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

Design and Analysis of a Natural-Gradient Ground-Water Tracer Test in a Freshwater Tidal Wetland, West Branch Canal Creek, Aberdeen Proving Ground, Maryland

Scientific Investigations Report 2004-5190

U.S. Department of the Interior
U.S. Geological Survey

Cover. Side view of the ground-water tracer array in the wetland study area, West Branch Canal Creek, Aberdeen Proving Ground, Maryland. *(Note the line on the left side of the array platform indicating the flood level of Hurricane Floyd, September 16, 1999.)*

(Photograph by Tracey Spencer, U.S. Geological Survey)

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Reston, Virginia
2005

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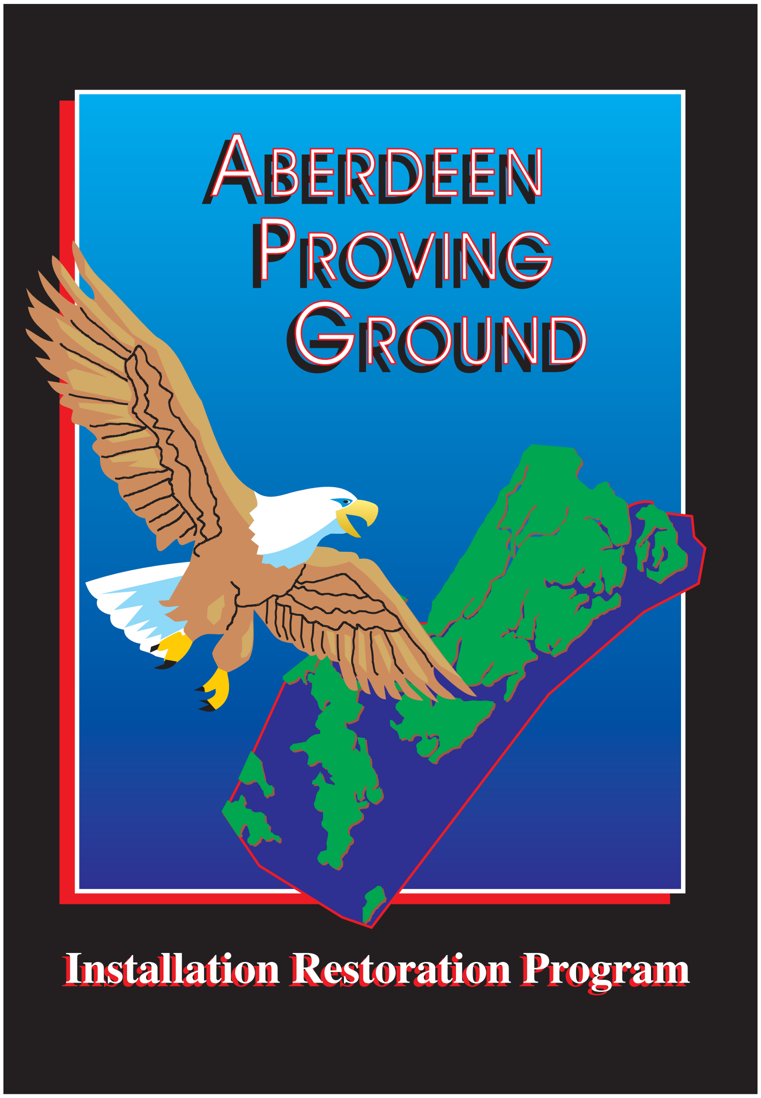

2005

Aberdeen Proving Ground, Edgewood Area

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Conversion Factors and Vertical Datum

Multiply	By	To obtain
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot (ft^3)	0.0929	cubic meter (m^3)

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.

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L), micrograms per liter (µg/L), or nanograms per liter (ng/L).

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

Design and Analysis of a Natural-Gradient Ground-Water Tracer Test in a Freshwater Tidal Wetland, West Branch Canal Creek, Aberdeen Proving Ground, Maryland

By Lisa D. Olsen *and* Frederick J. Tenbus

Abstract

A natural-gradient ground-water tracer test was designed and conducted in a tidal freshwater wetland at West Branch Canal Creek, Aberdeen Proving Ground, Maryland. The objectives of the test were to characterize solute transport at the site, obtain data to more accurately determine the ground-water velocity in the upper wetland sediments, and to compare a conservative, ionic tracer (bromide) to a volatile tracer (sulfur hexafluoride) to ascertain whether volatilization could be an important process in attenuating volatile organic compounds in the ground water. The tracer test was conducted within the upper peat unit of a layer of wetland sediments that also includes a lower clayey unit; the combined layer overlies an aquifer. The area selected for the test was thought to have an above-average rate of ground-water discharge based on ground-water head distributions and near-surface detections of volatile organic compounds measured in previous studies. Because ground-water velocities in the wetland sediments were expected to be slow compared to the underlying aquifer, the test was designed to be conducted on a small scale.

Ninety-seven ¼-inch-diameter inverted-screen stainless-steel piezometers were installed in a cylindrical array within approximately 25 cubic feet (2.3 cubic meters) of wetland sediments, in an area with a vertically upward hydraulic gradient. Fluorescein dye was used to qualitatively evaluate the hydrologic integrity of the tracer array before the start of the tracer test, including verifying the absence of hydraulic short-circuiting due to non-natural vertical conduits potentially created during piezometer installation. Bromide and sulfur hexafluoride tracers (0.139 liter of solution containing 100,000 milligrams per liter of bromide ion and 23.3 milligrams per liter of sulfur hexafluoride) were co-injected and monitored to generate a dataset that could be used to evaluate solute transport in three dimensions. Piezometers were sampled 2 to 15 times each, from July 1998 through September 1999, to assess background conditions and monitor tracer movement. During the test, 644 samples were analyzed for fluorescein, 617 samples were analyzed for bromide with an ion-selective electrode, 213 samples were analyzed for bromide with colorimetric methods, and 603 samples were analyzed for sulfur hexafluoride, including samples collected prior to tracer injection to determine background concentrations. Additional samples were analyzed for volatile organic compounds (96 samples) and methane (37 samples) to determine the distribution of these contaminants and the extent of methanogenic conditions within the tracer array; however, these data were not used for the analysis of the test.

During the tracer test, the fluorescein dye, bromide, and sulfur hexafluoride were transported predominantly in the upward direction, although all three tracers also moved outward in all directions from the injection point, and it is likely that some tracer mass moved beyond the lateral edges of the array. An analysis of the tracer-test data was performed through the use of breakthrough curves and isoconcentration contour plots. Results show that movement of the fluorescein dye, a non-conservative tracer, was retarded compared to the other two tracers, likely as a result of sorption onto the wetland sediments. Suspected loss of tracer mass along the lateral edges of the array prevented a straightforward quantitative analysis of tracer transport and ground-water velocity from the bromide and sulfur-hexafluoride data. In addition, the initial density of the bromide/sulfur hexafluoride solution (calculated to be 1.097 grams per milli-

liter) could have caused the solution to sink below the injection point before undergoing dilution and moving back up into the array. For these reasons, the data analysis in this report was performed largely through qualitative methods.

The mass of bromide and sulfur hexafluoride tracers within the array was estimated from the mean concentrations during each of four major sampling episodes that took place between 103 and 375 days after tracer injection. Assuming an effective porosity of 0.40, the estimated mass of bromide ranged from about 68 percent (during the first major sampling episode) to as little as 4 percent of the mass that was initially injected, whereas the estimated mass of sulfur hexafluoride ranged from about 51 percent to 3 percent of the initial mass. These masses would be larger, however, if a higher porosity was assumed; for example, the mass of bromide estimated for the first major sampling episode would be 94 percent if an effective porosity of 0.55 was assumed. A comparison of bromide and sulfur hexafluoride concentrations relative to their respective injected concentrations indicates that a smaller proportion of the injected sulfur hexafluoride moved up into the tracer array compared to bromide. Breakthrough curves of bromide and sulfur hexafluoride concentrations with time showed differences between the two tracers in most parts of the array. In several instances, large concentrations of one tracer were not matched by large concentrations of the other. Breakthrough curves and isoconcentration contour plots indicate that the bromide tracer generally moved away from the injection point more efficiently than sulfur hexafluoride. The movement of the tracers coupled with the loss of tracer mass throughout the test shows qualitatively that there is a slight northward horizontal component to the ground-water flow in the area of the tracer array in addition to vertical flow.

Diffusion and advection are thought to be the major processes responsible for the tracer movement, based on the predominantly upward movement of the conservative tracers, coupled with the outward movement in all directions from the injection point. Decreases in concentration as the tracers moved upwards through the array were likely caused by dilution. Sorption was evaluated and eliminated as a potential source of mass loss or retardation for sulfur hexafluoride. Because the wetland sediments were saturated to land surface throughout the tracer test, potential losses of sulfur hexafluoride due to volatilization from the surface of the water table into an unsaturated zone could not be evaluated. Part of the sulfur hexafluoride could have volatilized into ambient bubbles of marsh gases at depth; this process could explain the early presence of sulfur hexafluoride in a few upper-level sampling points (because of gas-bubble rise) and the retardation of some of the sulfur hexafluoride (because of gas-bubble trapping) in the lower levels of the tracer array.

The tracer movement observed during this test can provide insights into the transport of volatile organic compounds in the wetland sediments at West Branch Canal Creek. Because the volatile organic compounds that are the contaminants of interest are nonconservative, sorption would be expected to retard their movement, though to a lesser degree than was observed for fluorescein, which has a higher octanol-water partitioning coefficient than the contaminants of interest. Dilution, which is thought to be a factor in reducing the tracer concentrations, could also affect volatile organic compounds in the wetland sediments; however, the higher proportion of daughter compounds detected in the shallow levels of the array (6 to 24 inches below land surface) compared to the deeper levels indicates that biodegradation is also acting to transform these compounds and reduce their mass. Finally, if volatile organic compounds are able to volatilize into bubbles of biogenic marsh gases at depth, their transport could be affected by potential acceleration or retardation due to gas-bubble rise or trapping, as was hypothesized with the sulfur hexafluoride.

Introduction

In cooperation with the U.S. Army, the U.S. Geological Survey (USGS) has been investigating the West Branch Canal Creek area of Aberdeen Proving Ground (APG), Maryland, (fig. 1) to assess the effectiveness of natural attenuation as a remediation option for ground-water contaminant plumes consisting of chlorinated volatile organic compounds (VOCs). Evaluating natural attenuation requires an understanding of the physical, chemical, and biological processes that control contaminant fate and transport,

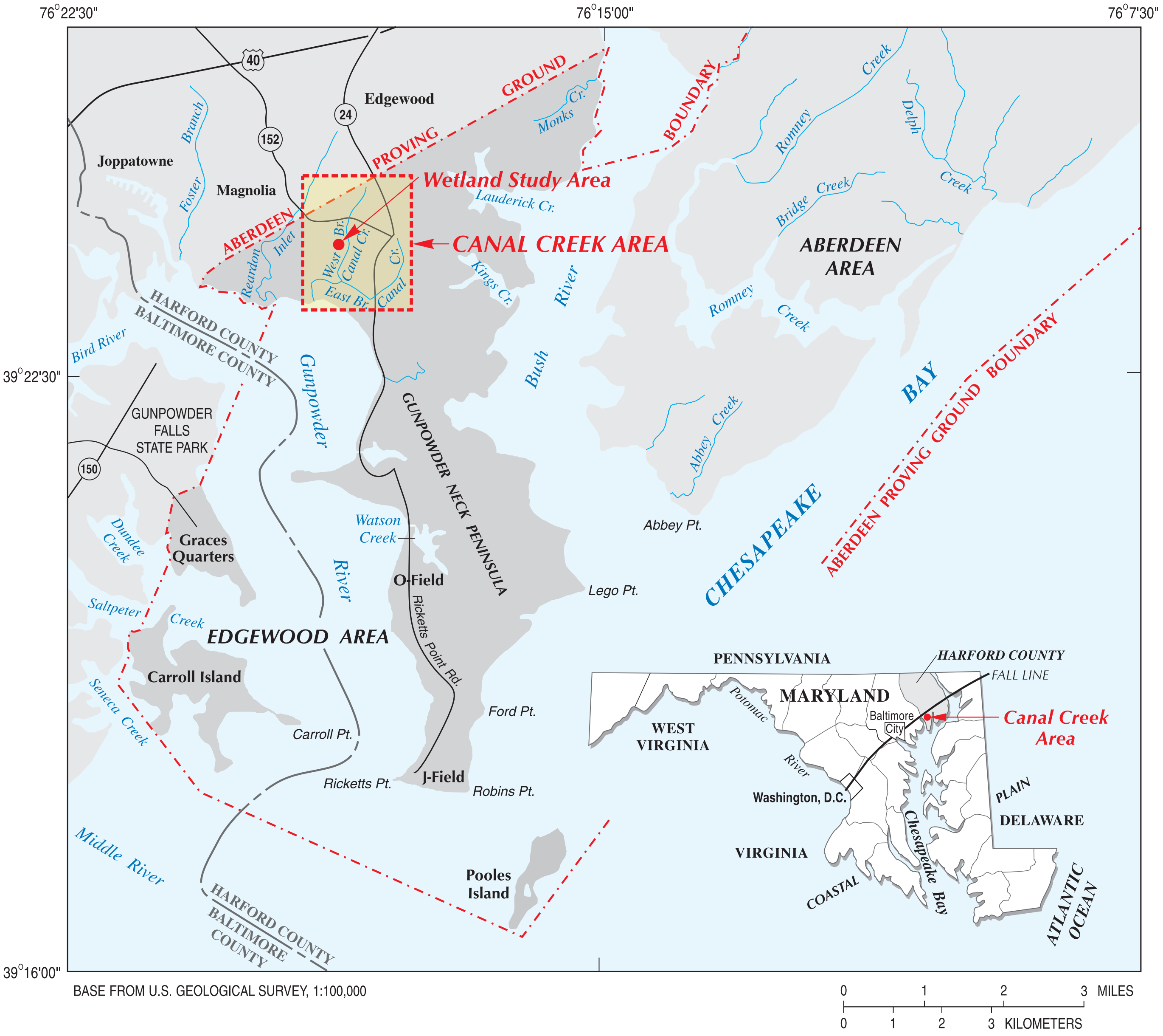


Figure 1. Location of the Canal Creek area and the wetland study area along West Branch Canal Creek, Aberdeen Proving Ground, Maryland.

including abiotic degradation, biodegradation, sorption, dispersion, diffusion, volatilization, and ground-water flow. From May 1996 through January 1997, abiotic degradation, biodegradation, and sorption were quantified through laboratory microcosm experiments and batch sorption tests (Lorah and others, 1997). Dispersion and diffusion were not measured or estimated during this phase of the study and are difficult to quantify in tidal environments. Gas-flux chamber experiments designed to assess volatilization showed no detectable concentrations of VOCs in the air above the marsh surface; however, concentrations of VOCs in near-surface ground water collected from the experimental sites were typically near or below the detection limit (Olsen and others, 1997; Lorah and others, 1997). Therefore, these experiments could not be used to determine whether volatilization could be a significant attenuation process if higher concentrations of VOCs were to reach the marsh surface. Ground-water velocities were not measured directly during these early investigations, but had been estimated based on data and assumptions provided in Lorah and others (1997) to be about 2.3 ft (feet) per year in an upward direction in the wetland sediments. However, it was believed that preferential flow could cause actual ground-water velocities to be more than an order of magnitude higher than this estimate.

From 1998 through 1999, the USGS, in cooperation with the U.S. Army Environmental Conservation and Restoration Division at APG, conducted a natural-gradient ground-water tracer test in a selected area of wetlands along West Branch Canal Creek. The objectives of this tracer test were to characterize solute transport and more accurately determine the ground-water velocity in the upper wetland sediments, and to compare a conservative ionic tracer (bromide) to a volatile tracer (sulfur hexafluoride) to determine whether volatilization could be a significant process in attenuating ground-water contaminants.

New methods were developed to overcome the difficulties associated with measuring tracer movement in wetland sediments with a low estimated ground-water velocity and upward ground-water flow, including the design of a small-scale three-dimensional array of ¼-in.(inch)-diameter inverted-screen piezometers and low-volume sampling methods. Analytical methods were selected to minimize the sample volumes required and therefore minimize the water volume withdrawn for analysis, preserving the natural hydraulic gradient. The tracer-test data were analyzed by the use of breakthrough curves and isoconcentration contour plots. The results and analysis of the tracer test could be used to improve the understanding of natural attenuation and contaminant fate and transport processes at West Branch Canal Creek.

Site History

The U.S. Army has used APG as a center for chemical warfare research since 1917. Until the late 1970s, West Branch Canal Creek and the surrounding wetlands were used for disposal of chlorinated solvents and other wastes, including carbon tetrachloride, chloroform, trichloroethylene, and 1,1,2,2-tetrachloroethane (Lorah and Clark, 1996). VOCs from these disposal activities are the source of the long-term contamination that persists in the Canal Creek aquifer, most likely through the slow dissolution of residual dense non-aqueous-phase liquids (Lorah and others, 1997). Fill material, including construction materials and debris from manufacturing facilities that were demolished in the late 1960s, was pushed out into areas of the wetland, displacing the natural wetland sediments. No known facilities that could have contributed contaminants to the ground water by way of the creek or the surrounding marshes have been active during the last two decades. A more detailed history of waste-disposal and landfilling activities in the Canal Creek area is available in Lorah and Clark (1996) and Nemeth (1989).

Previous Investigations

The first survey of soil, sediment, ground water, and surface water in the Edgewood Area (fig. 1) of APG was conducted by the U.S. Army Toxic and Hazardous Materials Agency, and is described in Nemeth and others (1983). In response to the U.S. Army’s concerns about contaminants in the Canal Creek area and data gaps in the initial survey, the USGS conducted a comprehensive investigation of contamination in the Canal Creek area. This investigation was conducted from 1985 through 1992, and is summarized in Lorah and Clark (1996).

In 1990, the Comprehensive Environmental Response and Compensation Liability Act (CERCLA) was passed, and Aberdeen Proving Ground was placed on the National Priorities List. This action led to an Interagency Agreement between the U.S. Army and Region III of the U.S. Environmental Protection Agency that required investigation and remediation of the Canal Creek area. From 1992 to 1996, the USGS began an investigation to determine the distribution, fate, and movement of chlorinated VOCs in the ground water along the West Branch Canal Creek. The objectives of the 1992–1996 investigation were to define the major ground-water flowpaths and hydrologic interactions between the aquifer, wetland, and surface water; to determine the distribution of contaminants along ground-water flowpaths; to determine the major geochemical and microbial processes affecting the VOCs; and to evaluate the effect and significance of natural-attenuation processes, including biodegradation, sorption, and volatilization, on the fate and mobility of VOCs in the wetland (Lorah and others, 1997). As part of the 1992–1996 investigation, ground-water flow velocities in the upward direction were calculated based on estimated porosities and data collected from piezometers that were screened in the aquifer sediments, which have relatively high hydraulic conductivities, and in the overlying fine-grained, organic-rich wetland sediments, which have lower hydraulic conductivities. These ground-water velocity estimates were representative of selected flowpaths extending through the aquifer and the wetland sediments, and were not necessarily representative of the wetland sediments as a hydrogeologic unit.

From 1996 through 1998, the USGS performed additional studies to further characterize natural-attenuation processes in the wetland sediments and their influence on the fate of VOCs. Because these studies demonstrated that the layer of wetland sediments along West Branch Canal Creek was effective in attenuating contaminants, the USGS designed, conducted, and analyzed a natural-gradient ground-water tracer test in the upper wetland sediments, from 1998 through 2003, to further investigate this hydrologic unit. The objectives of this tracer test were to better characterize solute transport, procure a dataset that could be used in subsequent studies to verify previous estimates of ground-water velocity, and compare a nonvolatile conservative tracer to a volatile conservative tracer to determine whether volatilization could affect ground-water contaminants in the wetland sediments.

Purpose and Scope

This report describes the design and analysis of a small-scale natural-gradient tracer test that was conducted in an area of wetland sediments at West Branch Canal Creek. The tracer test was designed to monitor tracer movement in three dimensions within the upper peat unit of the wetland sediments over a period of approximately 1 year. Design and construction details for the ¼-in. inverted-screen piezometers used for the tracer test, methods used for piezometer installation, and the arrangement of these piezometers within the "tracer array" are described. The techniques used to prepare and inject the tracers are discussed, and the methods used to collect and analyze samples from the tracer array are also presented.

Because one objective of the tracer test was to produce a dataset that could be used to verify previous estimates of ground-water velocity, the data that were collected throughout the test are provided, including the concentrations of fluorescein, bromide, and sulfur hexafluoride and the water volumes removed during sampling. Daily rainfall totals and tidal water-level data also are presented to provide a hydrologic context for the tracer data. Additional data are provided from ground-water samples that were periodically collected and analyzed for VOCs and methane to characterize the distributions of these solutes within the tracer array and determine whether their occurrence was consistent with observations in the upper wetland sediments. All of the chemical and hydrologic data included in this report were verified, and an evaluation of the data quality is presented for all of the compounds that were analyzed.

This report provides an analysis of the tracer movement based on the use of breakthrough curves and isoconcentration contour plots. Breakthrough curves are presented for bromide and sulfur hexafluoride only, whereas isoconcentration plots are presented for all three tracers. Mass losses from the tracer array are estimated for each tracer. A comparison of the movement of the three tracers (fluorescein, bromide, and sulfur hexafluoride) is provided, along with a discussion of the characteristics of the tracers and other solutes, such as the contaminants of interest, and the influence that solute characteristics can have on transport. A comparison of bromide, a nonvolatile conservative tracer, with sulfur hexafluoride, a volatile conservative tracer, is presented, with discussion of the possibility of volatilization.

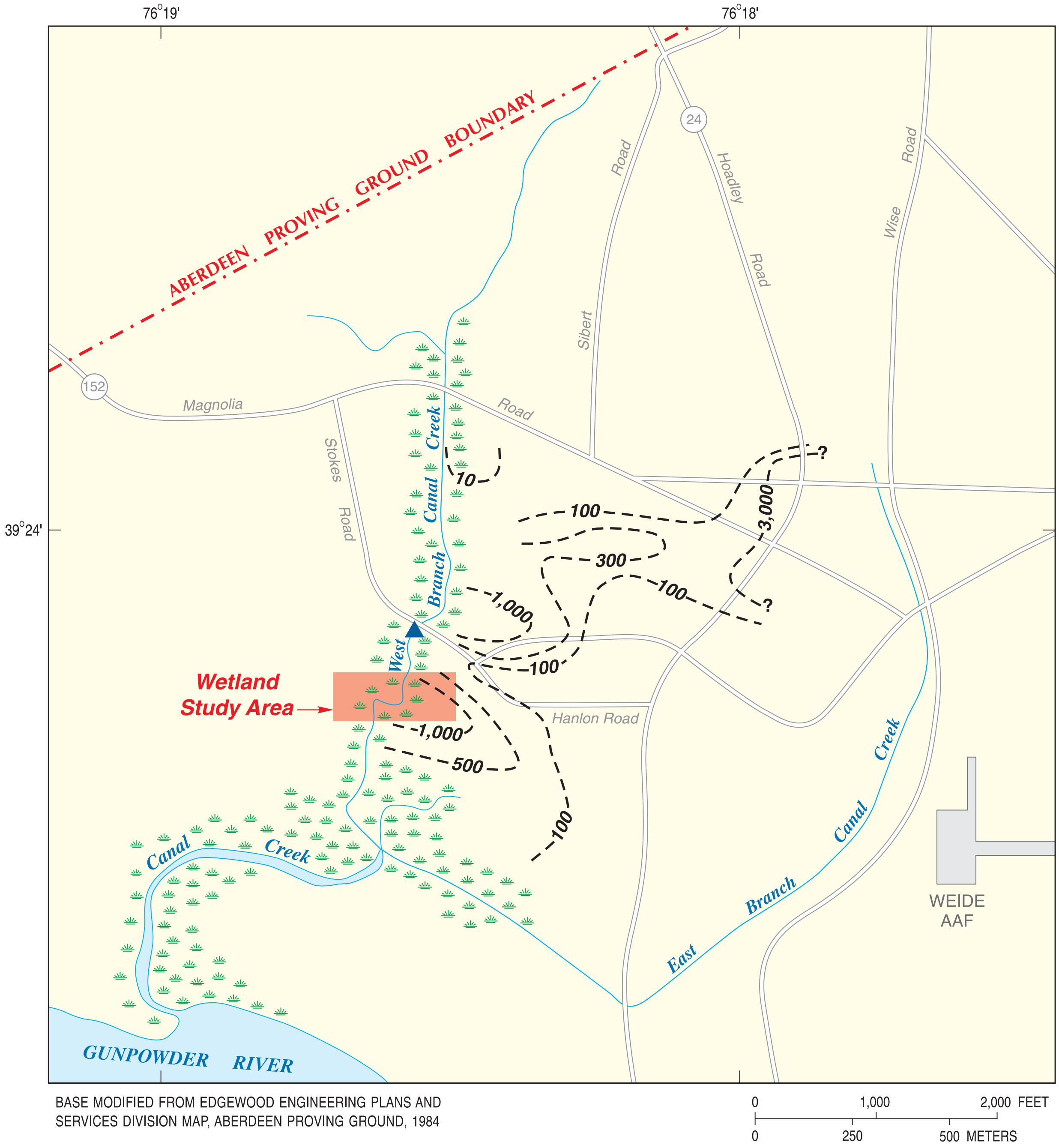
Description of Study Area

West Branch Canal Creek is located in the Canal Creek area of APG, near the head of the Chesapeake Bay, in the Coastal Plain Physiographic Province of Maryland (fig. 1). From the confluence of its East and West Branches, Canal Creek flows southward into the Gunpowder River, an estuary located at the southwestern edge of the study area (fig. 1). Freshwater wetlands characterize much of the West Branch Canal Creek area, though landfilling activities have decreased the area of some of these wetlands (fig. 2). Vegetation in the wetland study area consists mostly of common reed (*Phragmites australis*), with smaller zones of cattail, pickerelweed, and southern wild rice (Lorah and others, 1997).

During the 1992–96 investigation of the fate and transport of ground-water contaminants near West Branch Canal Creek, part of the creek and surrounding estuaries were designated as the "wetland study area" (fig. 2). An extensive network of drive-point piezometers was installed in this area from 1994 through 1995 to characterize the distribution and fate of contaminants in the ground water. The wetland study area and the piezometer network were subsequently used for the investigation of natural-attenuation processes in the wetland sediments, and the site selected for the tracer test is within this area.

Geologic Setting The geology of the Canal Creek area is characterized by thick, wedge-shaped deposits of unconsolidated Coastal Plain sediments that dip southeastward (Lorah and Clark, 1996). The Canal Creek aquifer, which is the contaminated aquifer of interest, is in the Patapsco Formation of Lower Cretaceous age, and ranges from 30 to 70 ft thick in the Canal Creek area (Lorah and Clark, 1996). The Canal Creek aquifer is confined in the East Branch Canal Creek area, and is semiconfined or unconfined near the West Branch Canal Creek area. The lower confined aquifer, which underlies the approximately 60-ft-thick lower confining unit, is not known to be contaminated (Lorah and Vroblesky, 1989; Lorah and Clark, 1996).

Sediments in the Canal Creek aquifer consist of medium- to coarse-grained sand and gravel, interfingered with thin layers or lenses of clay and silt. Upgradient from the wetland, the aquifer is overlain by fill material and the sediments of the upper confining unit. Within the wetland, the Canal Creek aquifer is overlain by wetland sediments, which are about 6 to 12 ft thick in the wetland study area. These wetland sediments consist of organic-rich peat, clay, silt, sandy clay, and clayey sand. Natural attenuation of VOCs occurs primarily in the upper peat unit of the wetland sediments, where the average total organic content was 18 percent (average of 15 sediment samples), and to a lesser extent in the lower clayey unit (Lorah and others, 1997). The effective porosity for the combined upper peat unit and lower clayey unit was assumed to be 0.40 (based on assumptions used in Lorah and others, 1997), but could range as high as 0.55 within the upper peat unit, based on National Soil Survey data for the area (Soil Survey Staff, 2004).



BASE MODIFIED FROM EDGEWOOD ENGINEERING PLANS AND SERVICES DIVISION MAP, ABERDEEN PROVING GROUND, 1984

EXPLANATION

?– –100– –	APPROXIMATE LINE OF EQUAL TOTAL ORGANIC HALOGEN CONCENTRATION, IN MICROGRAMS PER LITER (Interval is variable. Queried where uncertain. Sampled July-September 1988.)
▲	TIDE GAGE

Figure 2. Location of the wetland study area along West Branch Canal Creek, Aberdeen Proving Ground, Maryland, and the distribution of total organic halogen in the Canal Creek aquifer upgradient from the wetland *(modified from Lorah and Clark, 1996, p.106).*

Hydrologic Setting Shallow ground water on both sides of West Branch Canal Creek generally flows laterally and upward toward the creek channel. Ground water discharges from the Canal Creek aquifer through the wetland sediments into the creek and marsh areas. Deep flow in the aquifer may enter the regional flow system, which flows toward the southeast (Lorah and Clark, 1996). Recharge, in the form of rainfall infiltration, occurs upgradient from the creek. The average annual rainfall from 1997 through 1999 was 39.8 in. (Charles Clough, Meteorology Team, Aberdeen Test Center, U.S. Army, written commun., 2000). Daily rainfall totals from October 1997 through September 1999 were calculated from data provided by the U.S. Army Aberdeen Test Center Meteorology Team (Charles Clough, written commun., 2000) and are presented in Appendix A.

North of Magnolia Road (fig. 2), the West Branch Canal Creek is typically nontidal. South of Magnolia Road, the West Branch Canal Creek is influenced by tides that range from approximately –0.5 to 4.0 ft relative to sea level, with an average change in tidal amplitude of approximately 1 ft per tidal cycle. Surface water in the tidal area generally ranges from fresh—less than 1,000 µS/cm (microsiemens per centimeter)—to slightly brackish (1,000 to 4,000 µS/cm) in the late fall, winter, spring, and early summer, and from slightly brackish to more strongly brackish (4,000 to 10,000 µS/cm) in the late summer and early fall (Olsen and others, 1997; Phelan and others, 2001). Tidal water levels were measured by a gage that has been operating on the West Branch Canal Creek at Hanlon Road since 1987 (fig. 2). Graphs of 15-minute tidal water-level data for October 1997 through September 1999 are presented in Appendix A. Extremes in tidal amplitude are typically associated with storm events or strong winds pushing surface water northward up the Chesapeake Bay and the Gunpowder River or southward out of the Gunpowder River and the Chesapeake Bay. Under these conditions, water levels in West Branch Canal Creek do not necessarily coincide with predicted lunar tide levels. An example of wind effects on tidal water levels can be seen in data collected during two Nor'easters that affected the Chesapeake Bay area during January 27–29 and February 3–6, 1998 (Appendix A). Localized winds and freezing conditions can also cause deviations from the predicted lunar tide levels. Tidal fluctuations in the wetland can influence local ground-water heads, resulting in small, cyclical fluctuations in the water levels measured in some of the piezometers in the wetland study area (Lorah and others, 1997; p. 30, 36). The long-term effects of tidal fluctuations on the net ground-water velocity are thought to be negligible; however, these fluctuations would likely increase the effects of dispersion on dissolved substances in the wetland sediments. Due to the overall upward ground-water flux and periodic tidal inundation, the surficial sediments in the wetland study area generally remain saturated all of the time.

