdeen Proving Ground, Maryland—Continued*

Well number	Site identification number	Hydrogeologic unit	Well diameter (inches)	Screened interval (feet below land surface)	Land surface elevation (feet above sea level)
WB25A	392342076183502	Wetland sediments, upper peat unit	0.75	0.5–1.0	1.23
WB25B	392342076183503	Canal Creek aquifer	.75	13.5–14.0	1.20
WB25C	392342076183504	Canal Creek aquifer	.75	15.5–16.0	1.12
WB26A	392343076183502	Wetland sediments, upper peat unit	.75	1.0–1.5	.38
WB26B	392343076183503	Wetland sediments, upper peat unit	.75	2.5–3.0	.47
WB26C	392343076183504	Wetland sediments, upper peat unit	.75	4.0–4.5	.20
WB26D	392343076183505	Wetland sediments, lower clayey unit	.75	5.5–6.0	.33
WB26E	392343076183506	Paleochannel	.75	8.8–9.3	.28
WB26F	392343076183507	Canal Creek aquifer	.75	15.0–15.5	.33
WB26G	392343076183508	Canal Creek aquifer	.75	19.5–20.0	.40
WB26H	392343076183509	Canal Creek aquifer	.75	27.0–27.5	.50
WB27A	392343076183521	Wetland sediments, upper peat unit	.75	1.0–1.5	-.92
WB27B	392343076183522	Wetland sediments, upper peat unit	.75	3.2–3.7	-.97
WB27C	392343076183523	Wetland sediments, upper peat unit	.75	4.5–5.0	-.98
WB27D	392343076183524	Paleochannel	.75	8.2–8.7	-.88
WB27E	392343076183525	Canal Creek aquifer	.75	15.0–15.5	-.96
WB27F	392343076183526	Canal Creek aquifer	.75	18.0–18.5	-.90
WB27G	392343076183527	Canal Creek aquifer	.75	26.0–26.5	-.90
WB28A	392345076183511	Wetland sediments, upper peat unit	.75	1.2–1.7	.83
WB28B	392345076183512	Wetland sediments, upper peat unit	.75	4.5–5.0	.84
WB28C	392345076183513	Wetland sediments, upper peat unit	.75	9.0–9.5	.82
WB28D	392345076183514	Canal Creek aquifer	.75	14.5–15.0	.89
WB28F	392345076183516	Canal Creek aquifer	.75	34.5–35.0	.73
WB32B	392347076183202	Canal Creek aquifer	.75	26.5–27.0	10.77
WB33Y	–	Wetland sediments, upper peat unit	.25	1.9–2.0	2.96
WB33Z	–	Wetland sediments, upper peat unit	.25	4.5–4.6	2.96
WB33A	392353076183301	Canal Creek aquifer	.75	8.7–9.2	2.96
WB33B	392353076183302	Canal Creek aquifer	.75	14.0–14.5	2.95
WB33F	392353076183306	Canal Creek aquifer	.75	42.5–43.0	2.95
WB34A	392348076183410	Wetland sediments, upper peat unit	.75	1.5–2.0	1.43
WB34B	392348076183411	Canal Creek aquifer	.75	7.3–7.8	1.37
WB34C	392348076183412	Canal Creek aquifer	.75	15.0–15.5	1.36
WB34D	392348076183413	Canal Creek aquifer	.75	18.3–18.8	1.35
WB34E	392348076183414	Canal Creek aquifer	.75	26.5–27.0	1.35

Appendix. *Sampling locations for wells and piezometers in the West Branch Canal Creek study area, Aberdeen Proving Ground, Maryland—Continued*

Well number	Site identification number	Hydrogeologic unit	Well diameter (inches)	Screened interval (feet below land surface)	Land surface elevation (feet above sea level)
WB35A	392354076183402	Wetland sediments, upper peat unit	0.75	1.5–2.0	1.19
WB35B	392354076183403	Wetland sediments, upper peat unit	.75	2.8–3.3	1.29
WB35C	392354076183404	Canal Creek aquifer	.75	7.2–7.7	1.27
WB35D	392354076183405	Canal Creek aquifer	.75	13.0–13.5	1.27
WB35E	392354076183406	Canal Creek aquifer	.75	18.0–18.5	1.27
WB35F	392354076183407	Canal Creek aquifer	.75	27.5–28.0	1.31
WB36A	392355076183402	Wetland sediments, upper peat unit	.75	1.7–2.2	1.27
WB36B	392355076183403	Wetland sediments, upper peat unit	.75	2.7–3.2	.99
WB36C	392355076183404	Canal Creek aquifer	.75	7.1–7.6	1.04
WB36D	392355076183405	Canal Creek aquifer	.75	13.0–13.5	.98
WB36E	392355076183406	Canal Creek aquifer	.75	18.0–18.5	1.03
WB36F	392355076183407	Canal Creek aquifer	.75	27.5–28.0	1.00
WB36G	392355076183408	Canal Creek aquifer	.75	32.0–32.5	1.09
WB37A	392356076183402	Wetland sediments, upper peat unit	.75	1.7–2.2	.76
WB37B	392356076183403	Wetland sediments, upper peat unit	.75	2.5–3.0	.71
WB37C	392356076183404	Canal Creek aquifer	.75	7.1–7.6	.72
WB37D	392356076183405	Canal Creek aquifer	.75	13.5–14.0	.75
WB41A	392345076183601	Wetland sediments, upper peat unit	1.0	8.25–9.25	1.31
WB41B	392345076183602	Wetland sediments, upper peat unit	1.0	9.0–10.0	1.08
WB41C	392345076183603	Canal Creek aquifer	1.0	22.4–23.4	1.31
WB41D	392345076183604	Canal Creek aquifer	1.0	28.0–30.0	1.32
WB41E	392345076183605	Canal Creek aquifer	1.0	31.3–32.3	1.24
WB42A	392343076183601	Wetland sediments, upper peat unit	1.0	6.0–7.0	1.31
WB42B	392343076183602	Canal Creek aquifer	1.0	13.0–14.0	1.27
WB42C	392343076183603	Canal Creek aquifer	1.0	19.0–20.0	1.45
WB42D	392343076183604	Canal Creek aquifer	1.0	25.0–26.0	1.32
WB42E	392343076183605	Canal Creek aquifer	1.0	31.0–32.0	1.24
WB42F	392343076183606	Canal Creek aquifer	1.0	37.0–38.0	1.34