Acknowledgments

The authors thank the following people for their contributions to the ground-water tracer test at West Branch Canal Creek. John Wrobel of the U.S. Army Environmental Conservation and Restoration Division, APG, and Allison O'Brien, contractor for the U.S. Army Environmental Conservation and Restoration Division, provided project guidance and logistical support. Peter Pritchard and his crew from the U.S. Army Aberdeen Test Center are thanked for their ongoing efforts in maintaining the floating walkways and bridge within the wetland study area. Alan Rosencrance, Henry Gardner, and Thomas Shedd of the U.S. Army Center for Environmental Research, Fort Detrick, Maryland, are thanked for providing the on-site laboratory trailer and technical support associated with its operation.

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Design of the Ground-Water Tracer Test

Measuring ground-water velocity in a vertical flow environment is difficult, and the particularly low velocity expected in the wetland sediments in the study area at West Branch Canal Creek necessitated that the tracer test be conducted on a very small scale, requiring the development of several new methods. Factors considered in the design of the ground-water tracer test included selection of an appropriate tracer-test site; design and installation of the tracer-test array; selection, preparation, and injection of tracers; and sampling and analytical methods.

Selection of the Tracer-Test Site

The tracer test was conducted in the organic-rich peat sediments between piezometer sites WB35 and WB36 on the C–C′ transect in the wetland study area at West Branch Canal Creek (fig. 3). This site was selected based on ground-water flow patterns and head distributions, and the location of the contaminant plume.

The site that was selected for the tracer test had been determined from the previous investigation (Lorah and others, 1997) to be an area of converging ground-water flow (fig. 4), and therefore would likely have above-average ground-water discharge and relatively high ground-water velocity compared to other locations along the sampling transects. Based on head distributions, the average ground-water velocity in the wetland sediments near this site had been previously estimated to be 2.3 ft/yr (feet per year), calculated along a vertical flow line sited near piezometer cluster WB-35, assuming an effective porosity of 0.40 and an average vertical hydraulic conductivity in the wetland sediments of 0.007 ft/d (feet per day) (Lorah and others, 1997). In addition, the contaminant plume was close to the land surface in this area—VOCs had been detected in a shallow piezometer (WB35A, screened 1.5 to 2.0 ft below land surface) and in porous-membrane sampling devices (at depths of approximately 0.5 to 2.0 ft below land surface) installed in this area (Olsen and others, 1997; Spencer and others, 2000).

Selecting a site with a relatively high upward ground-water velocity was necessary to allow the test to be completed within the shortest possible timeframe, and to allow the velocity to be measured in an area in which contaminants are likely to be transported most quickly through the wetland sediments to the surface. In addition, the five shallowest piezometers in cluster WB35 (with screen depths ranging from 1.5 to 18.5 ft. below land surface) were known to be affected by tidal fluctuations (Lorah and others, 1997); therefore, the ground-water system in this location was expected to be influenced by tidally enhanced dispersion processes, which could further accelerate contaminant transport and spreading.

Design and Installation of the Tracer-Test Array

Ground-water tracer tests commonly involve injecting a single tracer or multiple tracers into an injection well, and monitoring the movement of the tracer(s) by collecting ground-water samples from nearby wells. Multi-level sampling devices or piezometers can be used instead of wells. Ideally, any apparatus used to monitor tracer movement should not itself significantly influence the natural hydraulic gradients or the formation properties that determine the tracer movement. For the small-scale tracer test conducted at West Branch Canal Creek, small-scale injection and monitoring apparatus were needed. Based on lessons learned from a prior unsuccessful tracer test that relied on multi-level sampling devices made of bundled strands of flexible tubing, the injection and monitoring apparatus used for this study featured single strands of rigid stainless-steel tubing. An injection piezometer and 96 monitoring piezometers were constructed of ¼-in.-diameter stainless-steel tubing fitted with internal piezometer screens designed to protect the piezometer openings from clogging with sediment (fig. 5).

The stainless-steel tubing was cut into lengths equal to the desired depth below land surface plus an additional 4.0–4.5 ft to extend above land surface to prevent tidal flooding of the piezometers, and to accommodate water levels above land surface that are possible under flowing artesian conditions. Prior to installation, the tubing was decontaminated by flushing the inside and outside several times with a mixture of warm water and Alquinox detergent, scrubbing the outside with methanol-soaked sterile cotton gauze, rinsing inside and out with methanol, and then rinsing inside and out three times with deionized water. The piezometer screens were decontaminated using the same sequence of solutions.

The 3-in.-long piezometer screens were constructed of 100-mesh (150-micron) stainless-steel wire mesh formed into a cylinder held open at one end by a ¼-in.-diameter brass collar and tapering to a flattened point at the other end (fig. 5). The piezometer screens were attached to the stainless-steel tubes by inserting the pointed end of the screen upward into the end of the tube until the entire wire screen was inside the tube. The brass collar of the screen was fitted flush with the end of the stainless-steel tube. If insertion of the screen was difficult, the end of the tubing was either reamed with a ¼-in. drill bit to slightly widen the opening, or the wire mesh of the screen was twisted slightly to compress it to fit inside the opening of the tube.

A two-tiered 3-ft by 3-ft plywood template drilled with ¼-in. holes was used to guide the spatial placement of the piezometers and to provide lateral support to the sections of the piezometers sticking above land surface. Prior to piezometer installation, the plywood template was painted with water-based latex paint to resist weathering, and was labeled with permanent marker with the radial coordinates for which the piezometers were named to facilitate in piezometer identification during sampling (fig. 6). The piezometers were then installed manually through the holes in the plywood template by pushing the screen end of the tube into the marsh sediments to the desired depth, while injecting a few milliliters of deionized organic-free water into the top of the piezometers to prevent the screen from clogging. This installation method had been tested elsewhere in the wetland and was found to be more effective at preventing screen clogging than inserting the piezometers with no water injection. Immediately following insertion, each piezometer was promptly purged of a few milliliters of water to remove the deionized water and to verify that the screen was sufficiently free of clogs. After installation, the piezometers were capped with vented ¼-in.-diameter slip caps (figs. 5 and 6).

The network of ¼-in.-diameter inverted-screen piezometers was installed in a spatial array that featured two concentric rings, with diameters of approximately 14 and 28 in., with discrete sampling points located at depths ranging from

0.5–5.0 ft below land surface. The injection piezometer was installed at the center of the array, at a depth of 4.0 ft below land surface, and 96 additional piezometers were installed above and around the injection piezometer to allow monitoring of the tracer movement (fig. 7). The concentric circle pattern was used so that multiple piezometers at each depth would be the same distance from the injection point, allowing comparisons of tracer concentrations and movement over time to be made among piezometers that were at equal distances from the injection point, but in different directions. A few piezometers were installed at 0.25 and 2.0 in. from the center axis because the ground-water flow direction in the wetland was thought to be mainly upward. The piezometers generally were installed about a month before water samples were collected to allow the wetland sediments to re-stabilize around the tubing. One piezometer (G18-180) was later installed 18 in. from the center of the circle because initial fluorescein data indicated that the tracer could be moving faster towards this location. Additional piezometers, including one that was later installed 24 in. from the center of the circle (D24-045) and four that were later installed below the injection point at 54 in. and 60 in. below land surface (I06-285, I07-112, J06-000, and J07-187), were not sampled until 250 days or more after tracer injection.

Tracer-test piezometer sites were named on the basis of their relative positions, using radial coordinates. The first character of each piezometer site name is a letter that corresponds to the depth of the piezometer below land surface, in 6-in. increments, so that “A” designates piezometers with intakes that are 6 in. below land surface, “B” designates piezometers with intakes that are 12 in. below land surface, and so on. The second two characters of each name are numbers that indicate the radius of the circle on which each piezometer is located, in inches from the center axis—for example, D07-000 is a piezometer with an intake positioned 24 in. below land surface, 7 in. from the center of the tracer array. The last three characters of the name designate the position of the piezometer on the circle, in degrees (°), measured from a reference of 0°, which was designated as a northwesterly direction pointing directly towards the creek, 52° counterclockwise from magnetic north. For example, D07-180 is 24 in. below land surface, 7 in. from the center of the tracer array, at the point on the circle that is farthest away (180°) from the creek, 138° clockwise from magnetic north. Radial coordinates, rectilinear coordinates, and distances from the tracer injection point were determined for each piezometer site and are presented in Appendix B1.

Selection, Preparation, and Injection of Tracers

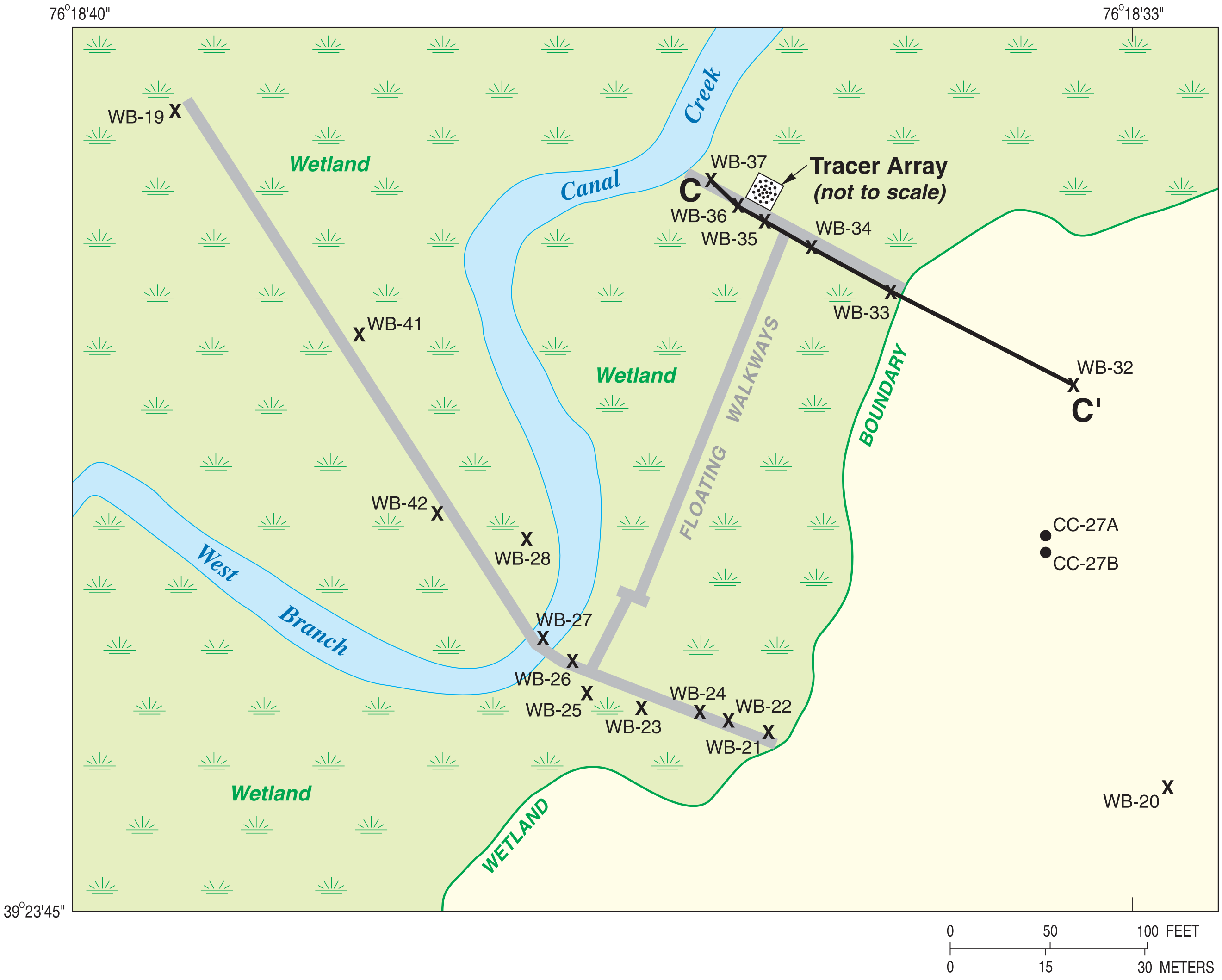
The three tracers used in this study were fluorescein dye, bromide ion, and sulfur hexafluoride. Fluorescein dye, a reactive tracer, was injected on July 17, 1998, to test the hydrologic integrity of the tracer array prior to the injection of the conservative tracers (bromide ion and sulfur hexafluoride). A solution of bromide ion saturated with sulfur hexafluoride was injected 49 days later, on September 4, 1998, and was monitored through September 14, 1999.

Fluorescein Dye Sodium fluorescein is a reactive dye tracer commonly used to trace surface-water and ground-water movement (Kasnavia and others, 1999; Mull and others, 1988; Smart and Laidlaw, 1977). Fluorescein dye is essentially nontoxic (acute oral $LD_{50,\mathrm{rat}}$ = 6.72 grams per kilogram; Smart, 1984) and may be easily and inexpensively detected at concentrations in the microgram per liter (µg/L) range using a fluorometer (Sabatini and Austin, 1991). Although fluorescein dye is sometimes considered a conservative tracer for tracing surface-water movement, it undergoes significant sorption on mineral surfaces (Kasnavia and others, 1999), and would be expected to demonstrate considerable sorption in sediments that are rich in organic matter (Sabatini and Austin, 1991), such as the wetland sediments at West Branch Canal Creek. Fluorescein dye also demonstrates decreased fluorescence in waters with pH values less than 5 (Sabatini and Austin, 1991; Mull and others, 1988; Wilson, 1968), which may be pertinent to ground water at West Branch Canal Creek, since pH values less than 5 have been observed in shallow piezometers near the tracer-test site (Olsen and others, 1997; Spencer and others, 2000).

In a column experiment to test the feasibility of using fluorescein dye as a ground-water tracer at West Branch Canal Creek, 25 mL (milliliters) of fluorescein dye, as a 1-percent solution (weight/weight), were placed at the top of a 12-in.-long column of wetland sediments contained in a 2.5-in.-diameter plastic sleeve. The column apparatus was covered with aluminum foil to prevent exposure to light, which can cause chemical degradation of the dye to non-fluorescing products. The dye was forced through the sediments in the column by additions of 50 to 150 mL of deionized water every 2 to 3 days for 8 weeks. The eluent from the column was collected and measured every few days for volume and concentration of fluorescein dye. The pH of the column eluent was measured at the beginning and end of the experiment and increased from 4.8 to 6.7, likely because much of the ambient ground water in the sediment column had been replaced by deionized water. The peak concentration of fluorescein dye occurred approximately 4 weeks after the start of the experiment. Concentrations gradually dropped to near the reporting limit by 6 weeks. After 8 weeks, a cumulative total of less than 5 percent of the initial mass of fluorescein dye had been recovered in the column eluent.

The low recovery observed in the column experiment confirmed that fluorescein would not be an appropriate tracer to quantitatively measure ground-water velocity. Fluorescein, however, was selected as a *qualitative* tracer, to evaluate the hydrologic integrity of the tracer array, and to verify that the vertically oriented piezometers would not cause artificial short-circuiting of the ground-water flow. If fluorescein was detected in the shallow depth of the tracer array shortly after injection, the tracer test could be aborted prior to injecting the conservative tracers.

On July 17, 1998, 25 mL of a 5-percent solution of fluorescein dye in deionized water (50,000,000 µg of sodium fluorescein per liter of solution) were injected into the tracer



EXPLANATION

WB-20 X 3/4-INCH PIEZOMETER SITE AND IDENTIFICATION NUMBER

CC-27A ● 4-INCH WELL FROM PREVIOUS STUDY AND IDENTIFICATION NUMBER

C—C' TRANSECT

Figure 3. Location of the ground-water tracer-test site and the C-C' transect within the wetland study area along West Branch Canal Creek, Aberdeen Proving Ground, Maryland *(modified from Lorah and others, 1997, p. 8)*.

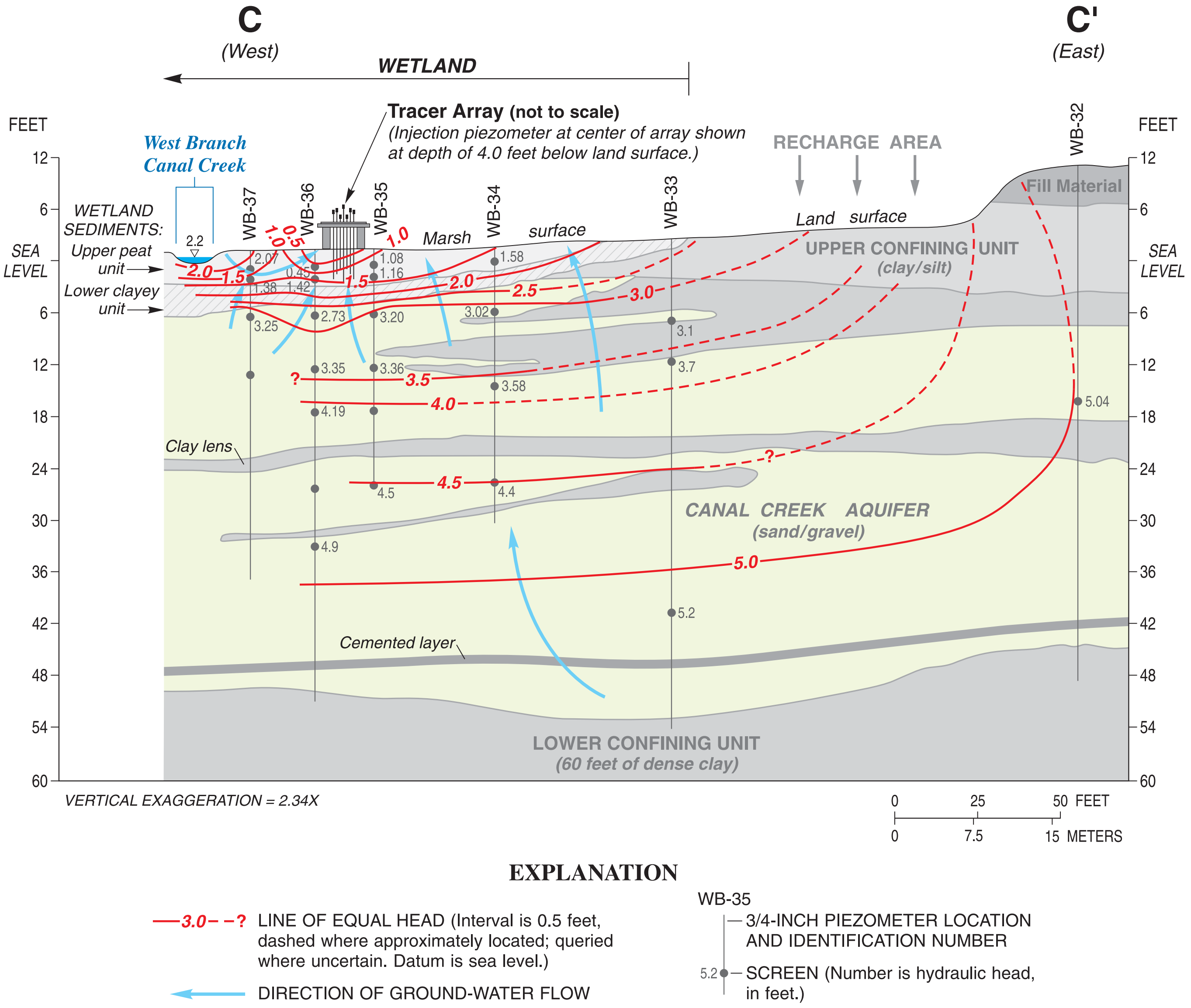


Figure 4. Section C-C' showing head distributions and ground-water-flow directions at high tide, May 2, 1996, and the location of the ground-water tracer-test site, West Branch Canal Creek, Aberdeen Proving Ground, Maryland *(modified from Lorah and others, 1997, p. 35). (Refer to figure 3 for location of transect.)*

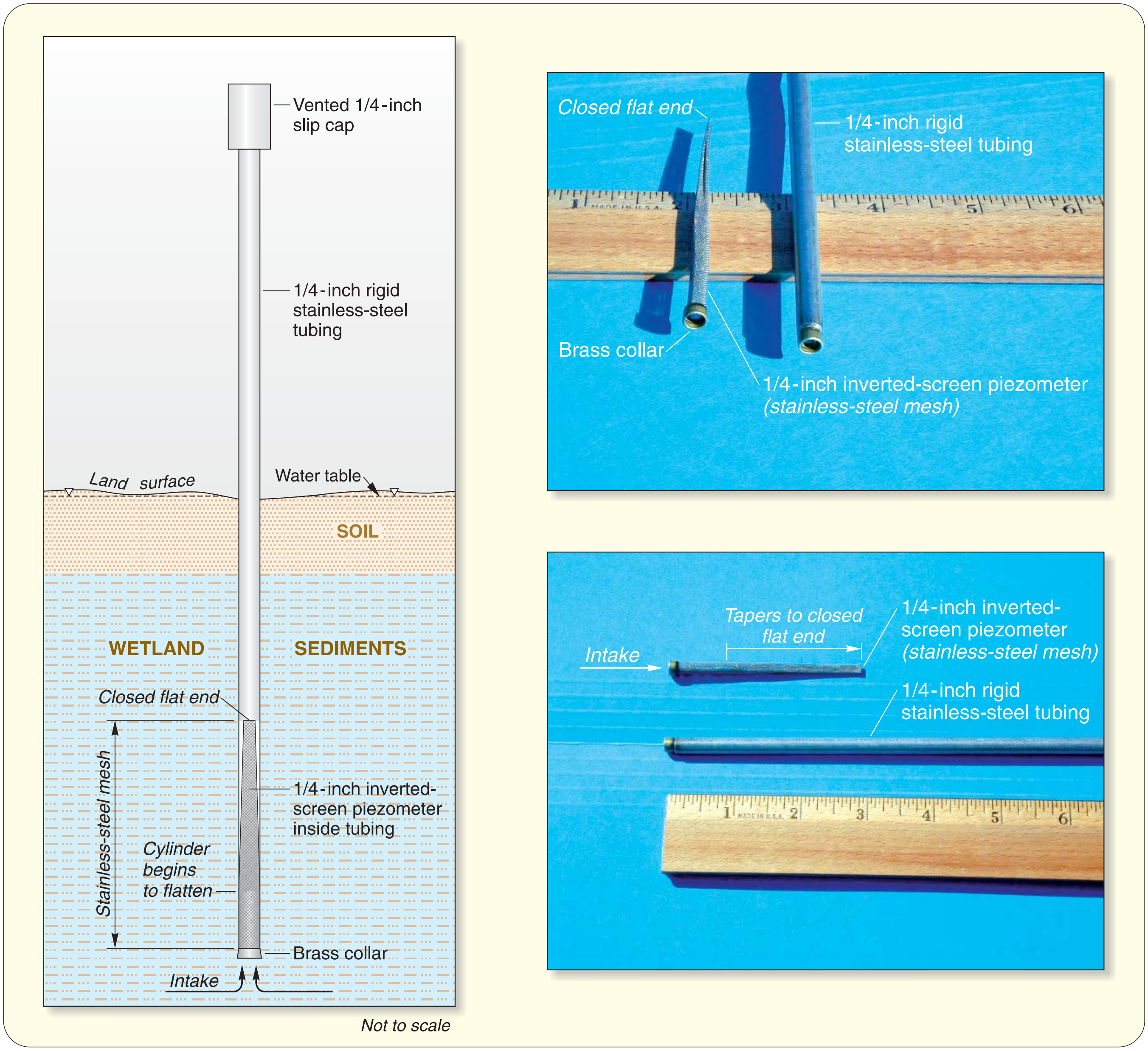


Figure 5. Design features of the 1/4-inch inverted-screen piezometers. *(Photographs by Daniel J. Phelan, U.S. Geological Survey)*

(A)
Side View

(B)
Top View

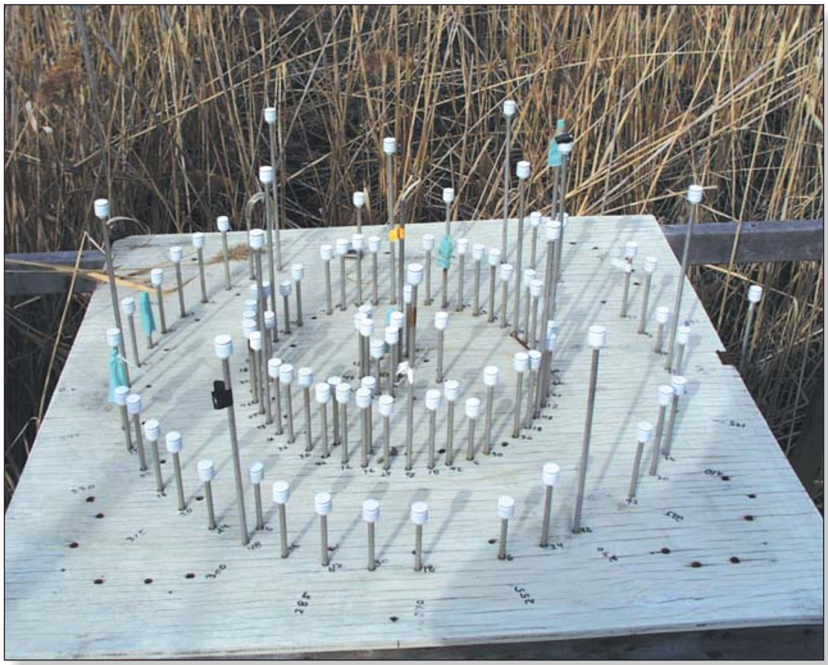


Figure 6. Ground-water tracer array on the C-C' transect within the wetland study area, West Branch Canal Creek, Aberdeen Proving Ground, Maryland, (A) side view, (B) top view.
(Photographs by Tracey Spencer, U.S. Geological Survey)

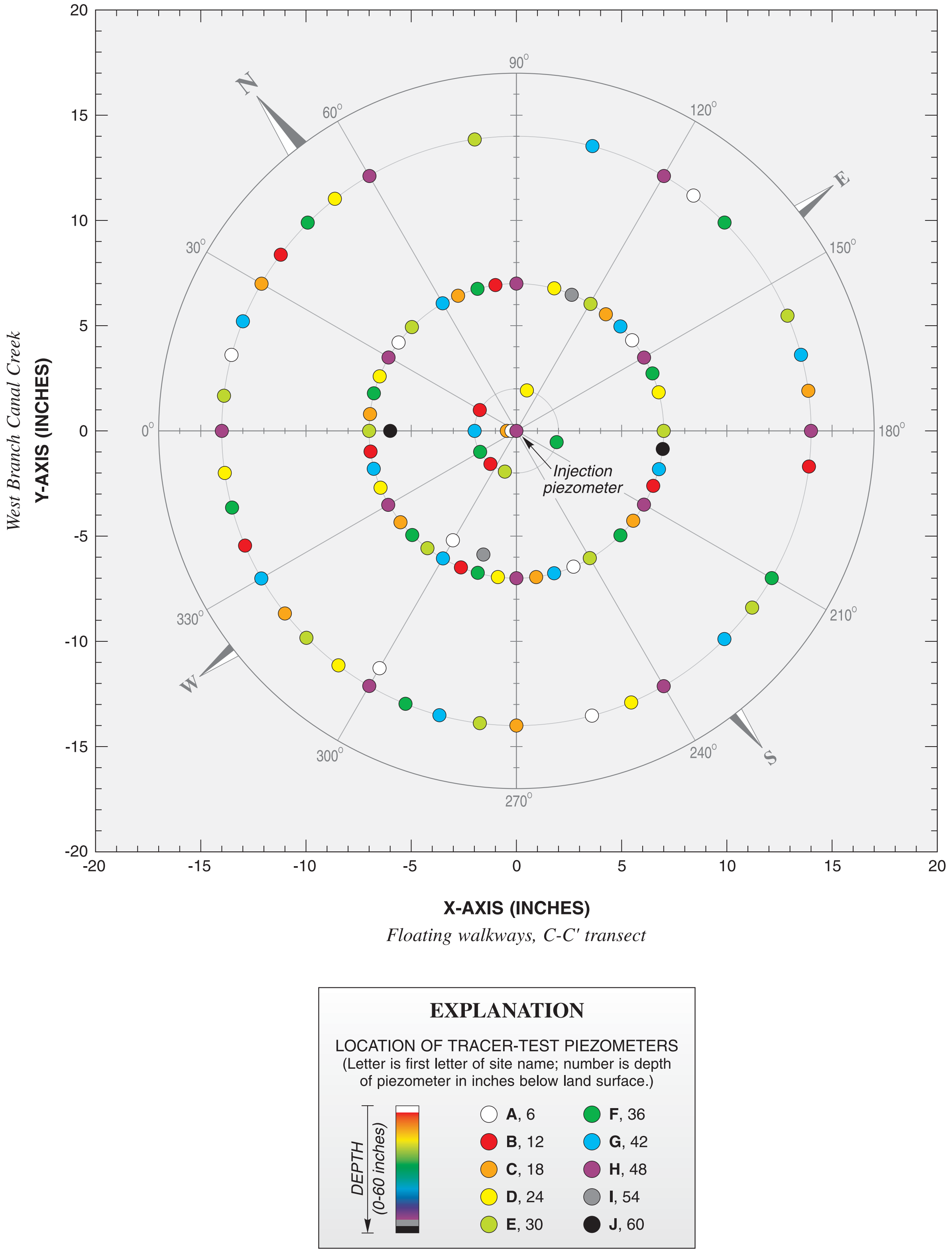


Figure 7a. Plan view of relative locations of the tracer-test piezometers in radial and rectilinear coordinates, and depths below land surface. *(G18-180 and D24-045 are not shown.)*

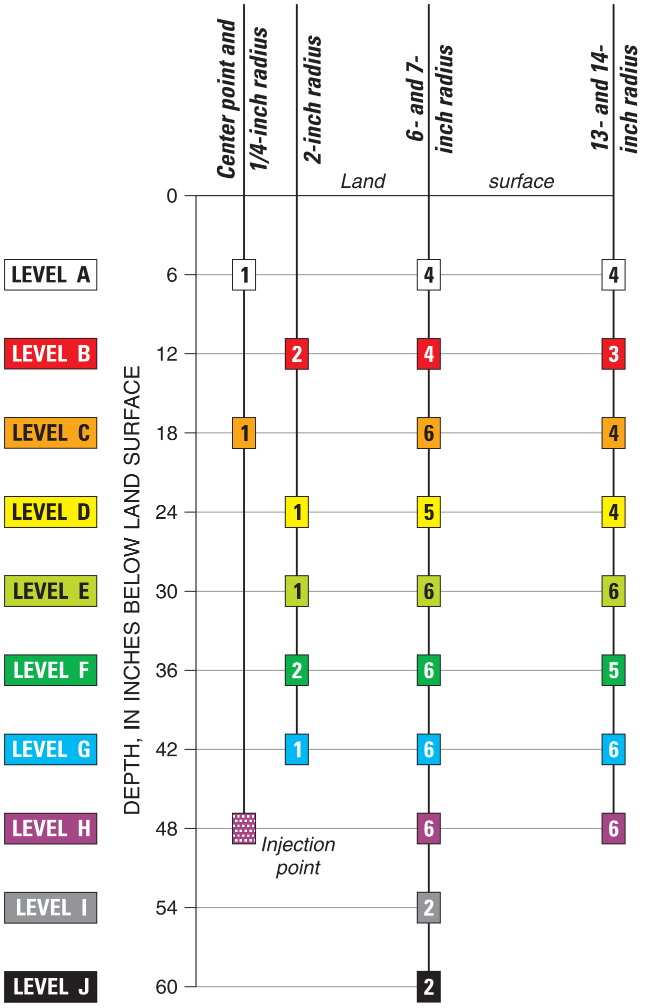


Figure 7b. Section view of relative depths below land surface of the tracer-test piezometers. *(Number of sampling points at each depth and radius is shown inside piezometer boxes.)*

array at piezometer H00-000. The concentration and volume of the fluorescein dye solution were selected based on the need to have a sufficient mass of fluorescein dye to overcome the effects of sorption and potential low pH in the ground water, and to minimize the volume so that injection of the dye would not cause a large displacement of ground water and thereby disrupt the natural hydraulic gradients in the ground-water-flow system. The resulting fluorescein dye solution had a density of 1.035 g/mL (grams per milliliter) and was dark, blood red, and nearly opaque.

Prior to the fluorescein dye injection, 45 mL of ground water were removed from the injection piezometer by using a 60-mL-capacity plastic syringe assembled with a 3-way polycarbonate valve attached to $^{1}/_{8}$-in.-diameter Teflon tubing that was lowered to the top of the screen. Teflon tape had been wound tightly around the outside end of the Teflon tubing to form a seal against the inside of the piezometer near the top of the piezometer screen. The 3-way valve was used to maintain vacuum on the Teflon injection tubing while the plastic syringe containing the 45 mL of ground water was disconnected from the valve assembly. Ten mL of the ground water were used to analyze for background fluorescence, and 18 mL were used to analyze for background bromide. Next, a 25-mL-capacity graduated glass syringe was attached to the 3-way valve and used to inject the fluorescein dye into the marsh sediments via the Teflon injection tubing. The 3-way valve was then closed to maintain pressure on the Teflon injection tubing, while 1 mL of the previously removed ground water was used to rinse the dye residue from the 25-mL glass injection syringe. The 1 mL of rinsate, which was bright yellow, was then injected to ensure that the entire volume of dye was used. An additional 7 mL of previously removed ground water were subsequently injected in order to completely clear the dye from the Teflon injection tubing and push it into the surrounding formation. (This volume was approximately equal to the interior volume of the Teflon injection tubing and piezometer screen.) The 3-way valve was then closed and left attached to the Teflon injection tubing inside the injection piezometer to maintain neutral pressure (neither pushing nor pulling) on the water column until additional tracers could be added. Confirmation that the dye had completely cleared the injection tubing and piezometer screen and had not mixed with the 7 mL of ground water that had been left in the injection tubing was made 49 days later during the injection of the bromide ion and sulfur hexafluoride, when the standing water in the injection tubing was observed to have no yellow color.

Bromide and Sulfur Hexafluoride Bromide ion, typically from sodium or potassium bromide salts, is an inorganic conservative tracer that is not harmful to the environment and is widely used in ground-water studies (Prych, 1999; Springer, 1998; Wilson and Mackay, 1993). Sulfur hexafluoride (SF_6) is an inert gas that is detectable over a wide range of concentrations (Busenberg and Plummer, 2000), and it has recently gained acceptance as a conservative tracer in ground water (Busenberg and Plummer, 1997; Wilson and Mackay, 1993; Wilson and Mackay, 1996; Smart and Biggin, 1989). The movement of bromide in ground water would be expected to be controlled by advection and dispersion processes, whereas the movement of sulfur hexafluoride could also be affected by volatilization.

On September 4, 1998, 139 mL of 100,000-mg/L bromide solution saturated with sulfur hexafluoride gas (resulting in a concentration of 23.3 mg/L sulfur hexafluoride) were injected into the tracer array at piezometer H00-000. The bromide/SF_6 solution was injected 49 days after the fluorescein dye to allow sufficient time to determine whether the tracer array or its installation had created any artificial vertical conduits in the wetland sediments, based on the fluorescein movement.

The bromide/SF_6 solution was made by preparing sodium bromide solution and then saturating it with sulfur hexafluoride gas. A 250-mL quantity of 100,000-mg/L bromide-ion solution was made by dissolving 32.1930 g (grams) of sodium bromide into deionized organic-free water in a volumetric flask. The density of this solution was calculated to be 1.096 g/mL. Next, a 150-mL aliquot of the bromide solution was transferred to a pre-weighed Tedlar bag with a valve opening, which was then reweighed to confirm the volume of bromide solution added. Approximately 100 mL of sulfur-hexafluoride gas were introduced to the bromide solution through the valve of the Tedlar bag, mixed by shaking the bag gently for several minutes, allowed to equilibrate for 10 to 15 minutes, and then expelled through the valve. This process was repeated three times using fresh sulfur hexafluoride gas to ensure complete saturation of the bromide solution. Approximately 50 mL of gas-phase sulfur hexafluoride were retained in the Tedlar bag in contact with the bromide/SF_6 solution, to maintain the concentration of sulfur hexafluoride in the solution at saturation levels during tracer injection.

Prior to the injection of the bromide/SF_6 solution, the $^1/_8$-in.-diameter Teflon tubing used for the fluorescein injection was removed from the injection piezometer (H00-000) and quickly replaced with ¼-in. diameter Teflon tubing attached directly to the top of the piezometer tube and secured with a 3-way valve. Attaching the tubing directly to the top of the injection piezometer (instead of placing it inside the piezometer) allowed for a more secure seal, which was needed to prevent the potential escape of sulfur hexafluoride gas from the piezometer after the injection of the bromide/SF_6 solution. Seventy-five mL of ground water (slightly more than the 72.4 mL calculated volume of standing water in the piezometer) were then removed from H00-000 through the Teflon tubing using the 3-way valve and two 60-mL-capacity syringes. This water was inspected for color associated with the fluorescein dye and was observed to be clear except for the last 2 mL, which were pale yellow and were therefore returned to the injection piezometer. This inspection confirmed that the procedure used for injecting the fluorescein dye was successful and that none of the concentrated dye had traveled back upwards into the injection piezometer during the first 49 days after injection.

The Tedlar bag filled with bromide/SF_6 solution was carefully suspended above the piezometer to minimize external pressure on the bag. A pinch clamp was placed on the Teflon injection tubing to keep it closed while the tubing was disconnected from the 3-way valve and was then connected to the valve of the Tedlar bag. The valve of the Tedlar bag was then opened and the clamp removed so that the bromide/SF_6 solution could flow freely into the piezometer. The vacuum that had been created by the earlier removal of ground water from the injection piezometer caused the wetland sediments to suck in the first two-thirds of the tracer solution, and it was necessary to adjust the valve on the bag to regulate the initial flow of tracer solution. The remaining one-third of the solution was introduced by gravity feed from the suspended bag. The Tedlar bag was then detached and replaced by the 3-way valve (with interim use of the pinch clamp), and the 73 mL of previously removed ground water were injected to push the tracer solution from the injection piezometer and screen into the surrounding sediments. Finally, the 3-way valve was closed to maintain neutral pressure on the water column during the tracer test.

After the injection of the bromide/SF_6 solution, the Tedlar bag was weighed, and the volume of tracer solution injected was determined to be 139 mL. The temperature of the solution during the 4-hour injection period was assumed to be the same as the temperature immediately outside the bag, which had been periodically measured and averaged 25 °C (degrees Celsius), as shown below:

Bromide/sulfur hexafluoride solution temperatures during tracer injection on September 4, 1998

Time	Solution temperature (degrees Celsius)
9:00 AM	21.9
10:00 AM	24.0
11:00 AM	26.2
12:00 noon	27.9
Average	**25.0**

The concentration of hexafluoride in the tracer solution was calculated to be 23.3 mg/L (23,300,000 nanograms per liter), based on a sulfur hexafluoride solubility of 35.5 mg/L in pure water at 25 °C (Wilhelm and others, 1977), and a salting-out coefficient of 0.189 for sulfur hexafluoride in sodium bromide solutions, which was determined by assuming proportionality with salting-out coefficients for sulfur hexafluoride in sodium chloride, potassium chloride, and potassium bromide solutions presented in Morrison and Johnstone (1955).

Sampling and Analytical Methods

Ground-water samples were periodically collected from the tracer array and analyzed for fluorescein, bromide, and sulfur hexafluoride to monitor the movement of the tracers. Four major sampling episodes, in which all or nearly all of the piezometers were sampled, were conducted at 103–104, 167–174, 243–250, and 363–375 days after injection of the bromide/SF_6 solution. Prior to sampling, the piezometers in the tracer array were purged and allowed to recover. Recovery times were typically 5 to 30 minutes. Purging was limited to one piezometer volume (usually less than 20 mL, depending on the depth of the water column) to minimize the volume of ground water removed from the piezometers, thereby reducing the potential to create artificial hydraulic gradients that could influence the natural movement of the tracers. The piezometers were purged and sampled using $^1/_8$-in.-diameter Teflon tubing inserted to a depth just above the screen. The Teflon tubing was attached to a 3-way valve connected to a graduated 10-mL glass syringe that allowed ground water to be withdrawn, measured, and expelled, without aerating the sample water or the water left in the piezometer. All volumes of water withdrawn during purging and sampling were carefully recorded. Following sample collection, the tubing, syringe, and 3-way valve were decontaminated by washing three times with a mixture of deionized water and phosphate-free, biodegradable detergent, and rinsing three times with deionized water before use in the next piezometer.

Ground-water samples (4–5 mL) collected for analysis of fluorescein and bromide by selective-ion electrode were put in test tubes that doubled as cuvettes for the fluorometer, and were capped and stored in the dark until analysis. Additional samples (16 mL) collected for bromide analysis by colorimetric method were collected in 30-mL brown polyethylene bottles and promptly shipped to the USGS National Water Quality Laboratory (NWQL) in Lakewood, Colorado, for analysis. Samples for the analysis of sulfur hexafluoride were collected by injecting 2 mL of the ground water from the glass syringe through a stainless-steel needle into sealed 25-mL serum vials that had been purged with ultra-high purity nitrogen gas and evacuated of 2 mL of gas prior to sample collection. During the tracer test, samples were periodically collected from a subset of the piezometers for analysis for VOCs and methane, to evaluate their distribution over the depth range of the tracer test. VOC samples were collected with no headspace in 8-mL glass vials with Teflon septa and refrigerated until analysis. Methane samples (2 mL) were collected in sealed 25-mL serum vials in the same manner as that of sulfur hexafluoride, except that mercuric chloride was added to the vials prior to sample collection to prevent microbial activity from affecting the methane concentrations prior to analysis.

Analytical techniques were modified to minimize the volume of sample required. Each fluorescein analysis required only 4 to 5 mL of sample water. The sample from the fluorescein analysis was often reused for analysis of bromide by ion-selective electrode. Bromide analysis by colorimetric method required 16 mL of sample, which were diluted 1:2 with deionized water to provide sufficient volume for the analysis. Headspace analysis for sulfur hexafluoride required only 2 mL of sample. Analyses for VOCs and methane required only 8 mL and 2 mL for each sample, respectively.

Fluorescein-Dye Analysis Fluorescein dye analyses were performed at an on-site laboratory by using a Turner Model 10 filter fluorometer configured for fluorescein analyses. The methods of analysis are described in detail in Wilson (1968) and in manuals provided by the manufacturer. The fluorometer was zeroed with deionized organic-free blank water and calibrated with standards in concentrations of 5.0, 25, 100, 200, 500, and 1,000 µg/L of sodium fluorescein. The calibration curve was linear from 5.0 to 500 µg/L, but began to curve downwards at 1,000 µg/L due to concentration quenching, which is common at high concentrations (Wilson, 1968). The average relative response factor used to quantify the fluorescein concentrations in the environmental samples was therefore calculated using only the five lowest standards. A least-squares regression that included the 1,000 µg/L standard was used, however, as an estimation tool for samples with concentrations exceeding 500 µg/L to aid in determining the amount of dilution needed to reduce the concentrations in those samples to fall within the linear calibration range. Background fluorescence of the ambient ground water was determined by analyzing samples collected prior to fluorescein injection, and was generally below 5.0 µg/L.

Bromide Analysis Bromide samples were either analyzed by ion-selective electrode at the on-site laboratory or sent to the NWQL for analysis by colorimetric method. Two different methods were used for the bromide analyses because each method was thought to have advantages and disadvantages that precluded complete reliance on either method. Ion-selective electrodes have been considered to be unreliable; however, the colorimetric method required much more water for analysis (16 mL compared to 4 mL for the ion-selective electrode) and had higher costs and a longer turn-around time to get the data compared to the ion-selective electrode. Therefore, some of the samples were collected for analysis by ion-selective electrode to conserve water and minimize analytical costs, some of the samples were collected for analysis by colorimetric method (to the extent that sufficient water was thought to be available), and some of the samples were collected as split samples to evaluate whether the ion-selective electrode data were comparable in quality to the colorimetric data.

The bromide analyses by ion-selective electrode were typically performed on the same 4–5 mL of sample water that were used for the fluorescein analysis, following the general method described in EPA Method 9211 (USEPA, 1996). Each day of use, the bromide electrode was calibrated using a 2-point calibration with 50 and 100 mg/L standards. This calibration was then verified using additional standards in concentrations of 1.0, 5.0, 200, and sometimes 500 mg/L, depending on the concentrations measured in the environmental samples. A tiny amount of ionic-strength-adjustor solution was added to each sample prior to analysis as a buffer to maintain constant ionic strength; the amount added depended on the sample volume, and the slight dilution effect of the added solution was accounted for in the reported concentrations by application of a multiplier. Samples with high (greater than 500 mg/L) bromide concentrations generally were diluted with deionized water to a concentration between 50–100 mg/L, and reanalyzed so that the results would fall within the linear calibration range; results were then multiplied by the dilution factor before reporting.

The bromide analyses by colorimetric method were performed following methods described in Fishman and others (1994). The minimum sample volume required for the analysis was approximately 30 mL. To minimize the volume of water withdrawn from the tracer array, only 16–18 mL of sample were typically collected, which were then diluted at the NWQL using volumetric glassware to make up the necessary volume (usually 1:1 with deionized water). Additional sample dilution was sometimes necessary to reduce the bromide concentrations to below 20 mg/L, which is the upper reporting limit (RL) for the colorimetric method (Fishman and others, 1994). Because the colorimetric method was markedly more sensitive than the ion-selective electrode (lower RL of 0.01 mg/L compared to 1.0 mg/L for the electrode), the dilution of samples for colorimetric analysis did not affect the comparability of the two methods.

Sulfur Hexafluoride Analysis Sulfur hexafluoride samples were analyzed at the USGS Reston Chlorofluorocarbon Laboratory by the West Branch Canal Creek project staff, under the guidance of Eurybiades Busenberg, using a gas chromatograph (GC) with an electron-capture detector. The method of analysis is described in Busenberg and Plummer (2000). To accommodate the small-volume requirements of the tracer test, only 2 mL of water were collected for each sample and injected into prepared 25-mL serum vials. For each analysis, a 1-mL aliquot of headspace was withdrawn from the serum vial and diluted by injection into a 292.8-mL glass mixing vessel containing ultra-high purity nitrogen gas. Thirty to 60 mL of the sample/nitrogen mixture were then withdrawn from the mixing vessel and injected into a fixed-volume sample loop that was maintained at atmospheric pressure. If a very low concentration was expected, the mixing vessel was not used, and the 1-mL aliquot of headspace was introduced directly into a gas-tight syringe containing a measured volume (30–60 mL) of nitrogen gas, and the resulting mixture injected into the sample loop. For each analysis, one of two sample loops was generally used, with loop volumes of either 0.1130 mL or 0.3015 mL. The 30–60 mL of sample/nitrogen mixture used for each sample was of sufficient volume to flush the selected sample loop of any residual gases from the previous analysis and fill it for the next analysis. Once filled, the contents of the sample loop were introduced to the GC column, and the instrument's response was measured as peak area using an integrator. The mixing vessel and syringe were then thoroughly flushed with nitrogen gas before preparing the next sample.

The concentrations of sulfur hexafluoride in the aliquots of headspace were determined using an average relative response factor obtained by averaging the responses of several analyses of 0.100 µg/L sulfur hexafluoride standard measured using the 0.1130- and 0.3015-mL sample loops. The concentrations of sulfur hexafluoride in the ground-water samples were then calculated from the headspace data using the Ideal Gas Law and Henry's Law. Henry's Law constants used in the calculations were derived as described in Wilhelm and others (1977). The formulas and calculations used for the determination of sulfur hexafluoride concentrations in ground-water samples are very complicated; an example calculation for a single analysis is presented in Appendix C. Reporting limits for sulfur hexafluoride ranged from 0.01–0.34 ng/L (nanograms per liter), depending on the dilution factor used, the sample temperature, and the ratio of sample to headspace volume.

Volatile Organic Compound and Methane Analysis VOCs and methane were analyzed at the on-site laboratory at West Branch Canal Creek. Sample volumes for VOCs and methane were 8 mL and 2 mL, respectively. VOCs were analyzed using a purge-and-trap capillary gas chromatograph with a mass-selective detector. Laboratory quality-assurance practices included analyzing at least one calibration standard and one laboratory blank daily (or with each batch of samples) and verifying that each sample met internal quality-control limits, including internal standard and surrogate response criteria. The analytical method is equivalent to EPA Method 524.2, and includes modifications presented in Rose and Schroeder (1995). Additional modifications to the method include the following:

- Dibromofluoromethane was substituted for 1,2-dichloroethane-d4 as the earliest eluting surrogate standard. This compound has a shorter retention time than 1,2-dichloroethane-d4, and thus provides better coverage of early eluting compounds (such as vinyl chloride, *cis*-1,2-dichloroethene, and *trans*-1,2-dichloroethene) that are of central interest to the research supported by these analyses. The use of dibromofluoromethane as an acceptable surrogate for VOCs analyzed by purge and trap gas chromatography/mass spectrometry is documented in EPA Method 8260.

- Sample volumes were 5 mL instead of 25 mL. The volumes of sparge tubes, gas-tight syringes, luer-lock syringes, volumetric flasks, and other glassware were adjusted accordingly. Potential reduction of analyte response due to the smaller volume was offset by the improved purge efficiency associated with purging a smaller volume of sample.

- A lower RL of 0.5–2.0 µg/L was used for all VOCs of interest, based on the lowest calibration standard that was consistently observed during each period of calibration. Non-detections and detections that were less than the RL are reported as less than (<) the RL value, with no additional qualifiers. Because ground-water samples from the West Branch Canal Creek area can have high concentrations (greater than 1,000 µg/L for some analytes), results should be used for screening purposes only and not for determining regulatory compliance by State or Federal agencies. The lower RL of 0.5 µg/L corresponds to a signal-to-noise ratio of 10 or higher for analytes of interest, and is sufficiently larger (typically by a factor of 10 or more) than the method detection limits that are generally attainable using the same instrument configuration, such as those reported in Connor and others (1998).

- Calibration was performed using 12 to 14 calibration standards with concentrations ranging from 0.1–250.0 µg/L. Calibration curves were constructed for each analyte of interest, using the set of standards that provided the widest concentration range while achieving a relative standard deviation (RSD) of less than or equal to 20 percent. The highest calibration level accepted for each analyte was used as the upper RL for that analyte. Data exceeding the upper RL were reported as greater than (>) the RL value.

Methane was analyzed using a gas chromatograph with a flame-ionization detector, using techniques described in Baedecker and Cozzarelli (1992). Concentrations of methane in the ground-water samples were calculated using Henry's Law, based on the concentrations detected in aliquots of the headspace withdrawn from the sample vials. The instrument calibration was checked daily using standard compressed gas ranging in concentration from 10–10,000 parts per million. The lower RL for aqueous methane concentrations depended upon the volume of the sample, the volume of the sample vial, and the temperature of the sample at the time of analysis, and ranged from 49.7–79.4 µg/L for the samples collected from the tracer array.

Results and Evaluation of the Chemical Analyses

Ground-water samples were collected from the tracer-test piezometers on 50 dates from July 14, 1998 through September 14, 1999, and analyzed for fluorescein dye (644 samples), bromide ion (830 samples), and sulfur hexafluoride (603 samples), including samples collected prior to tracer injection for determining background concentrations. Most of the piezometers were sampled 9 to 12 times throughout the experiment; however, four major sampling episodes in which all (or nearly all) of the piezometers were sampled were conducted at 103–104, 167–174, 243–250, and 363–375 days after injection of the bromide/SF_6 solution. The sequence of sampling dates and water volumes removed each day are shown in figure 8. The cumulative volume of water removed during sampling (after injection of the bromide/SF_6 solution) was 17,448 mL (17.448 L) (fig. 9), which is equivalent to about 9 percent of the volume of water within the tracer array (assuming an effective porosity of 0.40). Results of the fluorescein, bromide, and sulfur hexafluoride analyses, along with water volumes removed, were tabulated for each piezometer, and are presented in Appendix B2. The results are grouped alphabetically by site name and are listed in chronological order for each site.

Fluorescein-Dye, Bromide, and Sulfur Hexafluoride Data

Fluorescein dye was analyzed for 644 ground-water samples (Appendix B2), including 42 replicate samples (6.5 percent). Of these samples, 191 had detections, with concentrations ranging from 5.1–35,800 µg/L, and 453 were below the RL of 5.0 µg/L. Background concentrations measured in fluorescein samples collected from a variety of depths prior to injection of the dye (July 17, 1998) were generally below 5.0 µg/L. Ground-water sampling for fluorescein dye was temporarily suspended between 154–291 days after the injection of the fluorescein dye (from December 18, 1998 through May 4, 1999), because the fluorometer was unavailable during this period; therefore, no fluorescein data were collected during the second major sampling episode.

Bromide was analyzed by ion-selective electrode in the on-site laboratory for 617 ground-water samples (Appendix B2), including 43 replicate samples (7.0 percent). Of these samples, 545 had detections, with concentrations ranging from 1.0–991 mg/L, and 72 were below the RL of 1.0 mg/L. Background concentrations from samples collected from a variety of depths prior to injection of the bromide/SF_6 solution (September 4, 1998) and analyzed by ion-selective electrode, were generally below 2.0 mg/L, with a few exceptions. The highest concentration of bromide in a background sample analyzed by ion-selective electrode was 3.2 mg/L, in a sample collected from A06-300 on August 4, 1998.

Bromide was also analyzed by colorimetric methods at NWQL for 213 ground-water samples (Appendix B2), including 20 replicate samples (9.4 percent). Of these samples, 212 had detections, with concentrations ranging from 0.03–1,090 mg/L, and one sample was below the RL of 0.02 mg/L. The highest concentration of bromide in background samples analyzed by colorimetric methods was 0.34 mg/L, in a sample collected from A14-127 on August 4, 1998.

Sulfur hexafluoride was analyzed for 603 ground-water samples (Appendix B2), including 35 replicate samples (5.8 percent). Of these samples, 556 had detections, with concentrations ranging from 0.03–356,000 ng/L, and 47 were below the RL, which ranged from 0.01–0.34 ng/L. Of the three tracers used, sulfur hexafluoride was detected over the widest range of concentrations, with detections spanning eight orders of magnitude. Background concentrations measured in three sulfur hexafluoride samples collected prior to the injection of the bromide/SF6 solution (September 4, 1998) were 0.03, 0.16, and 1.27 ng/L.

Volatile Organic Compound and Methane Data

VOCs were analyzed for 96 ground-water samples (Appendix B3), including 5 replicate samples, to determine the spatial and temporal distribution of VOCs within the tracer array during the test. Of the 59 VOCs analyzed, only 18 compounds were detected in samples. VOC samples were collected in August and October 1998, and February, May, and September 1999. Fewer VOC samples were collected than the number of samples collected for the tracer compounds because of the need to minimize water withdrawal from the tracer array. The most frequently detected VOCs were *cis*-1,2-dichloroethene, *trans*-1,2-dichloroethene, and vinyl chloride. VOC data were not used for the calculations of ground-water velocity because the initial concentration distribution was unknown, and VOCs are known to participate in degradation and sorption reactions and therefore are not considered to be conservative solutes. The vertical distributions of VOCs in the tracer array were determined by pooling the data for each depth and finding the average concentration of each compound, and are presented

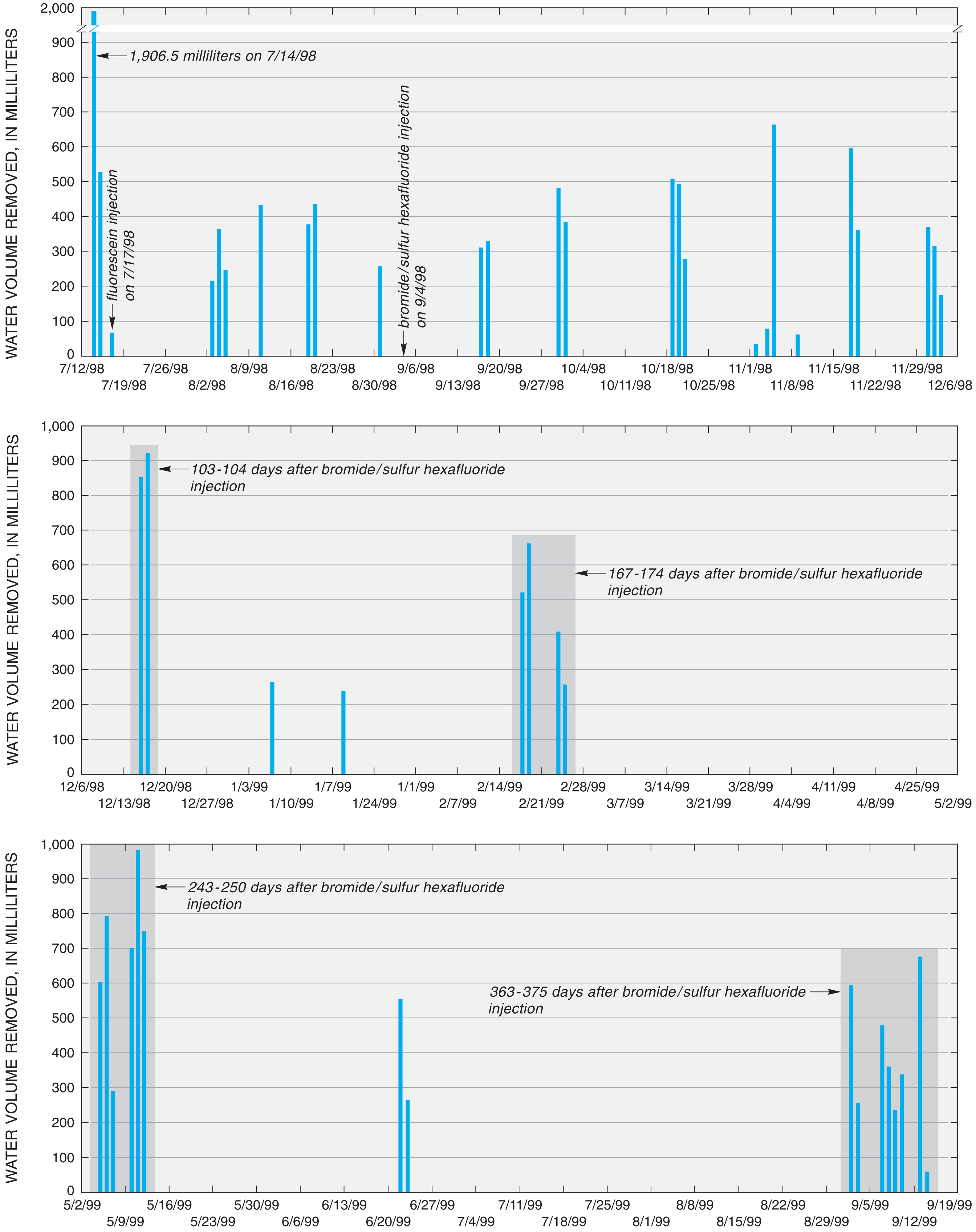


Figure 8. Sampling dates and water volumes removed for the ground-water tracer test.

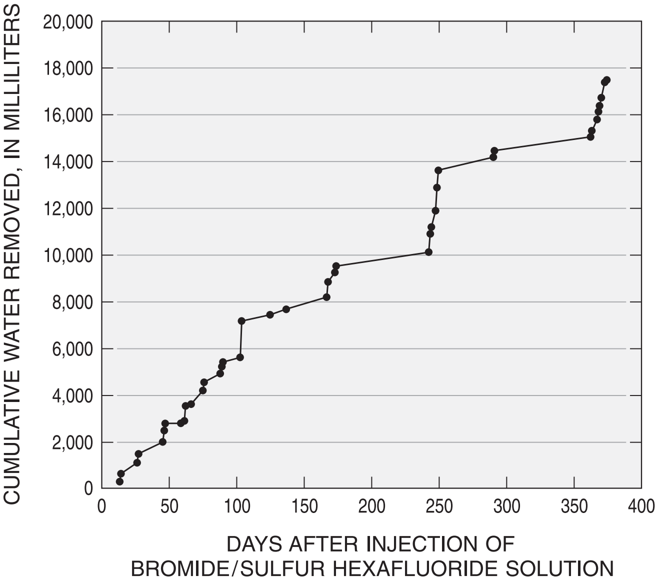


Figure 9. Cumulative water removed during sampling of the ground-water tracer test.

for each VOC-sampling event to illustrate the temporal variability in the concentrations of these compounds (fig. 10). The concentrations and proportions of individual compounds varied systematically with depth, with parent compounds such as 1,1,2,2-tetrachloroethane and trichloroethene predominating at the deeper depths, and daughter compounds such as *cis*- and *trans*-1,2-dichloroethene and vinyl chloride predominating at the shallower depths. In addition, the lowest total concentrations of VOCs were observed in the upper levels of the tracer array. This pattern is consistent with VOC data collected in previous studies from nearby piezometers and porous-membrane sampling devices (Lorah and others, 1997, p 66, fig. 32).

Methane was analyzed for 37 ground-water samples, with all samples collected and analyzed in duplicate (Appendix B4). Thirteen samples were collected in August 1998, and 24 samples were collected in September 1999. Methane samples were collected to determine the vertical extent of methanogenesis within the tracer array during the test. The vertical distribution of methane concentrations is presented in figure 11. Methanogenic conditions were previously shown (Lorah and others, 1997) to support biodegradation of the VOCs detected in the wetland sediments in the West Branch Canal Creek area, and appear to be associated with the transformation to daughter products and reductions in concentrations of the VOCs observed in the upper levels of the tracer array.

Quality Assurance of the Data

Quality-assurance samples were collected to evaluate bias and variability in the data collected for the three tracers and to compare the ion-selective electrode and colorimetric methods used to analyze for bromide. Bias is defined as systematic error that may result from contaminants being introduced into a sample or analytes being lost from a sample during collection, processing, or analysis. Variability is defined as random error in independent measurements of the same quantity, and may result from variations in sampling and analytical procedures. The quality-assurance samples evaluated for the tracer test included blanks, replicates, split samples, and a spiked split sample.

Blanks Laboratory blanks and field blanks were analyzed to evaluate the potential for systematic bias in the data due to contamination from equipment used for sampling and analysis or from the ambient environment. Laboratory blanks were typically analyzed at the start and end of each batch of analyses, with additional laboratory blanks sometimes analyzed in the middle of a batch if the batch had a large number of samples. Concentrations of tracer compounds in laboratory blanks were consistently below detection limits or substantially below the RL; therefore, the laboratory processes, analytical equipment, and deionized organic-free water used for the blanks were eliminated from consideration as sources of measurable bias in the tracer data.

Field blanks collected throughout the tracer test included ***wash blanks***, ***ambient blanks***, and ***air blanks***. Wash blanks were collected by passing deionized organic-free water through the same equipment that was used to collect samples (after the usual equipment-washing procedures had been performed) and were used to evaluate the potential for contaminants to be transferred from one sample to the next by way of the sampling equipment. Ambient blanks were collected by pouring deionized organic-free water directly into the sample vials at the field site and were used to evaluate the potential for contaminants to be transferred to samples from the ambient environment during collection. Air blanks were collected by syringing ambient air near the tracer array into the sample vials and, like the ambient blanks, were used to evaluate the potential for contaminants to be transferred from the ambient environment during sample collection.

Wash Blanks—Thirty-two wash blanks were collected and analyzed for fluorescein dye (Appendix B5). All of these wash blanks had concentrations below the RL of 5.0 µg/L; therefore, sampling procedures were eliminated from consideration as a source of measurable bias in the fluorescein data. Thirty-three wash blanks were collected and analyzed for bromide by ion-selective electrode at the on-site laboratory (Appendix B5). All of these wash blanks had concentrations below the RL of 1.0 mg/L; therefore, sampling procedures were eliminated from consideration as a source of measurable bias for the bromide data obtained by ion-selective electrode.

Seven wash blanks were collected and analyzed for bromide by colorimetric methods at the NWQL (Appendix B5). Bromide was detected in all seven wash blanks, at levels ranging from 0.01 (the RL) to 0.33 mg/L, with a mean of 0.10 mg/L and a standard deviation of 0.11 mg/L. These

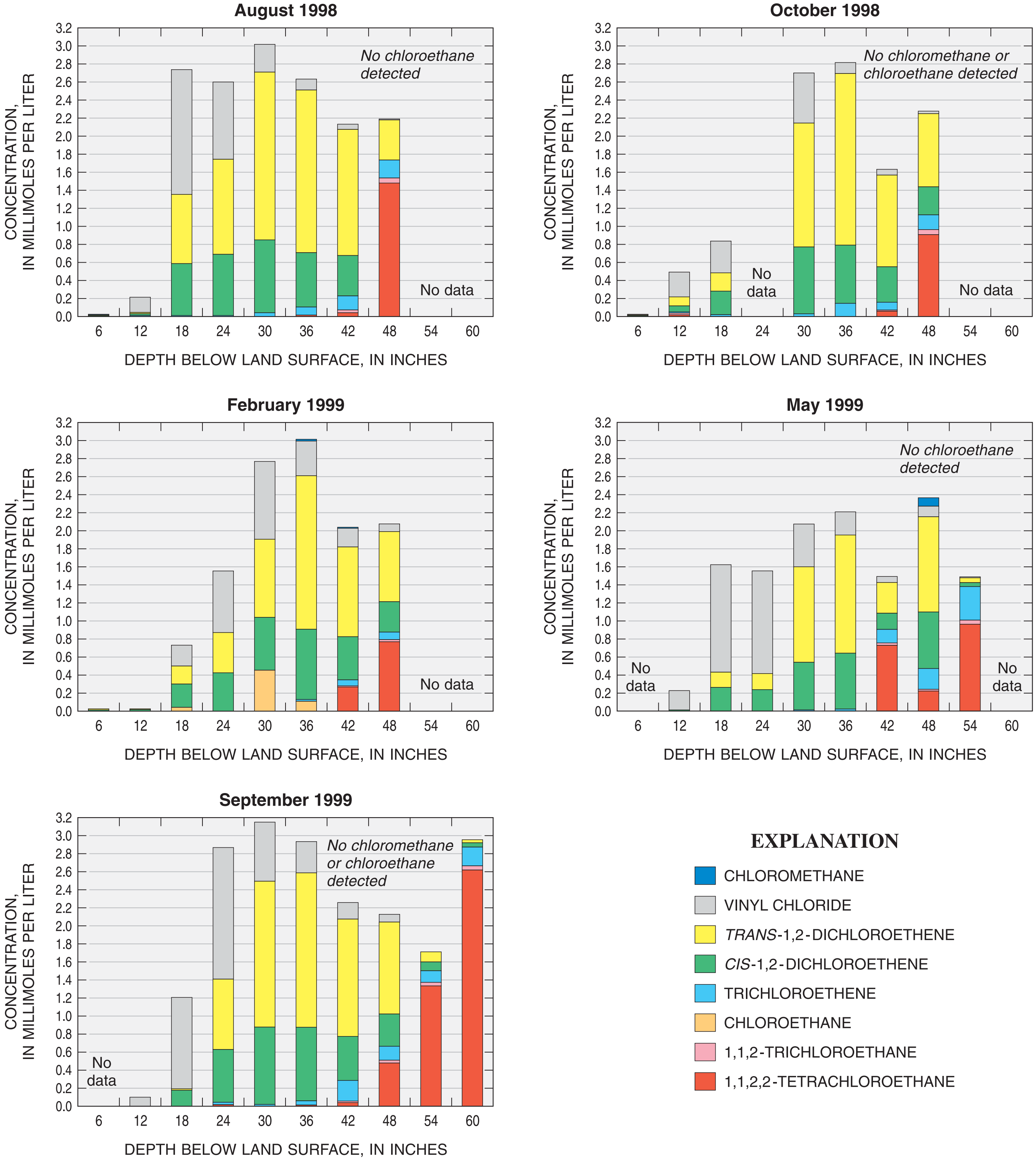


Figure 10. Depth-averaged concentrations of volatile organic compounds in ground-water samples collected from the tracer array, August 1998 to September 1999.

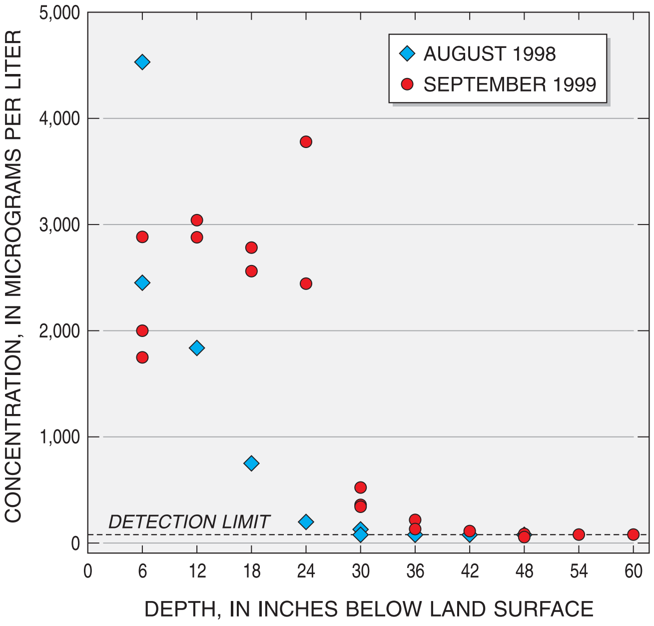


Figure 11. Concentrations of methane in ground-water samples collected from the tracer array in August 1998 and September 1999.

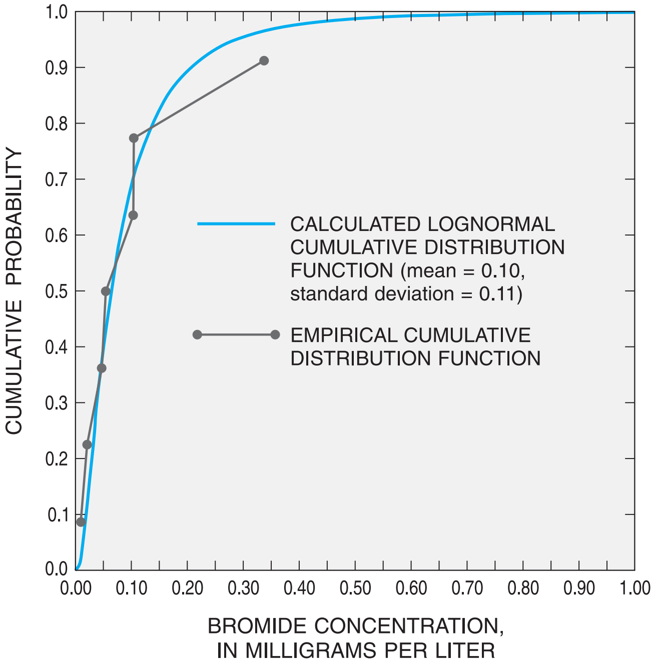


Figure 12. Comparison of the empirical cumulative distribution function for bromide concentrations in seven blanks analyzed by colorimetric method to the calculated lognormal cumulative distribution function for a mean of 0.10 milligrams per liter and a standard deviation of 0.11 milligrams per liter.

concentrations were lower than the highest detection in background samples analyzed by colorimetric methods (0.34 mg/L in A14-127 on August 4, 1998) and could be due to transfer of low-level bromide residues from sampling or analytical equipment. The empirical cumulative distribution function of bromide concentrations in these wash blanks was compared to a cumulative distribution function plotted for a lognormal distribution with a mean of 0.10 mg/L and a standard deviation of 0.11 mg/L (fig. 12). If the true population of bromide concentrations in wash blanks analyzed by colorimetric methods is lognormally distributed, the probability that any hypothetical blank collected from the true population would exceed background levels is small—3.4 percent. For interpretation purposes, the bromide data obtained using colorimetric methods were pooled with the ion-selective electrode data and assigned a combined RL of 1.0 mg/L (the higher RL of the two methods). Assuming the stated lognormal distribution, the probability that any hypothetical blank collected from the true population of bromide analyses by colorimetric methods would exceed the combined RL of 1.0 mg/L is very low—0.13 percent. Therefore, although the bromide data obtained using colorimetric methods would be expected to have a slight positive bias, this bias is small and assumed to be inconsequential in the interpretation of the tracer-test results.

Eight wash blanks were collected and analyzed for sulfur hexafluoride (Appendix B5). Sulfur hexafluoride concentrations in five of the wash blanks were below their RLs, which ranged from 0.01–0.96 ng/L, depending on the sample temperature at the time of analysis and the ratio of sample volume to headspace. Concentrations in three of the wash blanks exceeded their respective RLs, with concentrations of 0.72 ng/L (RL = 0.21 ng/L), 0.74 ng/L (RL = 0.22 ng/L), and 0.92 (RL = 0.21 ng/L). These concentrations are all lower than the highest concentration of sulfur hexafluoride detected in background samples (1.27 ng/L in F02-195 on August 3, 1998); therefore, the possibility of a slight positive bias in sulfur hexafluoride concentrations is assumed to be inconsequential in the interpretation of the tracer-test results.

Eight wash blanks were collected and analyzed for VOCs (Appendix B3). All VOC results for these wash blanks were below the RLs, with the exception of a single detection of trichlorofluoromethane (1.3 µg/L), a common refrigerant, in one wash blank that was collected on September 2, 1999. Three wash blanks were collected and analyzed for methane (Appendix B4), and the results for these blanks were below their RLs.

Ambient Blanks—Eleven ambient blanks were collected and analyzed for fluorescein dye and for bromide measured by ion-selective electrode (Appendix B3). All 11 ambient blanks had fluorescein concentrations below the RL of 5.0 µg/L and bromide concentrations below the RL of 1.0 mg/L; therefore, contamination from the ambient environment should not be considered a significant source of positive bias in the fluorescein and bromide data. Ambient blanks were not analyzed for bromide using the colorimetric method, which has a greater sensitivity and a lower RL than the ion-selective electrode method. It is possible that bromide could have been present in the ambient blanks at concentrations less than 1.0 mg/L; however, because bromide is not volatile, the likelihood of bromide transfer to blanks and samples from the ambient air is substantially lower than that of transfer via the surfaces of equipment used for sampling and analysis. Therefore, the slight positive bias observed in wash blanks analyzed by colorimetric methods should not be attributed to contamination from the ambient air.

Air Blanks—Because sulfur hexafluoride readily volatilizes from solution and partitions almost entirely into the gas phase, and is analyzed more practically in the gas phase (whereas fluorescein and bromide are more practically analyzed in the aqueous phase), air blanks were collected instead of conventional (aqueous) ambient blanks to evaluate the potential for bias in the sulfur hexafluoride data. For the two air blanks collected, sulfur hexafluoride concentrations were below detection limits in one sample (less than 1.20 ng/L on November 19, 1998) and 1.52 ng/L in the other (on November 18, 1998). These data indicate that sulfur hexafluoride could have been present at times in the air near the tracer array during sampling and could have come in contact with the sample water and the sampling equipment. Sulfur hexafluoride in the air near the tracer array could have come from volatilization from the purge water that was collected at the site. Sulfur hexafluoride concentrations as high as 79,400 ng/L were detected in the ground-water samples collected on November 18, 1998. The purge water collected that day would have been a composite of water from all of the piezometers sampled and is a possible source of the 1.52-ng/L detection in the air blank. The low concentrations of sulfur hexafluoride in three of the eight wash blanks could have been caused by sulfur hexafluoride transfer from residues on the sampling equipment or from the ambient air at the site. This potential bias could also have affected the environmental sample data; however, the magnitude of the potential bias is comparable to the sulfur hexafluoride concentrations in background samples and should not affect the overall interpretation of the tracer-test results.

Replicate Samples Replicate samples (138 pairs) were collected sequentially at selected sites and times to assess the overall variability of the tracer data. If a replicate sample was collected for one or more of the tracers from a particular piezometer on a specific date, the first sample is designated with a "1" in the "Replicate" column, and the second sample is designated with a "2" in the "Replicate" column in Appendix B2. "NR" designates samples for which no replicate was collected. Variability, a measure of the degree of difference between replicate measurements of the same quantity, was determined by calculating the relative percent difference (RPD) between the two sample concentrations (prior to rounding the data to the appropriate number of significant digits) using the formula:

$$\mathrm{RPD} = \frac{|C_1 - C_2|}{(C_1 + C_2)/2} \text{ x 100 percent ,} \qquad (1)$$

where C_1 and C_2 are the concentrations of a tracer compound in the replicate samples.

If the tracer concentrations in one or both of the replicate samples were below the RL, the RPD could not be calculated. The numbers of cases in which the concentrations were (1) below the RL in both samples, (2) below the RL in one sample, but at or above the RL in the other, and (3) above the RL in both samples (RPDs were calculated in this case), are as follows:

Type of replicate sample pair	Fluorescein dye	Bromide, ion-selective electrode	Bromide, colorimetric	Sulfur hexafluoride	Total, all tracers
1. Below the reporting limit for both samples	28	8	0	0	36
2. Below the reporting limit for one sample, but at or above the reporting limit for the other	2	1	0	1	4
3. Above the reporting limit for both samples (relative percent differences were calculated)	10	34	20	34	98
Total number of replicate sample pairs	**40**	**43**	**20**	**35**	**138**

Variability (expressed as RPD) was generally low for all of the tracers—less than 25 percent for most samples (fig. 13). No strong correlations were observed between sample variability and any of the following factors: sample date, sample depth, distance of the sampling point from the tracer injection point, sample concentration, and the volume of water removed during sampling—correlation coefficients were less than 0.21 for each of these factors. The distribution of RPDs was noticeably different, however, among the three tracers and between the two sets of bromide data (ion-selective electrode and colorimetric methods), indicating that the degree of sample variability is related to the characteristics of the individual tracer compounds and the analytical methods used to measure them. Histograms comparing the distributions of RPDs for each tracer are presented in figure 13, with separate histograms for bromide analyzed by selective-ion electrode and colorimetric methods.

Of the three tracers used, sulfur hexafluoride showed the greatest variability. Of the 34 replicate pairs evaluated for sulfur hexafluoride, 9 pairs (over 26 percent) had RPDs greater than 25 percent, and 1 pair had an RPD greater than 150 percent (fig. 13). Fluorescein and bromide (both methods) demonstrated lower variability than sulfur hexafluoride—over 75 percent of the replicate pairs for fluorescein and bromide had RPDs below 25 percent, and none had RPDs greater than 100 percent. The higher RPDs for sulfur hexafluoride are likely due to differences in its physical characteristics compared to those of the other tracers.

Because sulfur hexafluoride is a gas and volatilizes readily from water, it can partition into any gas phase present in the water, which would reduce its aqueous concentration. Gas-phase equilibrium processes represent a source of variability that could only have affected the sulfur hexafluoride and not the fluorescein or bromide. Gas bubbles could have been introduced to samples when the ground water was syringed from a piezometer, if care was not taken to expel all gases from the syringe and 3-way valve before collecting the sample, or if the piezometer did not contain enough water for continuous withdrawal of sample water without aeration. It is more likely, however, that gas bubbles in the samples were due to effervescence, which was observed in many of the ground-water samples. Ground-water pressure below the surface of the water table exceeds atmospheric pressure because of the weight of the overlying water, resulting in the water having a higher capacity for dissolved gases than would be possible at atmospheric pressure. Artesian conditions (evidenced by water levels in the piezometers in the study area being higher than the water table), due to the higher elevation of the surrounding recharge areas and the confining nature of the wetland sediments, is an additional source of pressure that would further increase the capacity for dissolved gases in the shallow ground water. Concentrations of dissolved biogenic marsh gases (such as methane, carbon dioxide, hydrogen sulfide, and carbon disulfide) in excess of their solubility limits for water at atmospheric pressure would be expected to effervesce as bubbles when the ground water was brought to the surface during sampling. For the effervescent samples, a portion of the dissolved sulfur hexafluoride that was added to the ground water as a tracer could have effervesced with the marsh gases or subsequently partitioned into bubbles that formed in the sample vials. The headspace analysis method used for the sulfur hexafluoride would have greatly minimized the variability associated with potential effervescence in the water after sample collection; however, intrinsic heterogeneities in the concentrations of dissolved gases within the ambient ground water itself could have contributed to the variability observed in the sulfur hexafluoride replicates.

Differences in variabilities also were observed between bromide measured by ion-selective electrode and by colorimetric methods (fig. 13). Over 90 percent of the replicate pairs (31 of 34) analyzed for bromide by ion-selective electrode had RPDs of less than 25 percent. Only 75 percent of the replicate pairs (15 of 20) analyzed for bromide by the colorimetric method had RPDs less than 25 percent. Sampling procedures for bromide analyzed by both methods were nearly identical; therefore, the differences in variabilities are more likely due to differences in laboratory procedures. Samples analyzed by the colorimetric methods typically were diluted at a 1:2 ratio with deionized water prior to analysis to provide adequate sample volume. For both analytical methods, samples with concentrations that exceeded the calibration range were diluted to reduce the concentrations to within the calibration range and re-analyzed. The upper RL for the ion-selective electrode was 500 mg/L, and the upper RL for the colorimetric method was 20 mg/L; therefore, a higher proportion of samples analyzed by colorimetric method were diluted, and for this method, the dilution step was performed in addition to the initial 1:2 dilution done for sample-volume purposes. These dilution steps could explain the higher variabilities in the replicate samples analyzed by the colorimetric method compared to the replicates analyzed by ion-selective electrode.

Variabilities also were evaluated for the VOCs, using the data in Appendix B3. Fifty-nine VOCs were analyzed for 5 replicate pairs, generating 295 possible comparisons between replicate analyses. Of these 295 possible comparisons, 272 were below the RL in both samples, 1 was below the RL in one sample but above the RL in the other, and 22 were above the RL for both samples. RPDs calculated for the 22 replicate analyses with detections in both samples were generally less than 40 percent, with the exception of the RPDs for a replicate pair collected from D07-022 (fig. 14). Because of the slow recovery rate for this piezometer, the second sample of this replicate pair was collected 1 day after the first sample. Because VOCs are volatile, they are susceptible to losses if the water is exposed to air during sampling and analysis; therefore, sampling and analytical methods were selected to minimize the potential for sample aeration. VOCs would also be susceptible to losses in gas bubbles from natural effervescence in the samples for which this occurred. Another possible source of variability in the VOC data is small-scale heterogeneities in the distribution of VOCs in the immediate vicinity of the piezometer screens

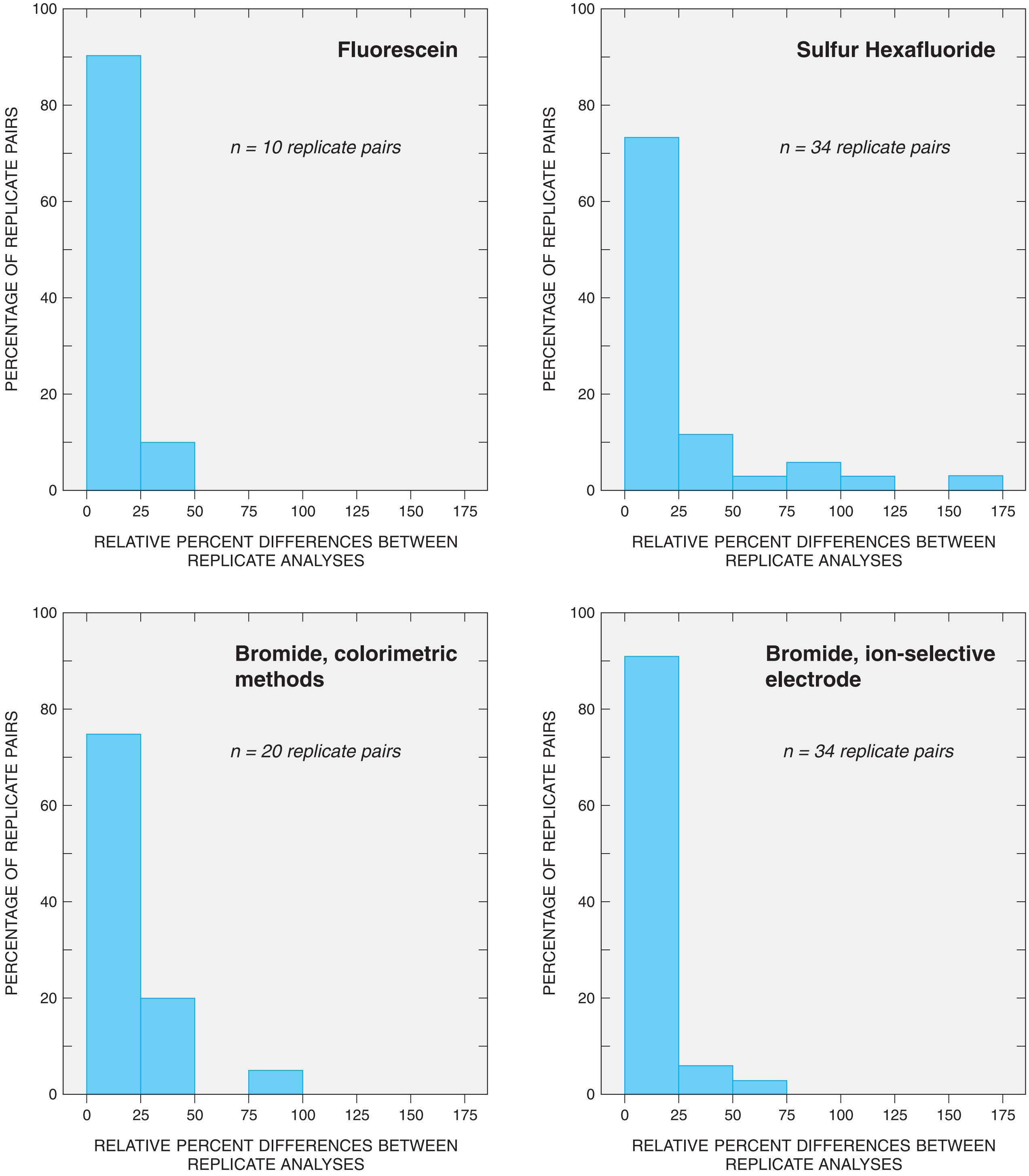


Figure 13. Variabilities calculated between replicate analyses (expressed as relative percent differences) for each of the tracers used in the ground-water tracer test.

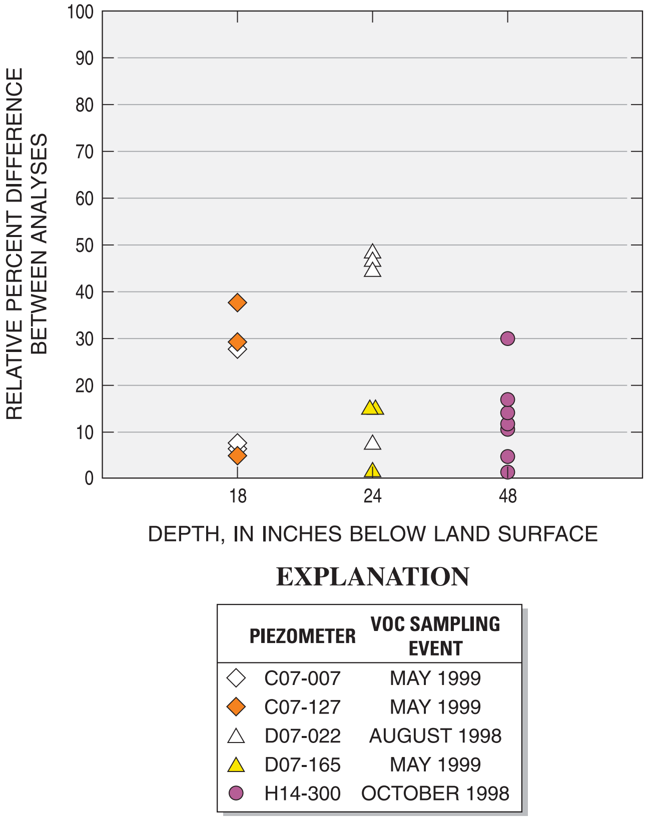


Figure 14. Relative percent differences between replicate analyses of individual volatile organic compounds.

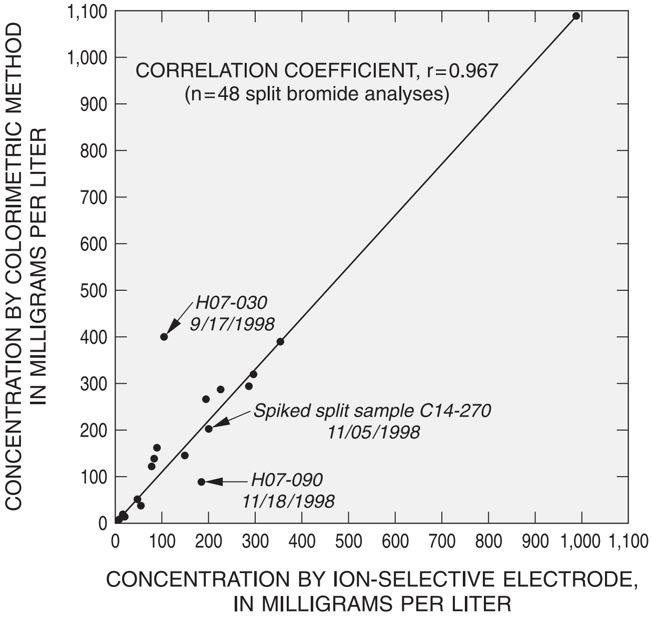


Figure 15. Correlation of bromide concentrations from split analyses analyzed by colorimetric method at the USGS National Water Quality Laboratory and ion-selective electrode at the on-site laboratory.

because of localized zones of increased degradation or sorption.

Split Samples and Spiked Split Sample Fifty-four split-sample pairs, including 1 spiked split-sample pair, were collected and analyzed for bromide by ion-selective electrode and colorimetric methods to evaluate the comparability of the two analytical techniques. The split samples were collected sequentially by filling a vial for analysis at the on-site laboratory by ion-selective electrode and then filling a vial for analysis at the NWQL by the colorimetric method, or vice versa. If replicate analyses were performed for either or both analytical methods for a split sample, the replicate values were averaged before comparing the split samples. The spiked split-sample pair was collected by adding a known quantity of concentrated bromide solution to a known volume of sample water that was collected from C14-270 on November 5, 1998, to produce an expected spike concentration of 199.95 mg/L. The spiked sample water was then divided into separate vials for analysis by the two methods.

Of the 54 bromide split-sample pairs analyzed, 48 pairs (including the spiked pair) had concentrations above the RL in both samples, and could be compared quantitatively. For these 48 pairs, concentrations in the samples analyzed using the ion-selective electrode correlated favorably (correlation coefficient, r = 0.967) with concentrations in the samples analyzed using colorimetric methods (fig. 15). Eliminating the spiked split-sample pair from the data set did not change the degree of correlation (r = 0.967). The remaining 6 split-sample pairs had concentrations below the RL of 1.0 mg/L for the samples analyzed by ion-selective electrode, and concentrations above the RL of 0.02 mg/L (but below 1.0 mg/L) for the samples analyzed by the colorimetric method.

The 2 bromide split-sample pairs that showed the most difference between the analytical methods were collected from H07-030 on September 17, 1998 (104 mg/L by ion-selective electrode, 392 mg/L by colorimetric method), and from H07-090 on November 18, 1998 (185 mg/L by ion-selective electrode, 87.7 mg/L by colorimetric method) (fig. 15). These samples were collected from sites that were very close (7 in.) to the injection piezometer and were collected 13 and 75 days, respectively, after the introduction of the bromide/SF_6 solution. The differences in the results for these split-sample pairs could be due to small-scale heterogeneities in the ground water, which could cause differences in tracer concentrations between the first and second aliquots of water withdrawn from these piezometers. Although the small water volumes withdrawn during sampling were expected to overcome most of the heterogeneity in tracer concentrations associated with small-scale changes in the composition of the ground water in the vicinity of the piezometer intakes, samples collected from piezometers closest to the injection piezometer and from the earliest dates after tracer injection would be the most susceptible to small-scale variations in tracer concentration.

Analyte recoveries for the spiked split sample were very good. Based on an expected bromide concentration of 199.95 mg/L, the recovery of bromide analyzed by the ion-selective electrode was 99.7 percent (199.28 mg/L), and the recovery of bromide analyzed using the colorimetric method was 105 percent (209.85 mg/L). Based on the results of the split-sample pairs and the spiked split-sample pair, bromide data obtained using the ion-selective electrode and the colorimetric methods were considered comparable, and were pooled for the purpose of data analysis and interpretation.

Analysis of the Tracer Movement

Analysis of tracer movement in a natural-gradient tracer test can be a complex process. The complexity of the analysis of tracer movement in this study was increased due to several aspects of the test environment and tracer array configuration. First, the test was conducted in a ground-water discharge zone, with the injection point near the bottom of the tracer array. This differs from most other field tracer tests, which are conducted with one or more injection points located at one end of an essentially horizontal flow field. Second, the area was affected by tides that inundated the land surface approximately twice a day. This resulted in uncontrolled diurnal variations in hydraulic gradient within the array, and may have resulted in surface water diluting the ground-water tracer concentrations within the shallowest depths of the array. Third, the size of the tracer array was necessarily small, because tracer movement was expected to be slow in this environment. The small array size meant that small variations in hydraulic properties (such as direction and magnitude of hydraulic gradient, and spatial heterogeneity in hydraulic conductivity caused by roots or other preferred flowpaths) could cause large differences in the actual results compared to what was expected, which was simple upward movement.

Tracer movement was expected to be affected by a number of hydrologic and chemical processes, including advection (transport of solutes by ground-water flow), mechanical dispersion (spreading of a solute plume because of differing ground-water velocities within a porous medium), and chemical diffusion (spreading of a solute plume from areas of high chemical concentration to areas of low chemical concentration). Advection moves solutes in the direction of ground-water flow, which in this area was expected to be generally upward. Mechanical dispersion will not occur without advection. It spreads the plume in all directions away from the center of mass, with most of the spreading in the longitudinal direction (parallel to flow) and lesser spreading in transverse directions. Chemical diffusion works in all directions and unlike mechanical dispersion, is not caused by ground-water flow. Chemical diffusion would be the dominant spreading factor in cases where ground-water flow is very slow or negligible. Where ground-water flow is faster, advection and mechanical dispersion usually dominate, with chemical diffusion often lumped into the dispersion term. Tracer movement was not expected to be affected by volatilization, except for sulfur hexafluoride in the uppermost level of the tracer array, because fluorescein dye and bromide are not volatile, and dissolved sulfur hexafluoride generally does not volatilize from solution unless a gas phase is present.

In addition to these processes, the density of the bromide/SF_6 solution required for the tracer test could have caused some initial downward movement of the tracer mass. Although the injected volume was only 139 mL and dilution would have acted rapidly to mitigate the density effects, it is possible that the center of tracer mass dropped below the injection point during the early days of the test. If one were to assume that the initial tracer mass had been a sphere that became diluted homogeneously as it expanded in all directions, a ten-fold dilution of the tracer solution would have increased of the radius of the plume from 1.7 in to 3.7 in. (assuming an effective porosity of 0.40), and decreased the solution density from 1.096 g/mL to 1.0096 g/mL, which would be closer to the density of the ground water in the tracer array. It is unlikely that such dilution would have occurred homogeneously throughout the plume however, therefore, the center of mass and concentration distribution in the early days of the test proved too difficult to quantify. In order not to artificially force the tracer to lower depths, samples were not collected from below the injection point (levels I and J) until late in the test (starting 250 days after bromide/SF_6 injection), so it is impossible to tell whether part of the tracer mass could have moved downwards below the array and been lost. This potential initial sinking of the tracer mass prohibits a straightforward mathematical analysis of the tracer test. It is possible that analytical methods or numerical models developed for variable-density fluid flow, such as SUTRA (Voss and Provost, 2002), could be used to characterize the tracer movement and differentiate between density effects and other hydrologic processes; however, this exercise was beyond the scope of this report. The following analysis of the tracer test is based on breakthrough curves and isoconcentration contour plots.

Breakthrough Curves

Breakthrough curves of bromide and sulfur hexafluoride concentrations with time were plotted for each sampling point to compare different spatial characteristics of tracer movement. In the following sections, the breakthrough curves and associated discussions are presented by depth, starting from the bottom of the tracer array (level H, 48 in. below land surface) and moving upward (to level A, 6 in. below land surface), because the tracer was injected at 48 in. below land surface and the hydraulic gradient generally was upward.

The tracer test was designed to minimize disturbance to the natural flow field—therefore, a small volume (0.139 liter) of highly concentrated tracer solution was injected. The initial concentration of bromide tracer was 100,000 mg/L, and the initial concentration of sulfur hexafluoride was 23.3 mg/L, or 23,300,000 ng/L. Minimal water was removed from the system during sampling. The first samples were collected 13 days after injection of the bromide/SF_6 solution, and relatively few samples were collected until 60–104 days after injection. This time lag between injection and the first major sampling round may be one reason that the peak tracer concentrations from samples were two or more orders of magnitude smaller than the initial concentrations.

Bromide Breakthrough Curves

Level H—The bromide breakthrough curves for level H (where the tracer was injected) are shown in figures 16a–c. At the injection point (the 0-in. radius), no samples were collected until 104 days after injection to reduce the possibility of removing a large fraction of the tracer mass. The small concentrations shown in this curve indicate that the bromide tracer had indeed moved away from the injection point before samples were collected. The largest concentrations in level H (about 250–300 mg/L) were at the 7-in. radius, at 30-, 90-, and 210-degree orientations to the creek (fig. 16b). The largest concentrations for all sampling locations on the 7-in. radius in level H were detected within 45 days after tracer injection. Peak concentrations detected on the 14-in. radius were smaller (less than 50 mg/L) than those on the 7-in. radius, and they occurred between 45–103 days after tracer injection (fig. 16c).

Level G—The peak bromide concentration in level G (6 in. above the injection level) was detected on the 2-in. radius, 47 days after tracer injection (fig. 17a). This concentration of 1,040 mg/L (average of replicate samples with concentrations of 991 and 1,090 mg/L) was the largest bromide concentration detected during the tracer experiment. Peak concentrations of bromide detected at points on the 7-in. radius of level G (fig. 17b) ranged as high as 340 mg/L, which is comparable to the peak concentrations in level H below. On the 14-in. radius, the highest concentration (104 mg/L) was detected 75 days after tracer injection, at a sampling point oriented 105 degrees from the creek (G14-105, fig. 17c). The next largest peak (49 mg/L) was detected 50 days later at a sampling point oriented 22 degrees from the creek (fig. 17c).

Level F—Breakthrough curves for bromide concentrations in level F (12 in. above the injection level) are shown in figures 18a–c. Peak concentrations of bromide of about 300–400 mg/L were detected in samples from the 2-in. radius in level F (fig. 18a). Peak concentrations for bromide at several locations on the 7-in. radius in level F (fig. 18b) were about half as large as the concentrations on the 2-in. radius for this level (fig. 18a), with peak concentrations ranging from 35 mg/L (at F07-315) to 185 mg/L (at F07-075) (fig. 18b). On the 14-in. radius in level F (fig. 18c), the largest peak concentration was 60 mg/L, at sampling location F14-045.

Level E—Breakthrough curves for bromide concentrations for level E (figs. 19a–c), which is 18 in. above the injection level, exhibit some features that were not apparent in curves from the lower levels. Unlike levels F, G, and H, the largest peak concentration (214 mg/L) was detected on the 14-in. radius (fig. 19c) rather than on the 2-in. (fig. 19a) or the 7-in. (fig. 19b) radius. Additionally, the peak concentration from the sampling point on the 2-in. radius (106 mg/L) was very similar to the largest peak concentration in sampling points on the 7-in. radius (E07-045, 112 mg/L), whereas in the F level, concentrations on the 2-in. radius (fig. 18a) were at least 100 mg/L larger than the peak concentrations on the 7-in. radius (fig. 18b). The drop in concentration for points on the 2-in. radius from level F to level E (371 mg/L in level F to 106 mg/L in level E) is consistent with the drop in concentration on the 2-in. radius from level G (1,040 mg/L) to level F (371 mg/L).

The large peak bromide concentration at E14-277 on the 14-in. radius (214 mg/L, 174 days after tracer injection) (fig. 19c) is difficult to explain with the available data. Not only is this peak the largest concentration in level E, it also is larger than any concentration on the 14-in. radii in levels H, G, or F below (figs. 16c, 17c, and 18c respectively). It is possible that (a) a slug of tracer moved towards E14-277 through a preferential pathway between the sampling points in the lower layers; (b) a slug of tracer moved past the various sampling points between sampling events (that is, the peak was missed); (c) a slug of tracer moved outside of the array boundary in the lower layers before moving back into the tracer array at level E; or (d) the concentration at E14-277 is incorrect because of an error in sample handling or analysis.

Level D—Breakthrough curves for bromide concentrations in level D (24 in. above the injection level) on the 2-, 7-, and 14-in. radii are shown in figures 20a–c. For the sampling location on the 2-in. radius, it appears that the peak concentration could have occurred between two sampling events and therefore was missed. Nearly identical concentrations in samples collected 46 and 89 days after tracer injection (fig. 20a) indicate that a peak could have occurred between those two sampling dates. Peak concentrations of bromide at three sampling points on the 7-in. radius (fig. 20b) and one point on the 14-in. radius (fig. 20c) exceeded the largest concentration detected at the location on the 2-in. radius for level D (fig. 20a). No concentration on any radius of the D level was as large as the 214-mg/L concentration on the 14-in. radius of level E (E14-277). The largest concentration on the 14-in. radius of level D (D14-052, 59 mg/L at 104 days after tracer injection) occurred earlier and on the opposite side of the tracer array from the anomalous peak in the level below, at E14-277 (figs. 19c and 20c).

Level C—Breakthrough curves for bromide in level C (figs. 21a–c), which is 30 in. above the injection level, are somewhat different from the lower levels, indicating a possible transition in tracer movement. The point on level C in the center of the array did not exhibit any clear peak (fig. 21a), and concentrations fluctuated below 10 mg/L for the duration of the tracer test. Many of the points on the 7-in. radius (fig. 21b) and 14-in. radius (fig. 21c) were similar. In addition, each breakthrough curve had a low point during the sampling event at 244 days (figs. 21a–c) and ended with a larger concentration at 374 days after tracer injection. The largest peak concentration of bromide in level C (48 mg/L at 76 days after injection) was detected at C07-067 on the 7-in radius (fig. 21b).

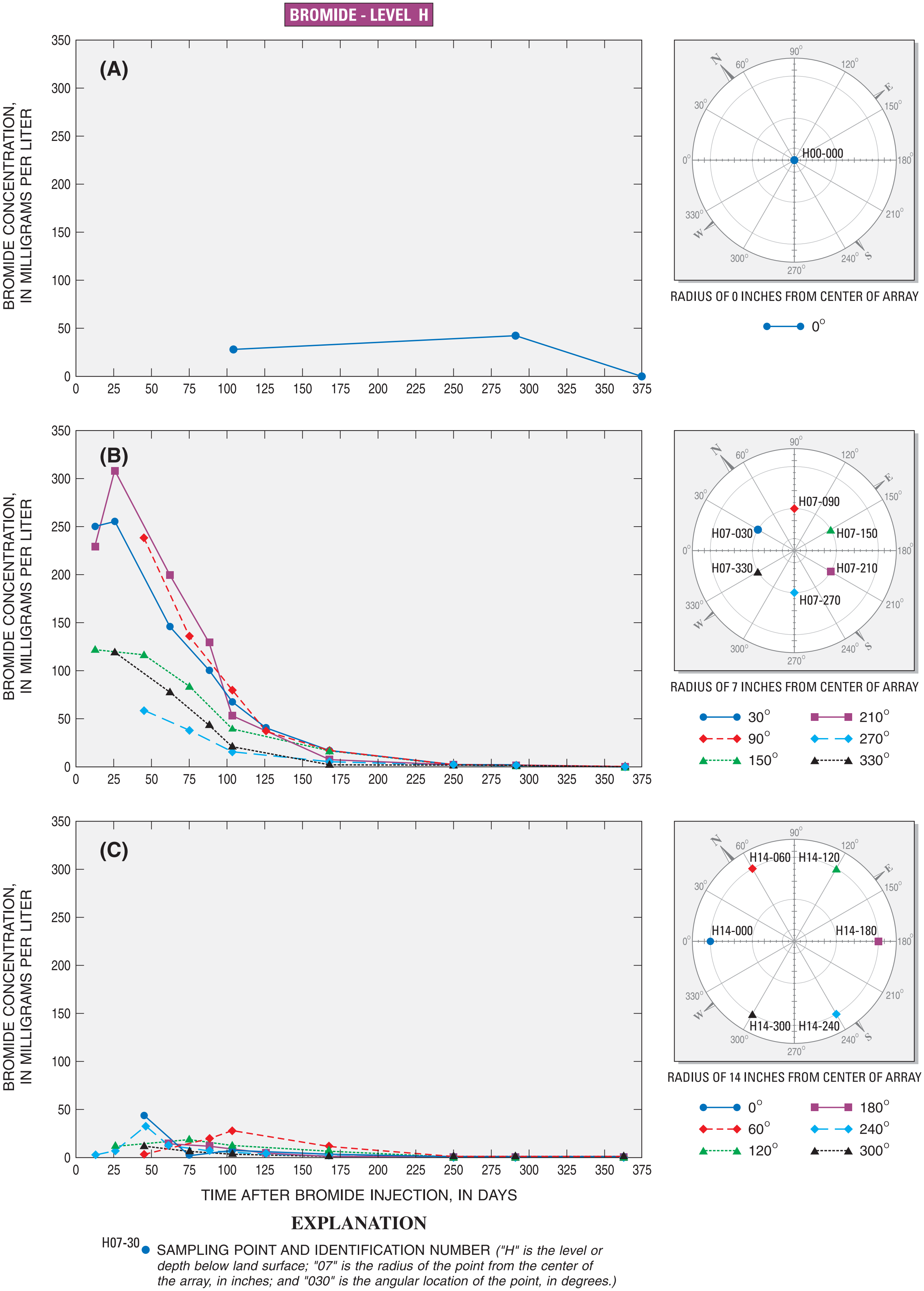


Figure 16. Bromide concentrations with time for sampling points in level H, 48 inches below land surface, at radii of **(A)** 0 inches, **(B)** 7 inches, and **(C)** 14 inches from the center of the array.

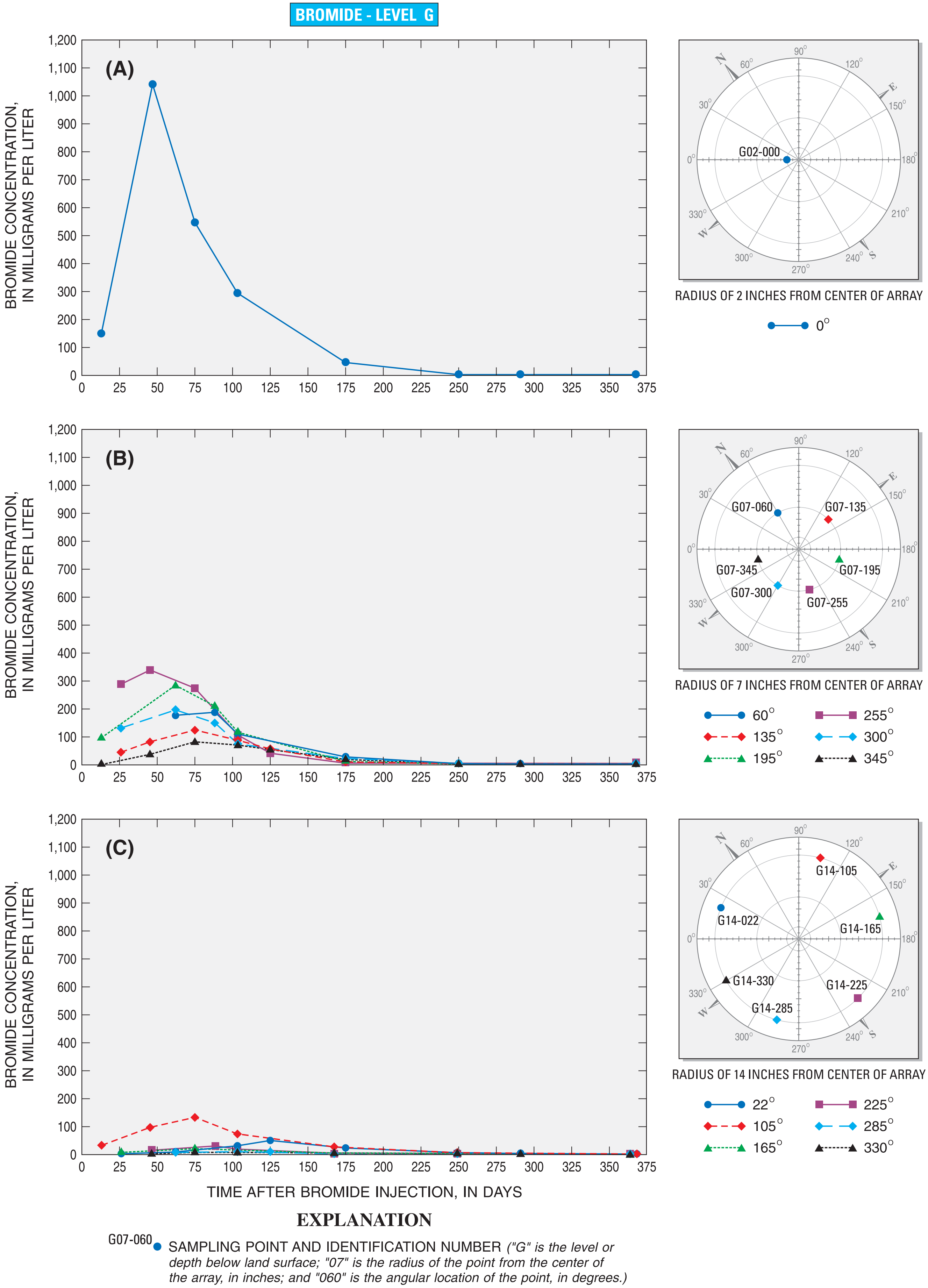


Figure 17. Bromide concentrations with time for sampling points in level G, 42 inches below land surface, at radii of **(A)** 2 inches, **(B)** 7 inches, and **(C)** 14 inches from the center of the array.

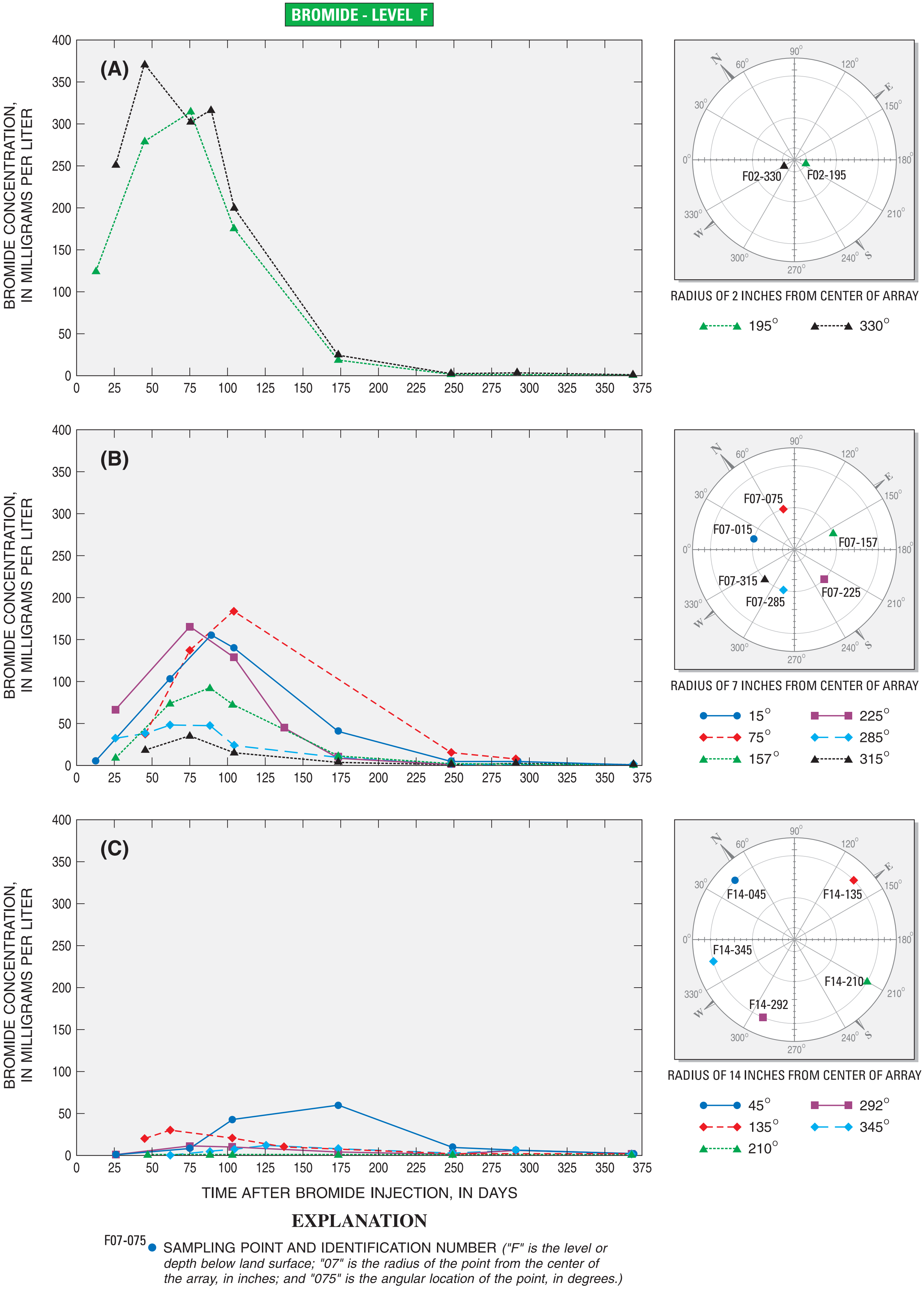


Figure 18. Bromide concentrations with time for sampling points in level F, 36 inches below land surface, at radii of **(A)** 2 inches, **(B)** 7 inches, and **(C)** 14 inches from the center of the array.

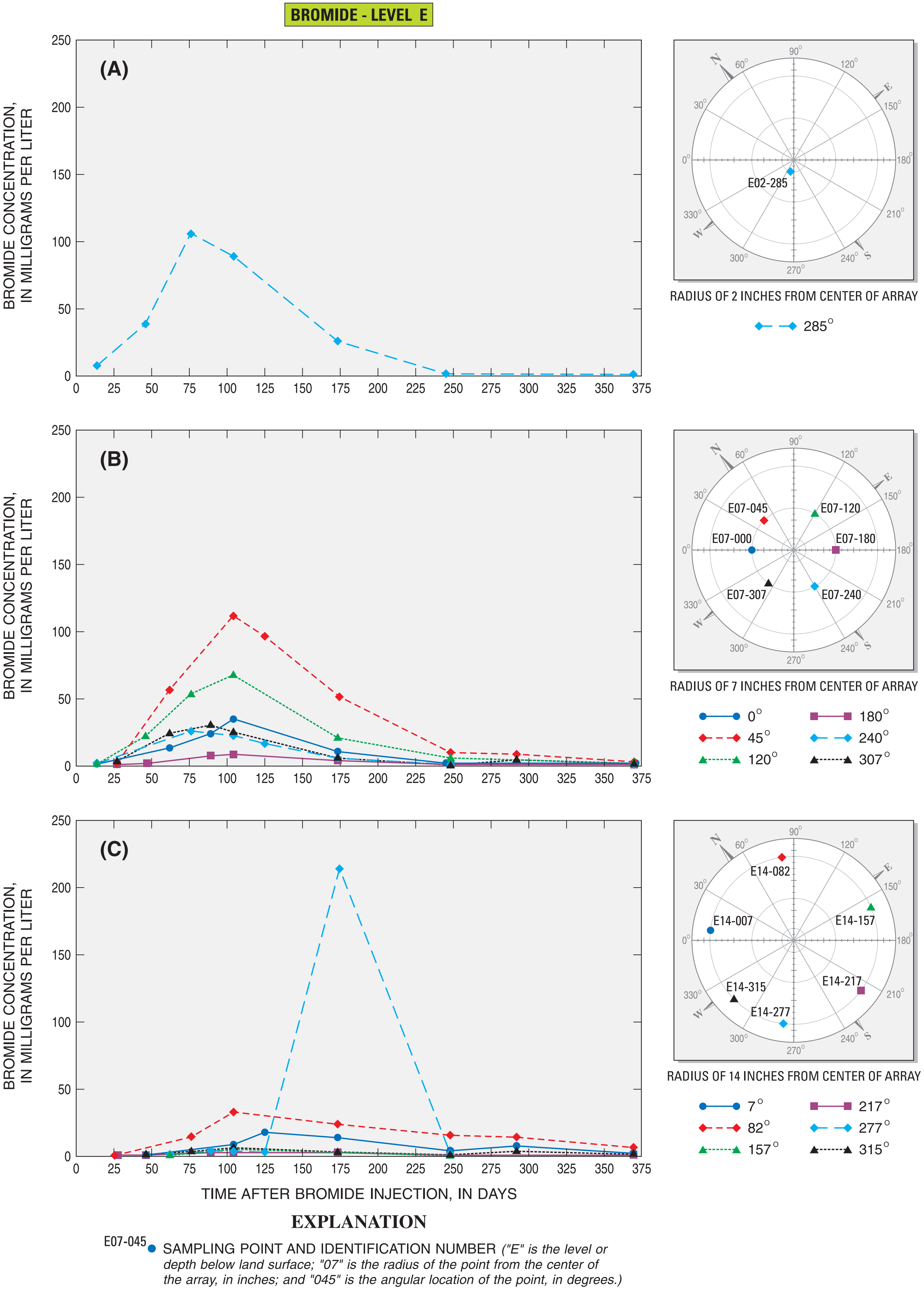


Figure 19. Bromide concentrations with time for sampling points in level E, 30 inches below land surface, at radii of **(A)** 2 inches, **(B)** 7 inches, and **(C)** 14 inches from the center of the array.

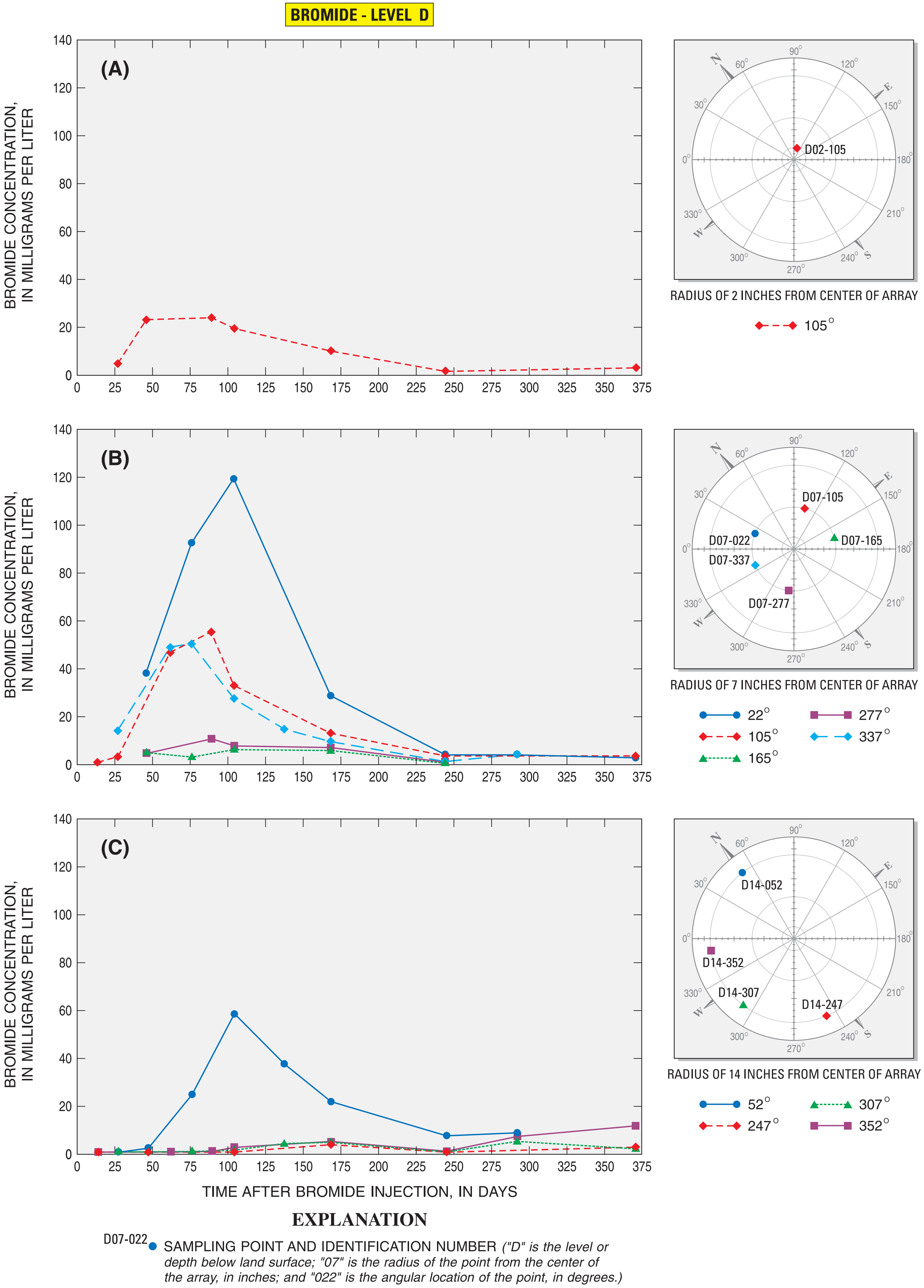
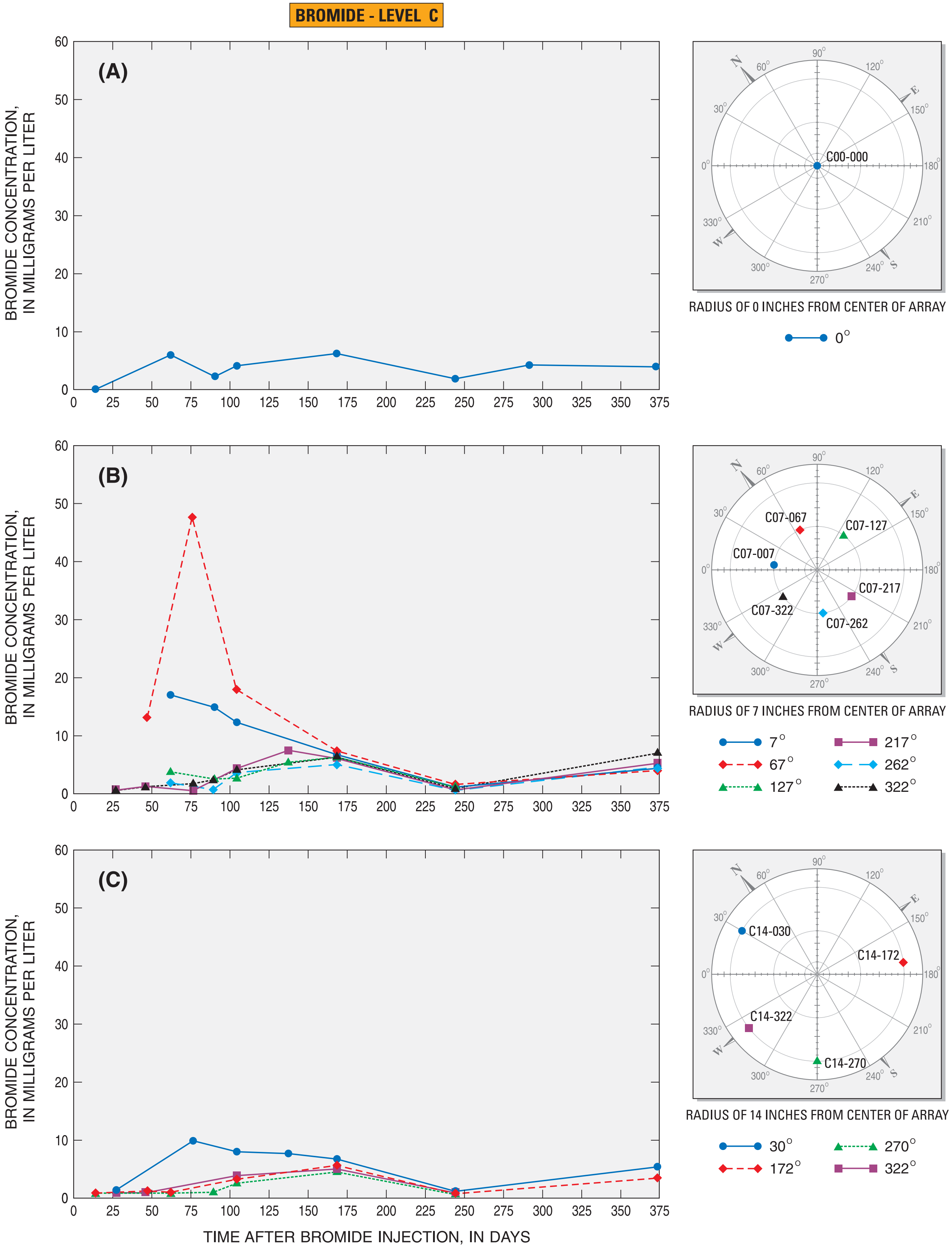


Figure 20. Bromide concentrations with time for sampling points in level D, 24 inches below land surface, at radii of **(A)** 2 inches, **(B)** 7 inches, and **(C)** 14 inches from the center of the array.



EXPLANATION

C07-007 ● SAMPLING POINT AND IDENTIFICATION NUMBER *("C" is the level or depth below land surface; "07" is the radius of the point from the center of the array, in inches; and "007" is the angular location of the point, in degrees.)*

Figure 21. Bromide concentrations with time for sampling points in level C, 18 inches below land surface, at radii of **(A)** 0 inches, **(B)** 7 inches, and **(C)** 14 inches from the center of the array.

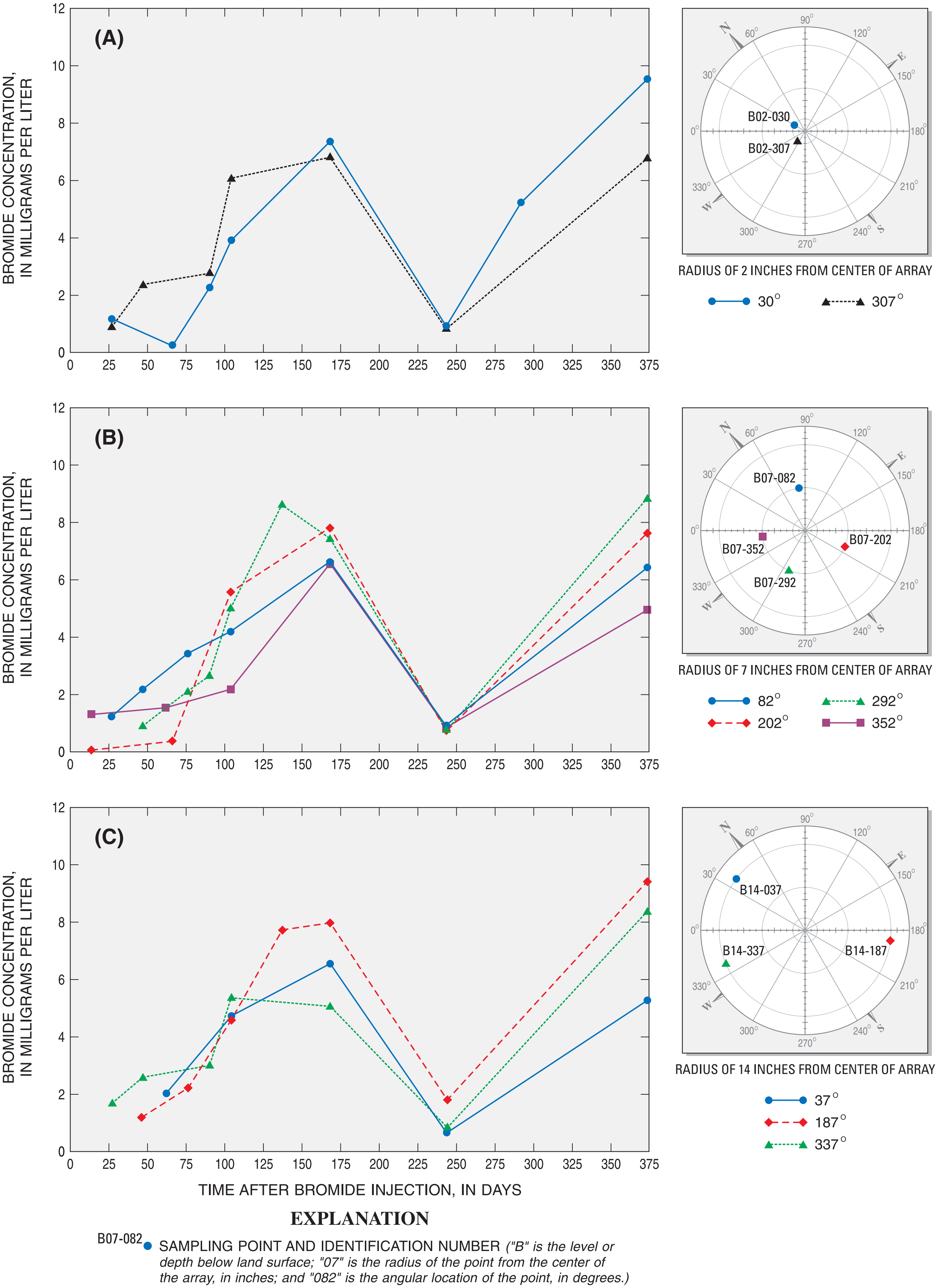
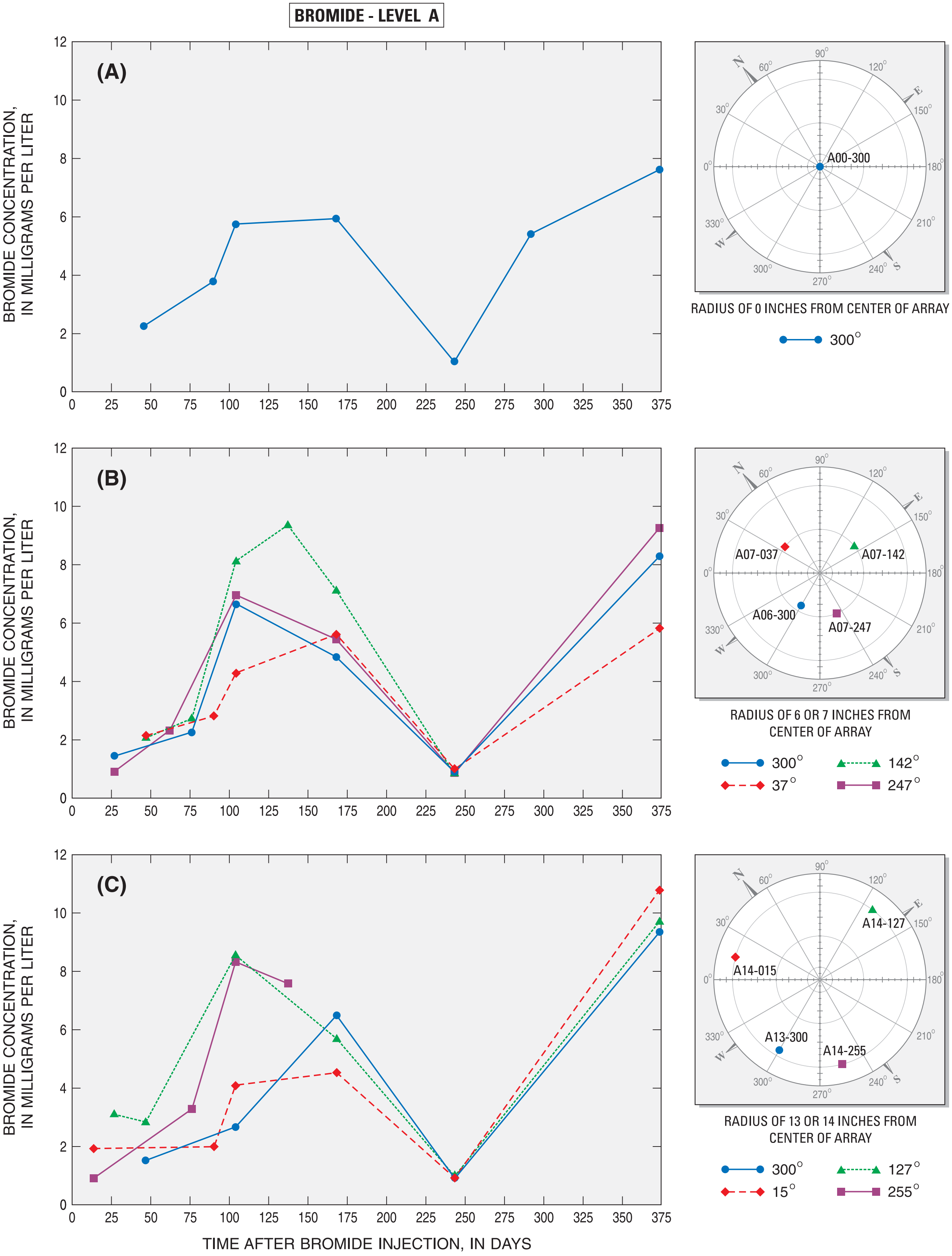


Figure 22. Bromide concentrations with time for sampling points in level B, 12 inches below land surface, at radii of **(A)** 2 inches, **(B)** 7 inches, and **(C)** 14 inches from the center of the array.



EXPLANATION

A06-300 ● SAMPLING POINT AND IDENTIFICATION NUMBER *("A" is the level or depth below land surface; "06" is the radius of the point from the center of the array, in inches; and "300" is the angular location of the point, in degrees.)*

Figure 23. Bromide concentrations with time for sampling points in level A, 6 inches below land surface, at radii of **(A)** 0 inches, **(B)** 6 or 7 inches, and **(C)** 13 or 14 inches from the center of the array.

Levels B and A—Bromide breakthrough curves in levels B and A (figs. 22a–c and 23a–c), 36 and 42 in. above the injection level, were similar to curves from many of the sampling points in level C. As was the case with concentrations in level C, concentrations in levels B and A generally fluctuated between about 1 and 10 mg/L (the only detection larger than 10 mg/L was at A14-015). A small concentration (less than or equal to 1 mg/L) was detected in each location during the sampling episode at 243 days, and concentrations increased again between 243–375 days after tracer injection (figs. 22a–c and 23a–c). For many of the sampling locations in levels B and A, the largest bromide concentrations detected were at the end of the test (figs. 22a–c and 23a–c). It is unclear why the concentrations fluctuated as they did in these upper two levels; however, the magnitude of these concentrations is very small compared to the bromide concentrations that were observed in the deeper levels of the array.

Sulfur Hexafluoride Breakthrough Curves Because sulfur hexafluoride and bromide are considered to be conservative tracers that do not adsorb onto sediment (Harden and others, 2003; Wilson and Mackay, 1993), it was expected that both tracers would behave in a similar fashion. Analysis of breakthrough data from the West Branch Canal Creek tracer test, however, showed differences between the two tracers in almost every sampling level of the tracer array. In several instances, for example, anomalously large concentrations of one tracer were not matched by large concentrations of the other. Differences in behavior between the tracers are described below.

Level H—Breakthrough curves of sulfur hexafluoride in level H (where the tracer was injected) are shown in figures 24a–c. As with bromide, no samples were collected from the injection point until 104 days after injection to reduce the possibility of removing a large fraction of the tracer mass. In contrast with bromide, the sulfur hexafluoride concentration in the sample from the injection point (fig. 24a) was large (355,584 ng/L) relative to the concentrations at other sampling locations. It was the largest concentration of sulfur hexafluoride detected during any of the four major sampling episodes, and it is an indication that the sulfur hexafluoride tracer did not move away from the injection point as efficiently as the bromide tracer.

Peak concentrations of sulfur hexafluoride from samples on the 7-in. (fig. 24b) and 14-in. (fig. 24c) radii in the injection level (level H) were much smaller than the largest concentration measured at the injection point. The breakthrough curves on the 7-in. radius (fig. 24b) showed concentration fluctuations over time, which indicates a high likelihood that peaks occurred between sampling events.

Level G—Sulfur hexafluoride breakthrough curves for level G (6 in. above the injection level) are shown in figures 25a–c. The largest peak concentration detected in this level was 87,427 ng/L at G02-000 on the 2-in. radius (fig. 25a). On the 7-in. radius (fig. 25b), the sulfur hexafluoride breakthrough curves in level G (6 in. above the injection level) fluctuated similarly to those from the 7-in. radius in the injection level (level H, fig. 24b). This concentration pattern was not as apparent on the 14-in. radius of level G (fig. 25c), but it is possible that the highest concentrations for these sampling points coincided with days that were between sampling events, and peak concentrations might have been missed.

Level F—Breakthrough curves for sulfur hexafluoride in level F (12 in. above the injection level) are shown in figures 26a–c. The largest peak concentration of sulfur hexafluoride (over 11,000 ng/L) in level F was detected on the 2-in. radius at F02-195 (fig. 26a). Concentrations of sulfur hexafluoride on the breakthrough curves for each of the level F sampling points on the 2-in. radius fluctuated throughout the tracer experiment. On the 7-in. radius in level F, sulfur-hexafluoride concentrations (fig. 26b) fluctuated in a similar manner to those on the 2-in. radius. On the 14-in. radius of level F, the peak concentrations for sulfur hexafluoride (fig. 26c) were very similar for two of the sampling points (943 ng/L at site F14-045 and 915 ng/L at site F14-210).

Level E—Sulfur hexafluoride breakthrough curves for level E (18 in. above the injection level) are shown in figures 27a–c. The largest concentration of sulfur hexafluoride in level E (5,611 ng/L) was detected at E07-045 on the 7-in. radius (fig. 27b). The magnitude of this peak was similar to some of the highest peak concentrations in level F, located 6 in. below level E. One data anomaly on the 14-in. radius of level E is that the large bromide concentration detected 174 days after injection at site E14-277 (fig. 20c) was not matched by a similarly large sulfur-hexafluoride concentration on any of the sampling days (fig. 27c).

Level D—Breakthrough curves of sulfur hexafluoride concentrations for level D (24 in. above the injection level) are shown in figures 28a–c. For the sampling point on the 2-in. radius (fig. 28a), concentrations of sulfur hexafluoride detected on the first and last sampling dates were virtually identical (474 and 476 ng/L, respectively) and were the largest concentrations detected at that point.

As with the bromide breakthrough curves for level D, concentrations of sulfur hexafluoride at three points on the 7-in. radius (fig. 28b) and one point on the 14-in. radius (fig. 28c) exceeded the peak concentrations detected in the sampling point on the 2-in. radius (fig. 28a). On the 7-in. radius, D02-022 showed the largest peak concentrations of the sulfur hexafluoride (fig. 28b) and bromide (fig. 20b) tracers. The sampling points that had the third largest peak concentrations on the 7-in. radius were different for each tracer (D07-337 for bromide, and D07-165 for sulfur hexafluoride; figs. 20b and 28b respectively).

Level C—Sulfur hexafluoride breakthrough curves in level C, which is 30 in. above the injection level and 18 in. below land surface, are shown in figures 29a–c. As was the case with the curves for bromide, no clear single peak sulfur hexafluoride concentration is apparent for the sampling point in the center of the tracer array (C00-000, fig. 29a); instead, peaks of similar concentration can be seen near the beginning and the end of the tracer test. On the 7-in. radius of level C, the largest sulfur hexafluoride peak was at C07-067 (760 ng/L; fig. 29b). This is more than

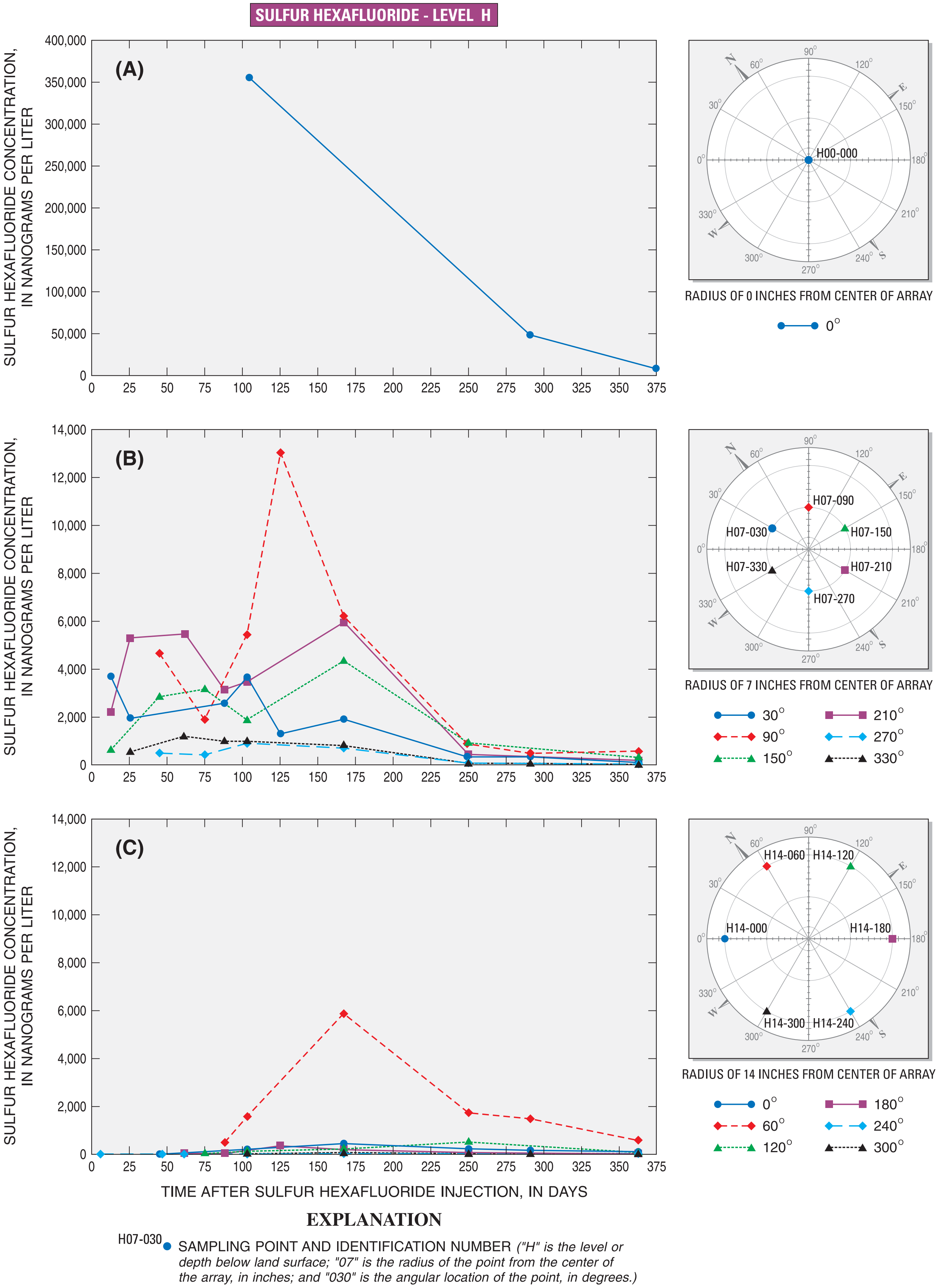


Figure 24. Sulfur hexafluoride concentrations with time for sampling points in level H, 48 inches below land surface, at radii of **(A)** 0 inches, **(B)** 7 inches, and **(C)** 14 inches from the center of the array.

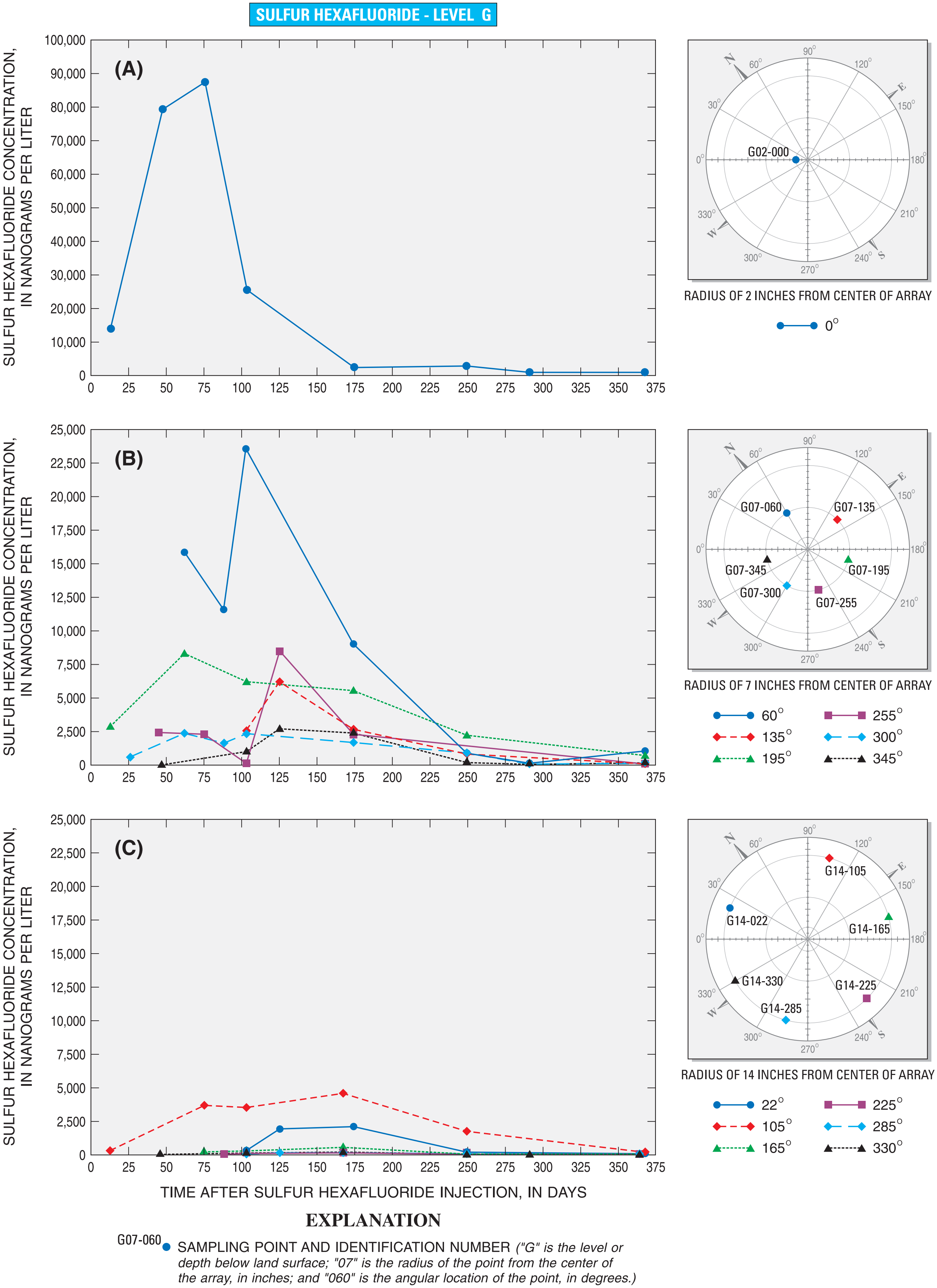


Figure 25. Sulfur hexafluoride concentrations with time for sampling points in level G, 42 inches below land surface, at radii of **(A)** 2 inches, **(B)** 7 inches, and **(C)** 14 inches from the center of the array.

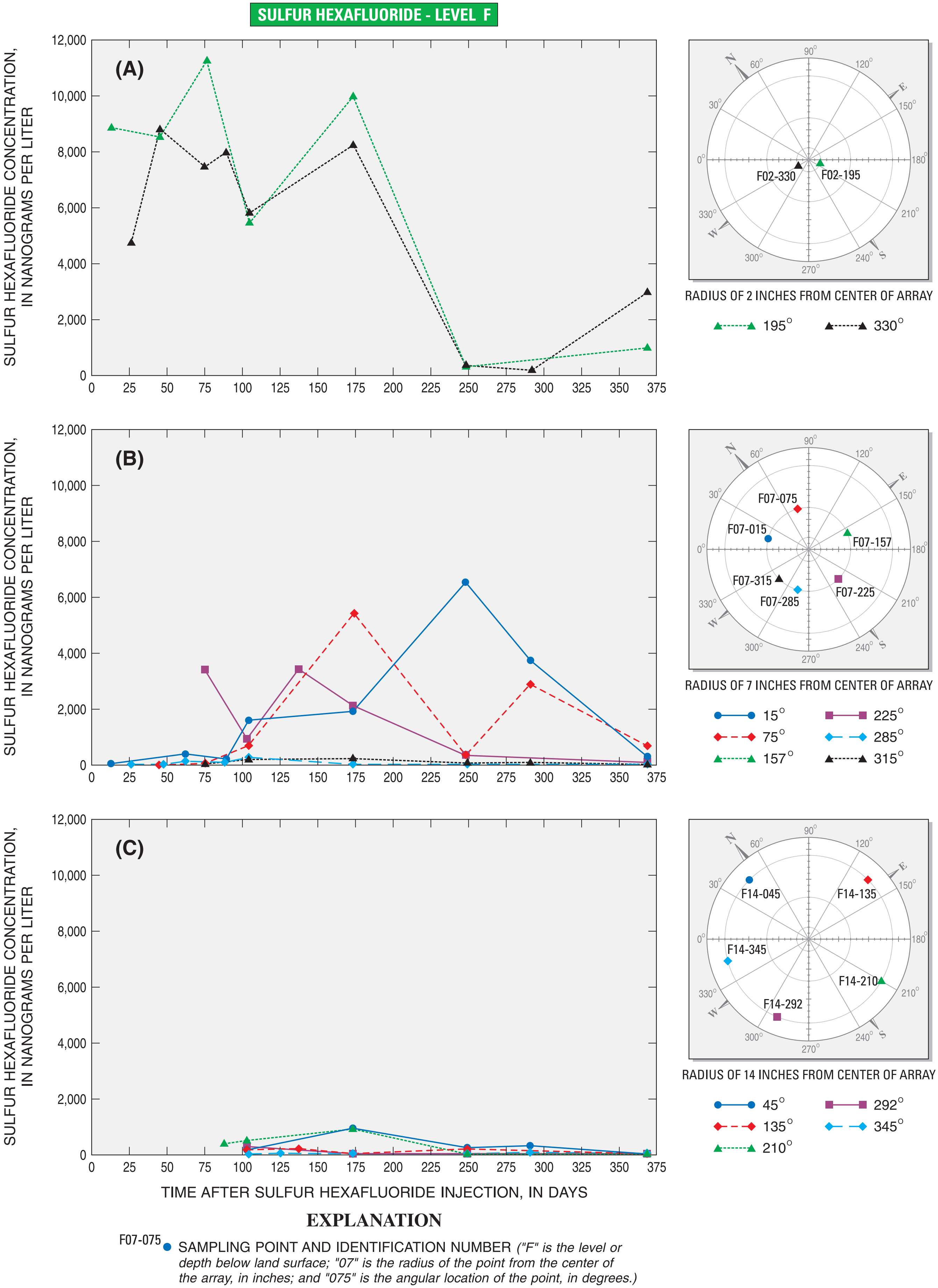


Figure 26. Sulfur hexafluoride concentrations with time for sampling points in level F, 36 inches below land surface, at radii of **(A)** 2 inches, **(B)** 7 inches, and **(C)** 14 inches from the center of the array.

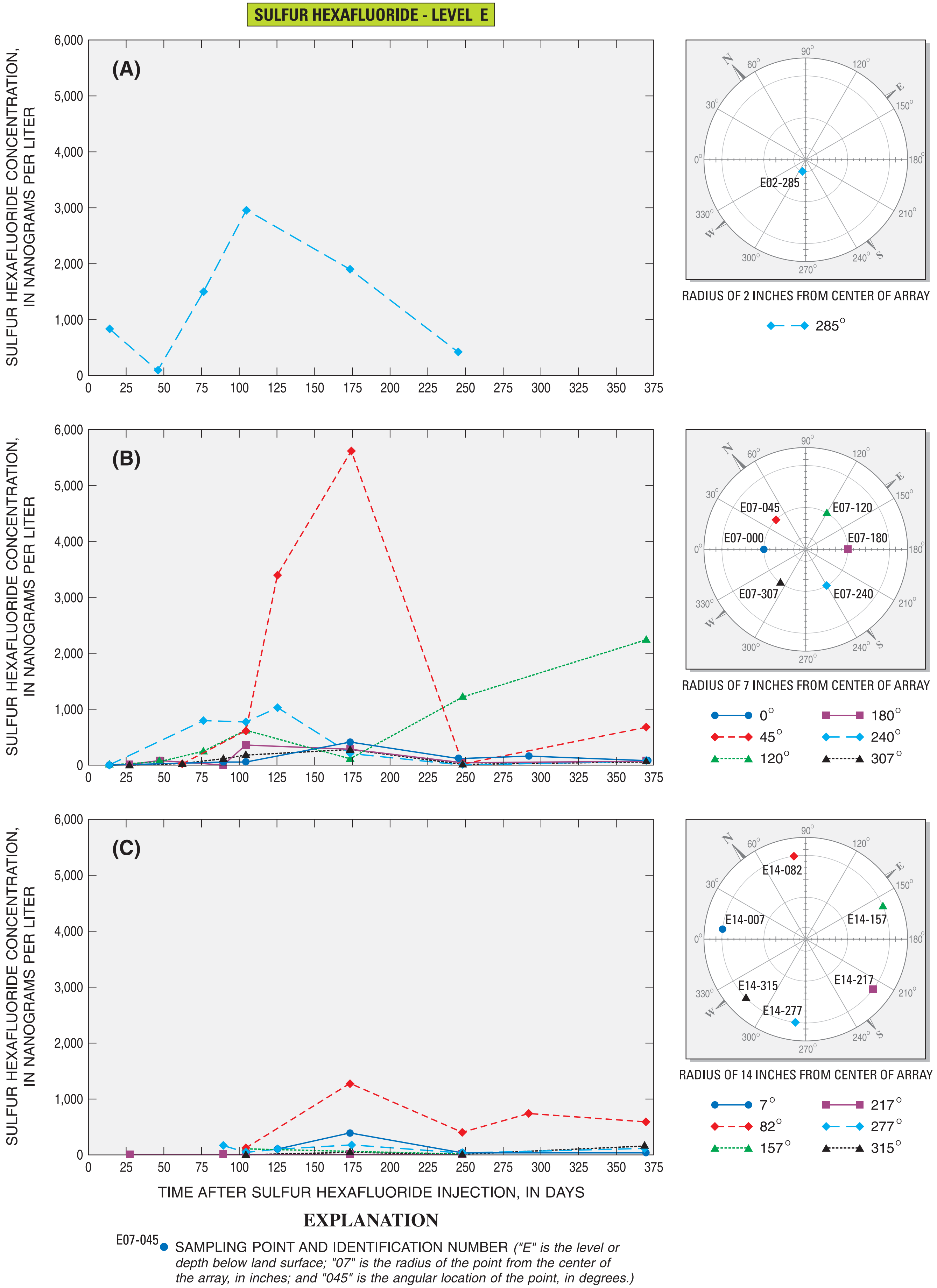


Figure 27. Sulfur hexafluoride concentrations with time for sampling points in level E, 30 inches below land surface, at radii of **(A)** 2 inches, **(B)** 7 inches, and **(C)** 14 inches from the center of the array.

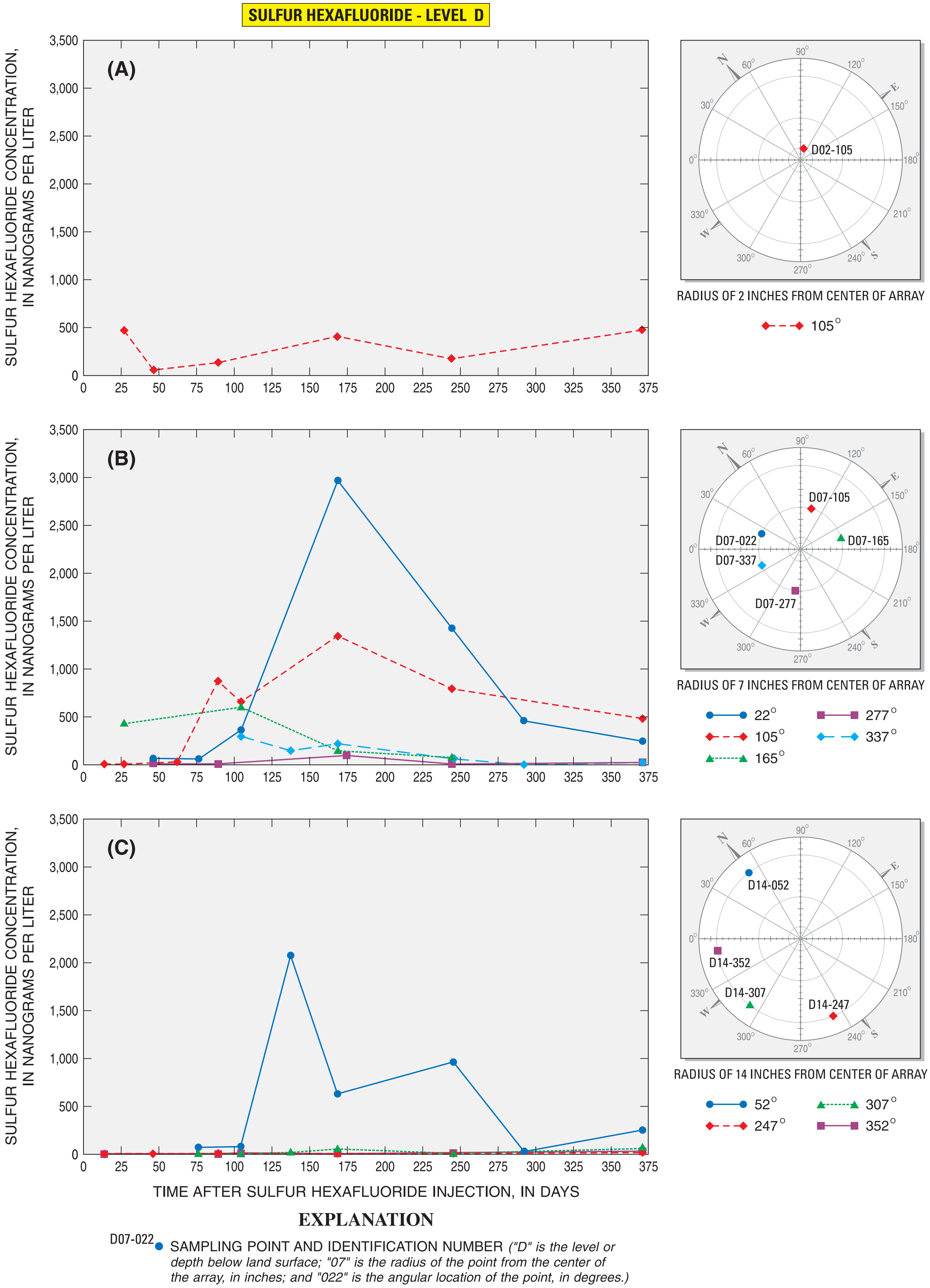


Figure 28. Sulfur hexafluoride concentrations with time for sampling points in level D, 24 inches below land surface, at radii of **(A)** 2 inches, **(B)** 7 inches, and **(C)** 14 inches from the center of the array.

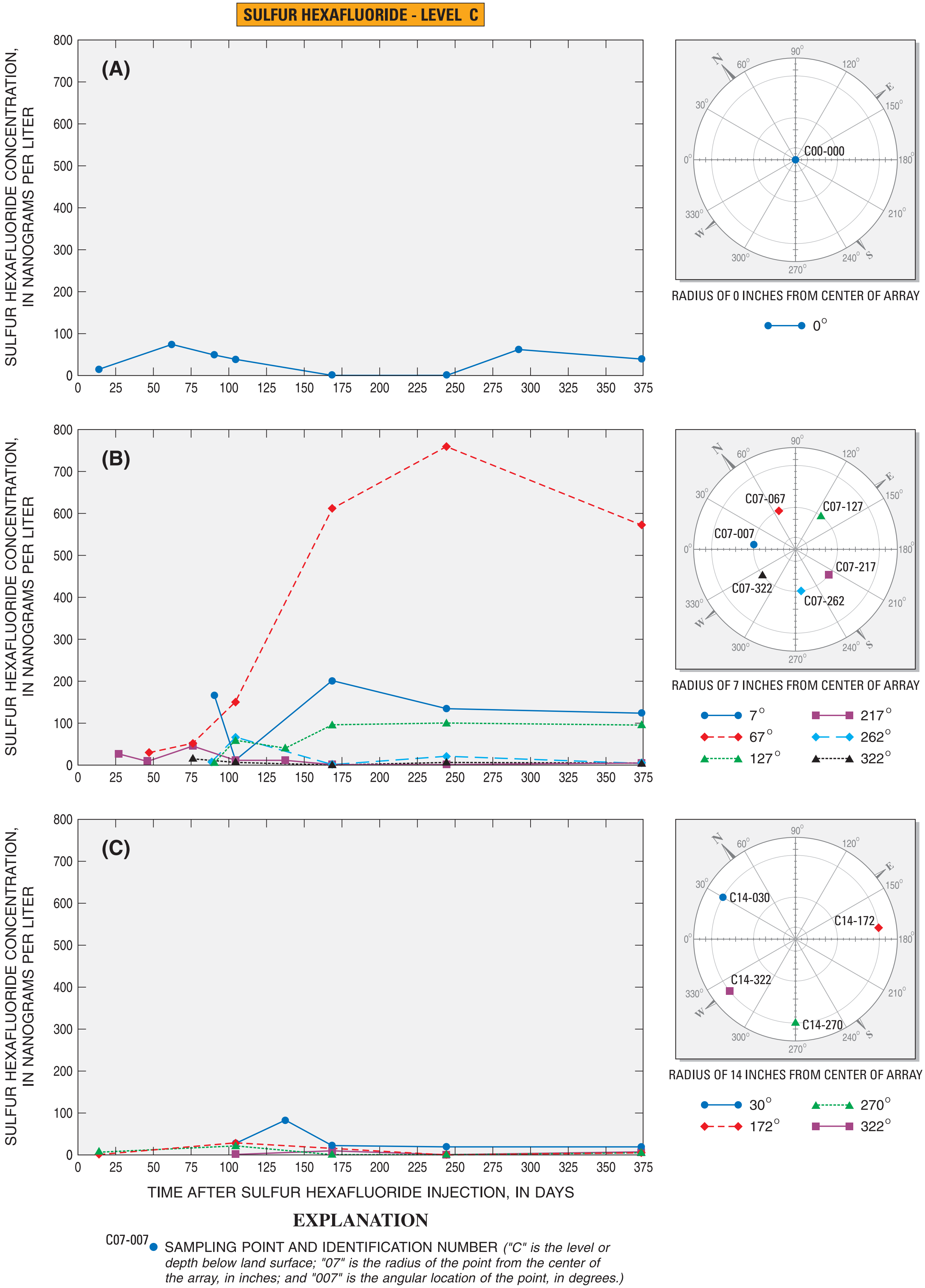


Figure 29. Sulfur hexafluoride concentrations with time for sampling points in level C, 18 inches below land surface, at radii of **(A)** 0 inches, **(B)** 7 inches, and **(C)** 14 inches from the center of the array.

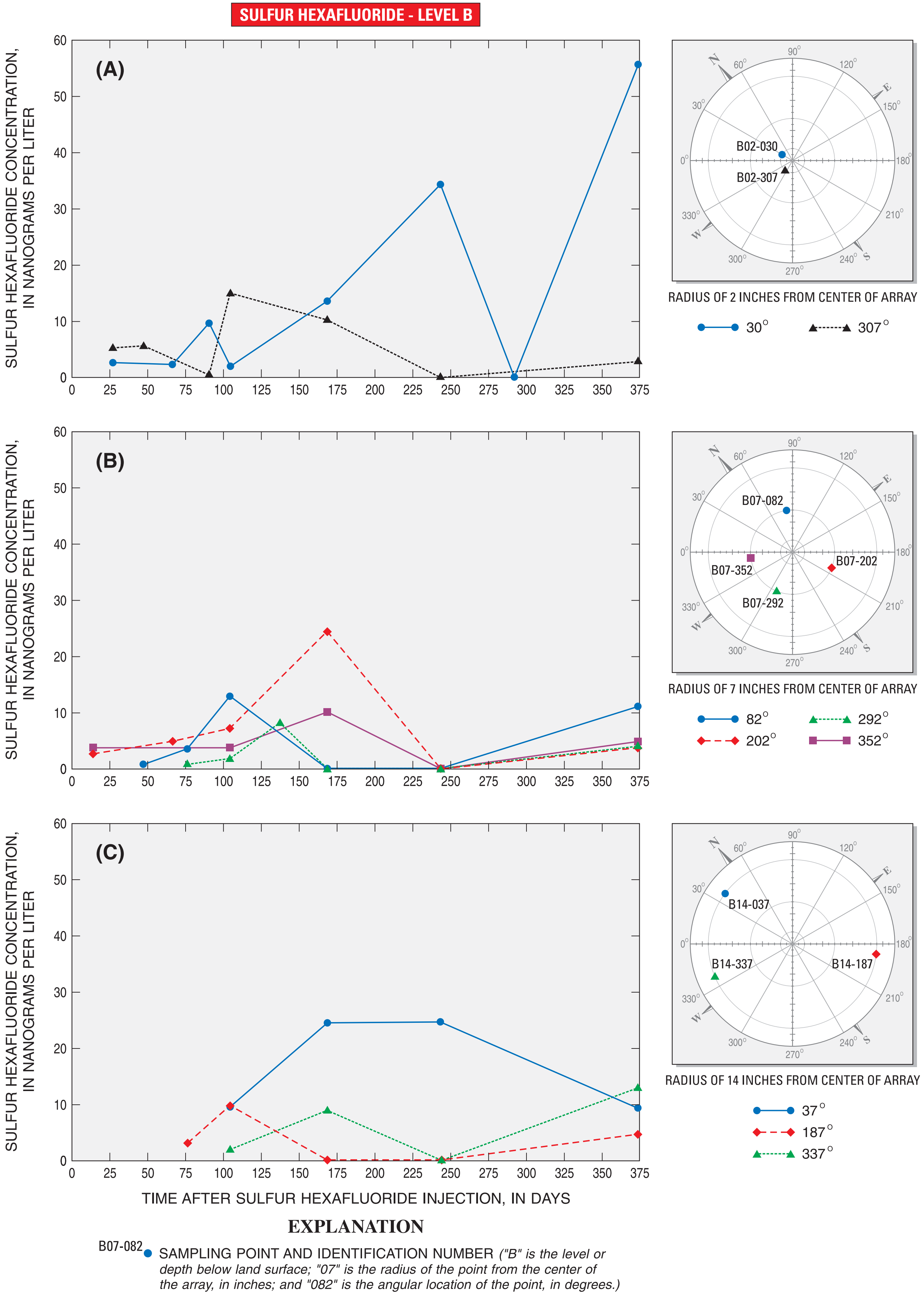


Figure 30. Sulfur hexafluoride concentrations with time for sampling points in level B, 12 inches below land surface, at radii of **(A)** 2 inches, **(B)** 7 inches, and **(C)** 14 inches from the center of the array.

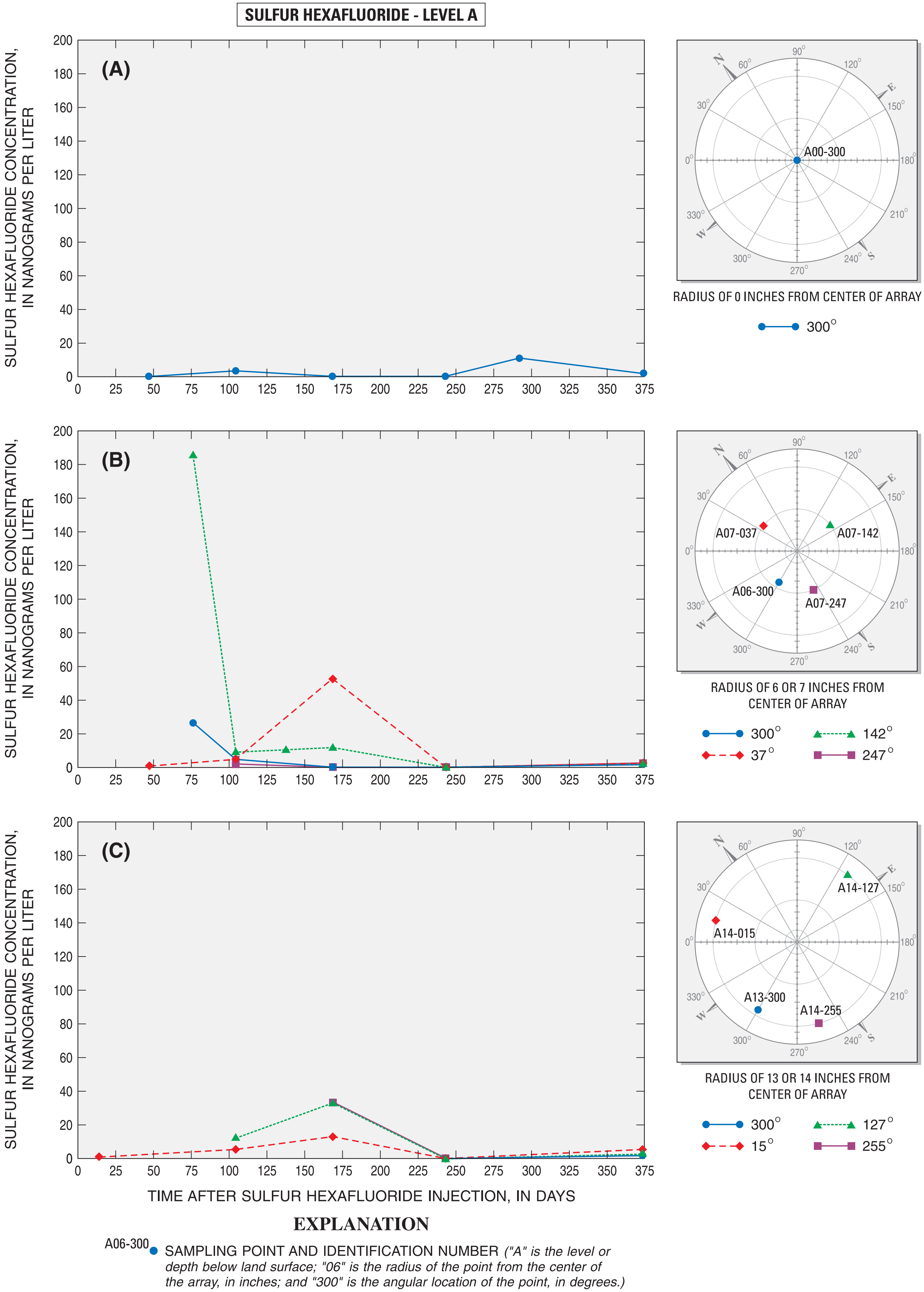


Figure 31. Sulfur hexafluoride concentrations with time for sampling points in level A, 6 inches below land surface, at radii of **(A)** 0 inches, **(B)** 6 or 7 inches, and **(C)** 13 or 14 inches from the center of the array.

10 times the peak concentration at the sampling point in the center of the array (72.3 ng/L at C00-000), and slightly less than 10 times the peak concentration on the 14-in. radius (82.8 ng/L at C14-030).

Level B—Breakthrough curves for sulfur hexafluoride concentrations in level B, which was 36 in. above the injection level and 12 in. below land surface, are shown in figures 30a–c. Breakthrough curves of concentrations of sulfur hexafluoride for sampling points on the 2-in. radius did not appear to have definitive peaks (fig. 30a). The largest peak concentration on the 2-in. radius in level B was the last sample collected from B02-307 (fig. 30a). It should be noted that the sulfur hexafluoride concentration was larger in the last sample (375 days) at each location than at the sample before, collected 243 days after tracer injection (fig. 30b). For the sampling points in level B on the 14-in. radius (fig. 30c), peak concentrations for the sulfur hexafluoride probably occurred between sampling dates.

Level A—Sulfur hexafluoride breakthrough curves for level A, located 6 in. below land surface and 42 in. above the injection level, are shown in figures 31a–c. The peak concentration of sulfur hexafluoride in the center of level A (A00-300, fig. 31a) was about 11 ng/L, which is very small. A much larger concentration of 186 ng/L was detected in the first sample collected from A07-142, on the 7-in. radius of the tracer array (fig. 31b). Peak concentrations detected in samples from the 14-in. radius at this level were similar in magnitude to those at the sampling point in the center of the array.

Isoconcentration Contour Plots

To facilitate interpretation of the tracer-test data and communication of the results, two-dimensional representations of the tracer concentration distributions were constructed for the four major sampling episodes (three for fluorescein). These two-dimensional representations include planar “depth slices” for the eight depths that were sampled throughout the experiment, and for the data points that were nearest to a single vertical planar section oriented along a north-south axis (figs. 32a–c, 33a–d, and 34a–d). Concentration values were plotted and isoconcentration contour lines were drawn for each horizontal depth slice and vertical planar section. Isoconcentration contour lines were generated using S-Plus 2000 Professional Release 3 (Copyright 1988-2000, Mathsoft, Inc.), using bivariate interpolation to perform smooth-surface fitting for the data, following methods described in Akima (1978). The resulting isoconcentration contours were then manually adjusted, using professional judgment, to eliminate or correct spurious results in data-poor areas of the plots and to accommodate knowledge of the system that could not be captured using pure bivariate interpolation.

Isoconcentration contour plots were generated for each of the three tracer compounds (fluorescein dye, bromide, and sulfur hexafluoride). Although fluorescein dye is considered to be a non-conservative tracer and would be expected to adsorb to sediments, its movement (or relative lack thereof) is useful as an indicator of the hydrologic integrity of the tracer array (figs. 32a–c). Hydrologic short-circuiting due to potential preferential flow along the sides of the injection piezometer or sampling piezometers, if it occurred, was expected to be noticeable as rapid upward movement of the dye within the first month of the tracer test. Such movement was not evident throughout the period of the tracer test (figs. 32a–c). Indeed, the fluorescein dye exhibited relatively little movement, even at 412–424 days after injection (fig. 32c). The behavior of the fluorescein dye, as illustrated by the isoconcentration contours, could provide insight into the likely behavior of other non-conservative solutes with similar properties.

As discussed earlier, the analysis of spatial moments is an effective way to track tracer mass over time and to fully characterize the results of a three-dimensional tracer test. This analysis ordinarily is accomplished by numerically solving one or more triple integrals of tracer concentration in the three-dimensional space of the test domain. The numerical integration would require that the tracer concentrations be interpolated onto a pre-determined grid. For the tracer experiment at West Branch Canal Creek, however, this would be difficult to do accurately because the concentration data (Appendix B2, and figs. 33–34) indicate that for the conservative tracers, much of the tracer mass was transported beyond the lateral boundaries of the tracer array, possibly because of density differences between the tracer solution and the ambient ground water in the early part of the test, or because of dispersive processes. Tracer concentrations in samples collected from piezometers in the 14-in. radius of the tracer array often were above the RLs. It is likely that tracer mass lost beyond the lateral boundaries of the array remained in close proximity to the array; however, the concentrations outside of the tracer array were not routinely measured. This means that the total mass cannot be accounted for by interpolation within the volume contained within the array of the sampling points, and that extrapolation would also be required. Unfortunately, there is no clear way to ensure that the method of extrapolation would produce the correct results, as different extrapolation assumptions would result in different interpreted configurations of tracer mass within and outside of the array.

In the analysis that follows, the tracer array was assumed to represent a cylinder of material that extended slightly beyond the volume delineated by the sampling points themselves. The height of this cylinder was assumed to be 48 in., extending from 3 in. above level A (6 in. below land surface) to 3 in. below level H (the injection level, 48 in. below land surface). This dimension was selected so that the volume of material from beyond the top and bottom levels of sampling points was equivalent to one-half of the volume contained between sampling levels. The radius of this cylinder was assumed to be 16.4 in., which was selected so that the volume of material between radii of 14 and 16.4 in. was equivalent to one-half of the volume contained between the 7- and 14-in. radii of sampling points. On the basis of the volume for a porous cylinder of the above specifications and an effective porosity of 0.40 (porosity from Lorah and others,

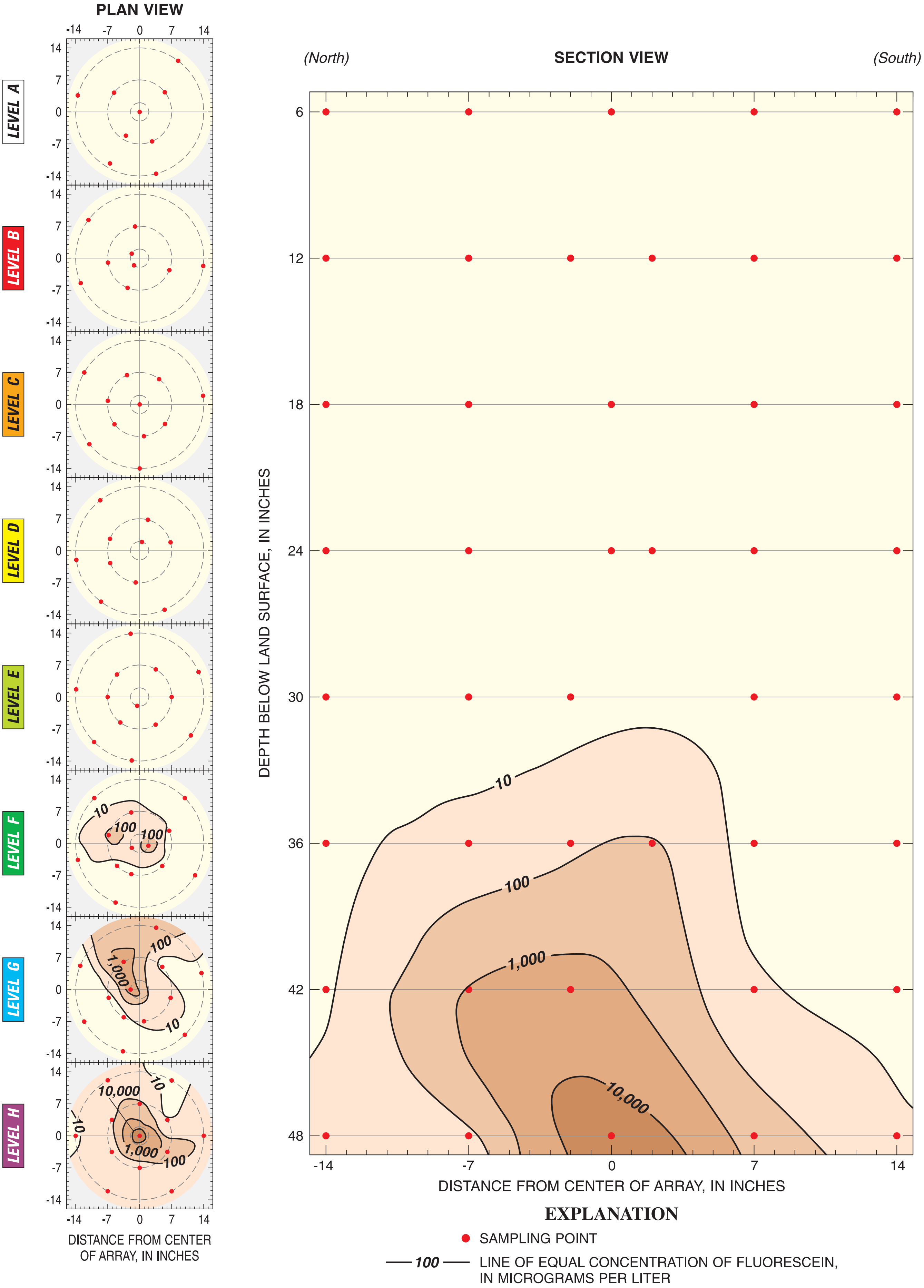


Figure 32a. Contour plots of fluorescein concentration by layer and along a north-south cross section of the tracer array at time steps of 152-153 days after tracer injection.

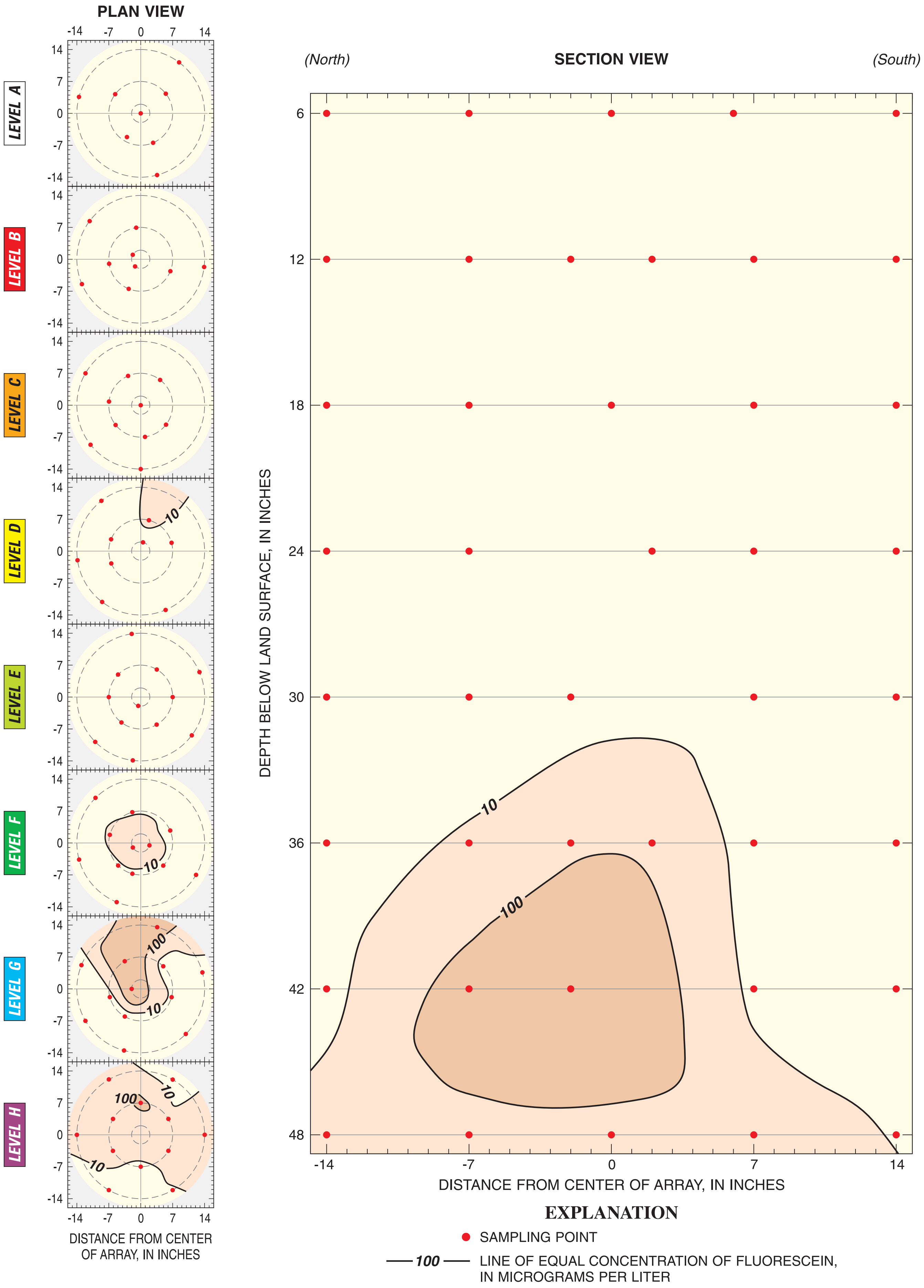


Figure 32b. Contour plots of fluorescein concentration by layer and along a north-south cross section of the tracer array at time steps of 292-299 days after tracer injection.

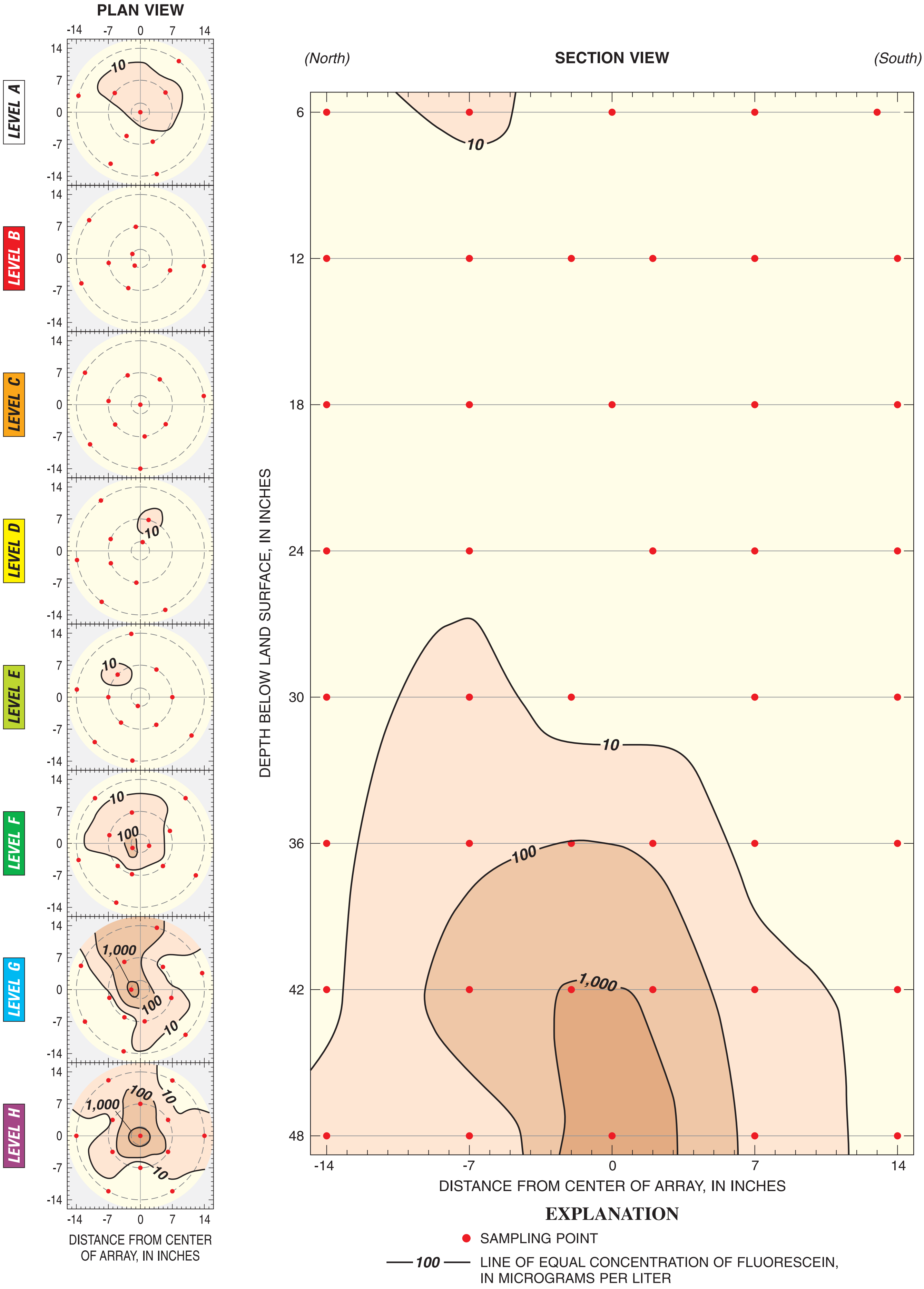


Figure 32c. Contour plots of fluorescein concentration by layer and along a north-south cross section of the tracer array at time steps of 412-424 days after tracer injection.

1997), the volume of water represented by the tracer array was determined to be 266 liters (L). If a higher porosity value of 0.55 were assumed, which would be consistent with National Soil Survey Center data for the area (Soil Survey Staff, 2004), the volume of water represented by the tracer array would be 366 L.

Estimates of the total tracer mass measured in the array were obtained for bromide and sulfur hexafluoride for each of the four major sampling episodes by multiplying the mean concentration for each sampling episode by the volume of water represented by the array. The tracer mass values for each major sampling episode were then divided by the injected tracer mass to determine the percentage of the original tracer mass that was recovered, and to evaluate possible mass loss outside of the sampled volume. [The mass of bromide initially injected into the array was 13,900 milligrams (100,000 mg/L * 0.139 L), and the mass of sulfur hexafluoride injected into the array was 3.2 x 10^6 nanograms (23.3 mg/L * 0.139 L).] Tracer mass values calculated in this manner can be uncertain because (1) the porosity is not known with certainty, (2) all of the sampling points were weighted equally even though they were not uniformly spaced throughout the array, and (3) tracer concentrations between sampling points and immediately outside of the array were assumed to be represented by the points that were sampled.

Bromide Concentrations The isoconcentration contour plots for bromide concentrations within the tracer array during the four major sampling episodes are shown in figures 33a–d. Isoconcentration contour plots representing sampling results from 103–104 days (fig. 33a), 167–174 days (fig. 33b), 243–250 days (fig. 33c), and 363–375 days (fig. 33d) after injection illustrate the movement of the bromide tracer over time.

The results of the first major sampling episode for bromide (103–104 days after tracer injection) are shown in figure 33a. The highest bromide concentration during this sampling episode (296 mg/L) was in level G (42 in. below land surface, and 6 in. above the injection layer), near the center of the array (fig. 33a). This concentration is almost three orders of magnitude smaller than the injected concentration of 100,000 mg/L, indicating that considerable dilution of the tracer slug had occurred. In addition, bromide concentrations greater than the background level of 0.5 mg/L (Spencer and others, 2000) were detected at all of the sampling points during this time step, which indicates that bromide was transported upwards and outwards into the array, and possibly beyond the boundaries of the array. Concentrations as high as 59 mg/L were detected in samples from the outermost radius of 14 in. (at level D, 24 in. above the injection layer), which indicates the loss of bromide out of the side of the array. The concentration distribution (fig. 33) also indicates that the tracer movement was mostly upwards, with a slight bias to the north. The mean bromide concentration for all samples from the first major sampling episode was 35.6 mg/L. Multiplying by the water volume in the array (266 L, assuming an effective porosity of 0.40) gives an estimated mass of 9,500 mg (milligrams) of bromide, or about 68 percent of the injected tracer mass. If an effective porosity of 0.55 were assumed, the tracer mass for bromide measured during the first major sampling episode would be about 13,000 mg, or approximately 94 percent of the injected tracer mass.

The second major sampling episode for bromide took place 167–174 days after injection. The results (fig. 33b) show little evidence of upward tracer transport compared to the previous sampling episode (fig. 33a). There was evidence, however, of horizontal movement to the north, indicated in levels D, F, and G, 24 to 42 in. below land surface (6 to 24 in. above the injection level). As with the first sampling episode, bromide concentrations above background (0.5 mg/L) were present in samples collected from the outer radius of the tracer array at all depths (fig. 33b), which indicates horizontal loss of bromide from the array. One unexpectedly large bromide concentration (214 mg/L at E14-277) was seen in the horizontal depth slice for level E (30 in. below land surface, 18 in. above the injection level), on the outside edge of the tracer array (fig. 33b). This concentration is about two orders of magnitude greater than the concentration at the same sampling point at 103–104 days after injection (fig. 33a). A transport pathway for this high bromide concentration is not evident from examination of the breakthrough curves (figs. 16–23) and the data table (Appendix B2); however, several potential causes of this anomalous concentration were noted in the earlier discussion of break-though curves for bromide on level E (p. 48, fig. 19c.), including the possibility that a slug of tracer moved towards E14-277 through a preferential pathway between the sampling points in the lower layers. The mean bromide concentration for the second major sampling episode was 13.4 mg/L, which indicates that an estimated mass of about 3,600 mg (26 percent of the initial mass) of bromide remained within the array, if an effective porosity of 0.40 were assumed. If an effective porosity of 0.55 were assumed, the bromide mass accounted for in the second major sampling episode would be about 4,900 mg, or 35 percent of the initial mass.

The third complete sampling episode (243–250 days after injection, fig. 33c) also did not indicate much upward movement, other than the reduced concentrations apparent in levels G and H (42 and 48 in. below land surface, respectively). Concentrations in all levels, however, appeared to be reduced, as only three sampling points had bromide concentrations greater than 10 mg/L (fig. 33c). Bromide concentrations at some points in levels F, G, and H (36, 42, and 48 in. below land surface) were at background levels (0.5 mg/L or less), and many points had bromide concentrations between 0.5 and 1 mg/L (fig. 33c). As with the earlier sampling periods (figs. 33a–b), mass loss out of the sides of the array is apparent (fig. 33c). The estimated mass of bromide tracer, calculated based on a mean concentration of 2.0 mg/L for the third time step, was 540 mg (almost 4 percent of the initial mass) for an effective porosity of 0.40, or 740 mg (over 5 percent of the initial mass) for an effective porosity of 0.55.

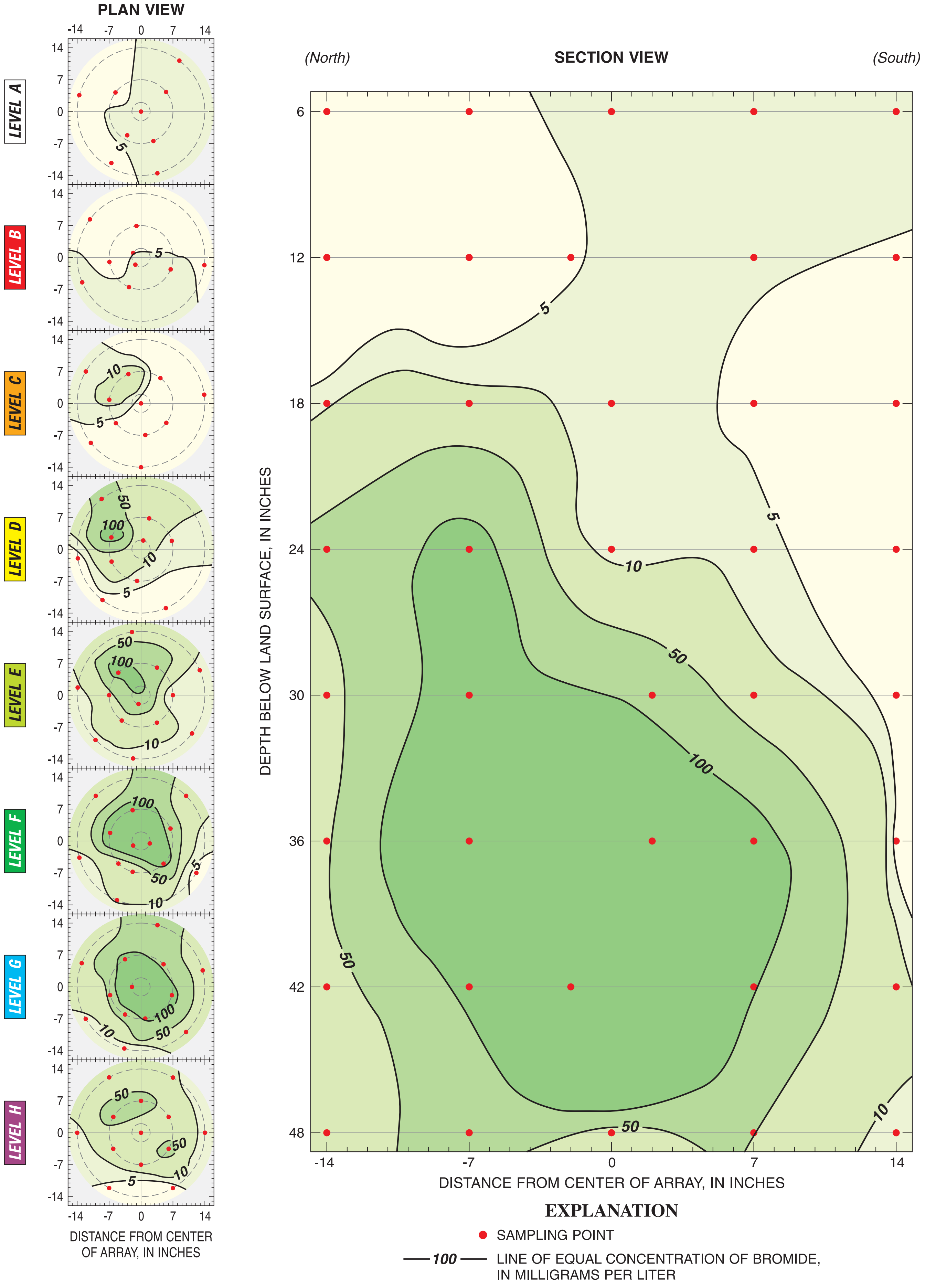


Figure 33a. Contour plots of bromide concentration by layer and along a north-south cross section of the tracer array at time steps of 103-104 days after tracer injection.

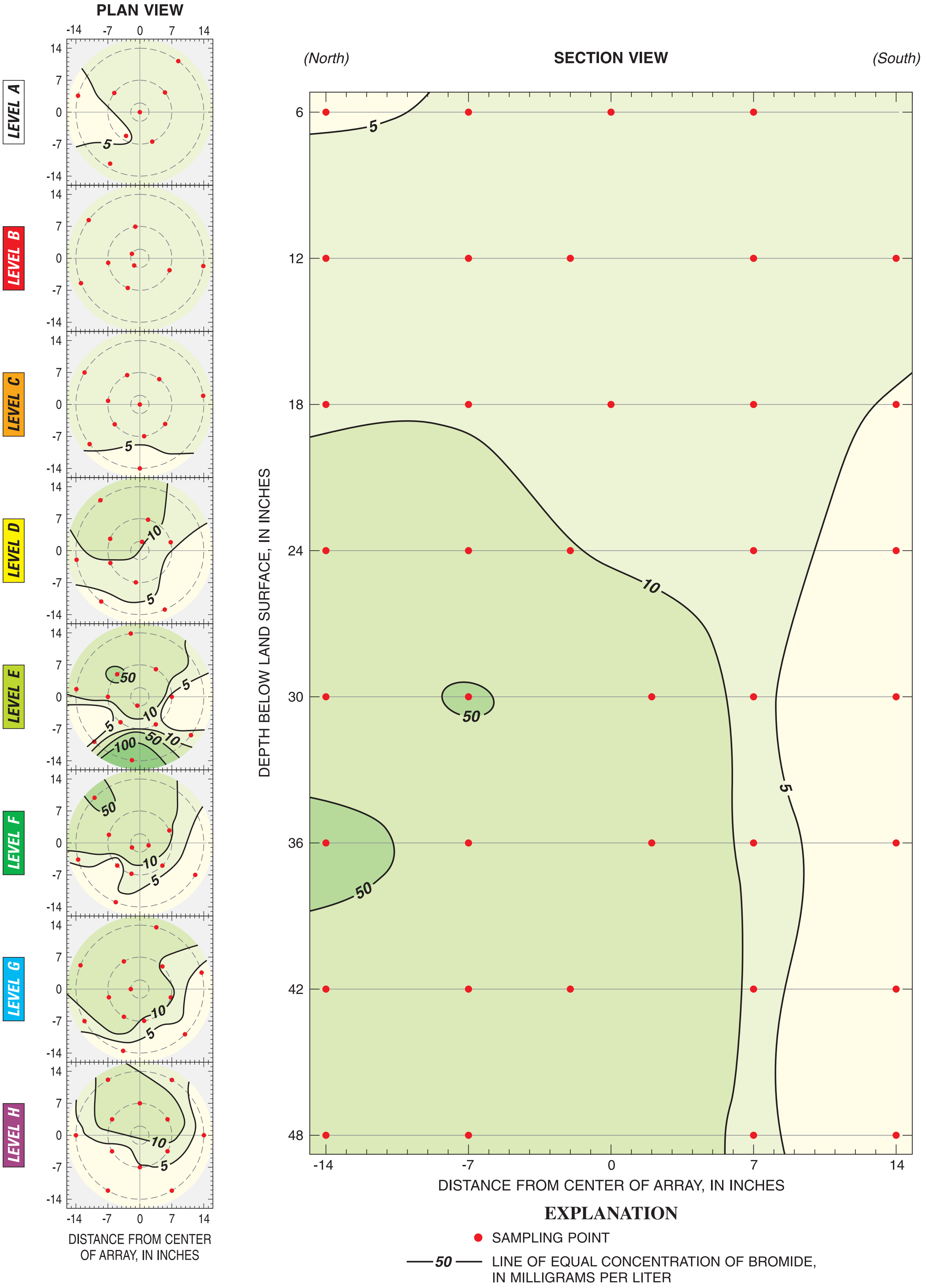


Figure 33b. Contour plots of bromide concentration by layer and along a north-south cross section of the tracer array at time steps of 167-174 days after tracer injection.

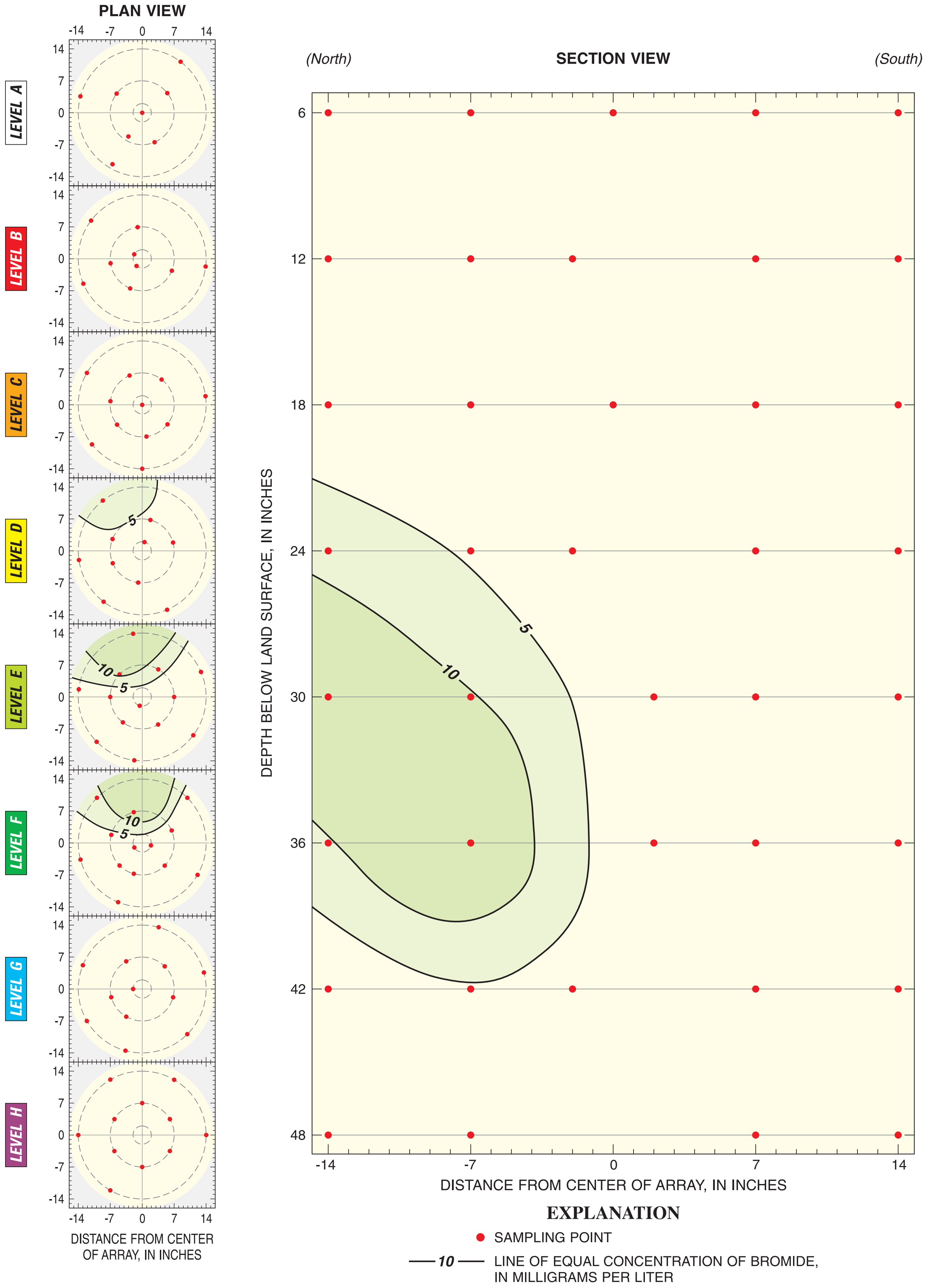


Figure 33c. Contour plots of bromide concentration by layer and along a north-south cross section of the tracer array at time steps of 243-250 days after tracer injection.

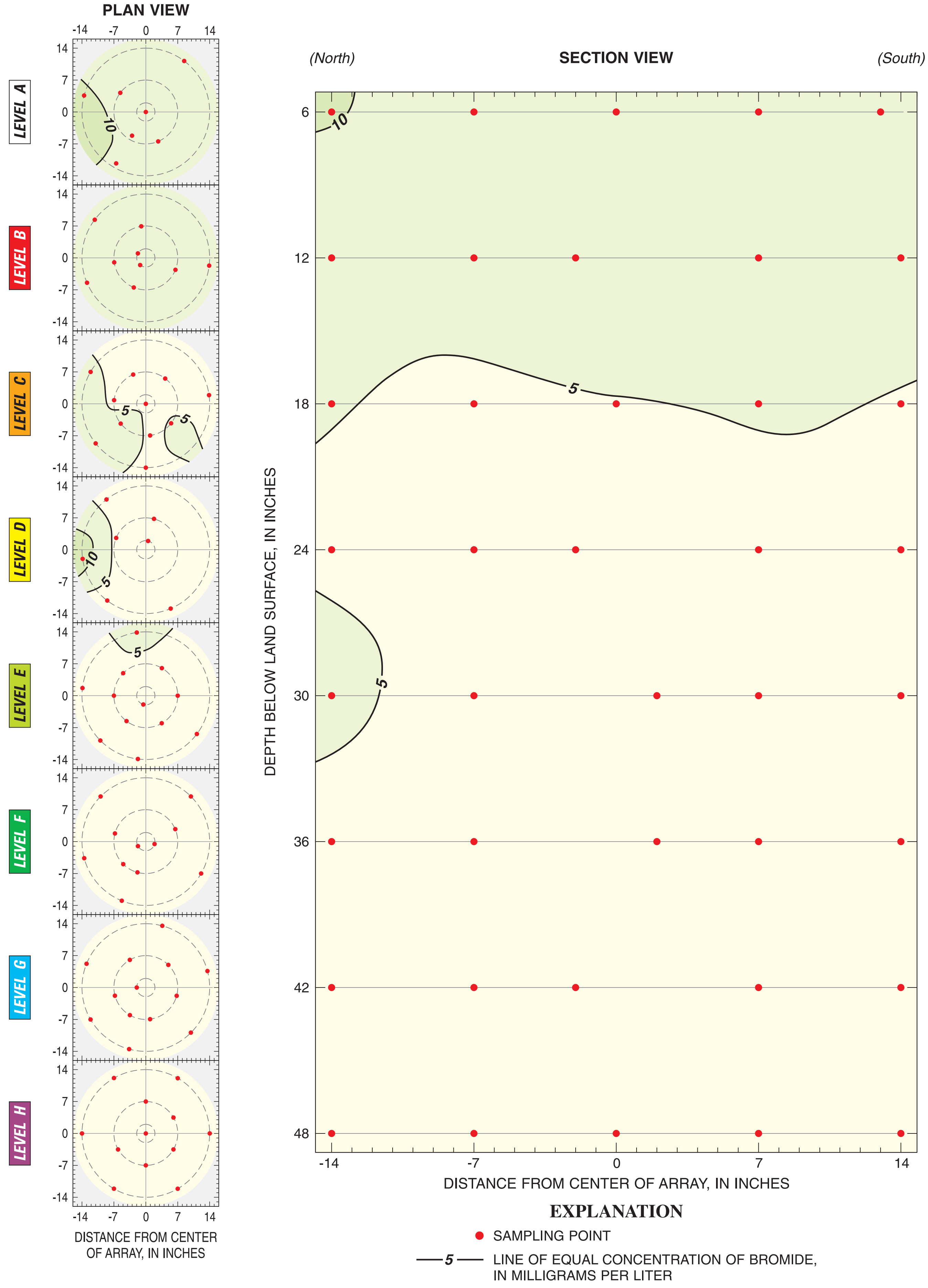


Figure 33d. Contour plots of bromide concentration by layer and along a north-south cross section of the tracer array at time steps of 363-375 days after tracer injection.

The fourth and final sampling episode took place 363–375 days after injection of the tracers (fig. 33d). Continuing the trend observed in the previous sampling episodes (figs. 33a–c), concentrations in levels G and H (42 and 48 in. below ground surface, fig. 33d) for the fourth sampling episode dropped below the reporting limit (1.0 mg/L), which is near the background concentration of 0.5 mg/L or less (Spencer and others, 2000). Bromide concentrations in the upper sampling points in the tracer array 6–12 in. below land surface, (fig. 33d) unexpectedly increased, however, after having decreased during the previous two sampling episodes (figs. 33b–c). These concentrations are an order of magnitude above background levels, so it is likely that they resulted from injected bromide tracer rather than background concentrations of bromide in the ambient ground water; however, the cause of the late increase in concentrations is not known. The mean concentration of bromide during the fourth sampling episode (3 mg/L) was slightly larger than the mean from the third sampling episode (2 mg/L). The mass of bromide in the fourth sampling episode was estimated to be 880 mg (about 6 percent of the initial mass) based on an effective porosity of 0.40, or 1,200 mg (almost 9 percent of the initial mass) based on an effective porosity of 0.55.

The inferred movement of bromide tracer (figs. 33a–d), coupled with the apparent loss of tracer mass throughout the test, shows qualitatively that in addition to vertical flow, there is a northward horizontal component to ground-water flow in the area of the tracer array. As it is possible that the tracer solution sank below the injection point at the beginning of the test and then did not move as a discrete pulse, calculations of the magnitude or direction of the velocity vector from these data would have some degree of uncertainty.

Sulfur Hexafluoride Concentrations Isoconcentration contour plots were constructed for sulfur hexafluoride concentrations to show the movement of this tracer over time (figs. 34a–d). The four major sampling episodes for sulfur hexafluoride were the same as for the bromide: 103–104 days (fig. 34a), 167–174 days (fig. 34b), 243–250 days (fig. 34c), and 363–375 days (fig. 34d) after tracer injection.

The results of the first complete sampling episode for sulfur hexafluoride (103–104 days after tracer injection) are shown in figure 34a. In contrast with the results from the bromide tracer (fig. 34a), the largest concentration of sulfur hexafluoride tracer (355,584 ng/L) was detected at the injection point rather than at a sampling point in the next highest level. This concentration is less than 2 percent of the initial sulfur hexafluoride tracer concentration (23,300,000 ng/L), which represents dilution that is similar to the dilution of the largest concentration of bromide (relative to the initial concentration) during the first sampling episode.

As with bromide, the movement of sulfur hexafluoride between the time of injection and the first major sampling episode (fig. 34a) appeared to be upward, with a slight bias to the north, primarily in levels H and G (48 and 42 in. below land surface, respectively). A concentration of 1,376 ng/L of sulfur hexafluoride at one sampling point and many other detections greater than 100 ng/L on the outermost (14-in.) radius indicate the loss of tracer mass beyond the lateral boundaries of the array (fig. 34a). In addition, the mean concentration of sulfur hexafluoride for the first major sampling episode was 6,150 ng/L, which, when multiplied by the water volume in the array, gives an estimated mass of 1.64×10^6 ng, or about 51 percent of the initial mass of sulfur hexafluoride injected at the beginning of the tracer test, if a porosity of 0.40 is assumed. If a porosity of 0.55 were assumed, the estimated mass of sulfur hexafluoride in the array would be 2.26×10^6 ng, or about 70 percent of the initial mass that was injected.

The second major sulfur hexafluoride sampling round took place 167–174 days after tracer injection. No sample was collected at the injection point during this sampling episode. The highest tracer concentration (25,536 ng/L) was in level G, 6 in. above the injection level (fig. 34b). Concentrations larger than 1,000 ng/L were detected at two or more points in each of the bottom five sampling levels (48 to 24 in. below land surface), which was generally about 12 in. farther upward from the injection point than the locations in which similar concentrations had been measured during the first sampling episode. Lateral spreading had continued, with many sampling points on the 14-in. radius having concentrations larger than 1,000 ng/L (fig. 34b). A comparison of concentration distributions indicated that the tracer motion was upward and somewhat to the north between the first two sampling episodes. In the upper layers of the array (24 to 6 in. below land surface), concentrations at many points had decreased to less than 1 ng/L from higher values measured during the previous sampling episode, possibly indicating an influx of ambient ground water into those layers. The mean concentration of sulfur hexafluoride during the second major sampling episode was 1,500 ng/L. Multiplying this concentration by the water volume in the tracer array results in an estimated mass of about 12 percent of the amount that was initially injected if an effective porosity of 0.40 were assumed, or about 17 percent of the injected mass if an effective porosity of 0.55 were assumed.

The third major sampling round for sulfur hexafluoride occurred 243–250 days after tracer injection. Tracer concentrations from this sampling event (fig. 34c) appear to be distributed similarly to the previous sampling event, but more dilute. The largest concentration of sulfur hexafluoride detected for the third time step was 8,263 ng/L (in level F, 12 in. above the injection level), but no sample was collected from the injection point. Concentrations larger than 1,000 ng/L were detected at only seven other sampling points (fig. 34c) during this time step. Samples from nearly all locations in levels B and A (12 and 6 in. below land surface) had concentrations less than 1 ng/L. The mean concentration for the array during the third major sampling episode was 450 ng/L, which results in an estimated mass of 118,000 ng of sulfur hexafluoride (assuming an effective porosity of 0.40), or less than 4 percent of the initial injected mass. If an effective porosity of 0.55 were assumed, the esti-

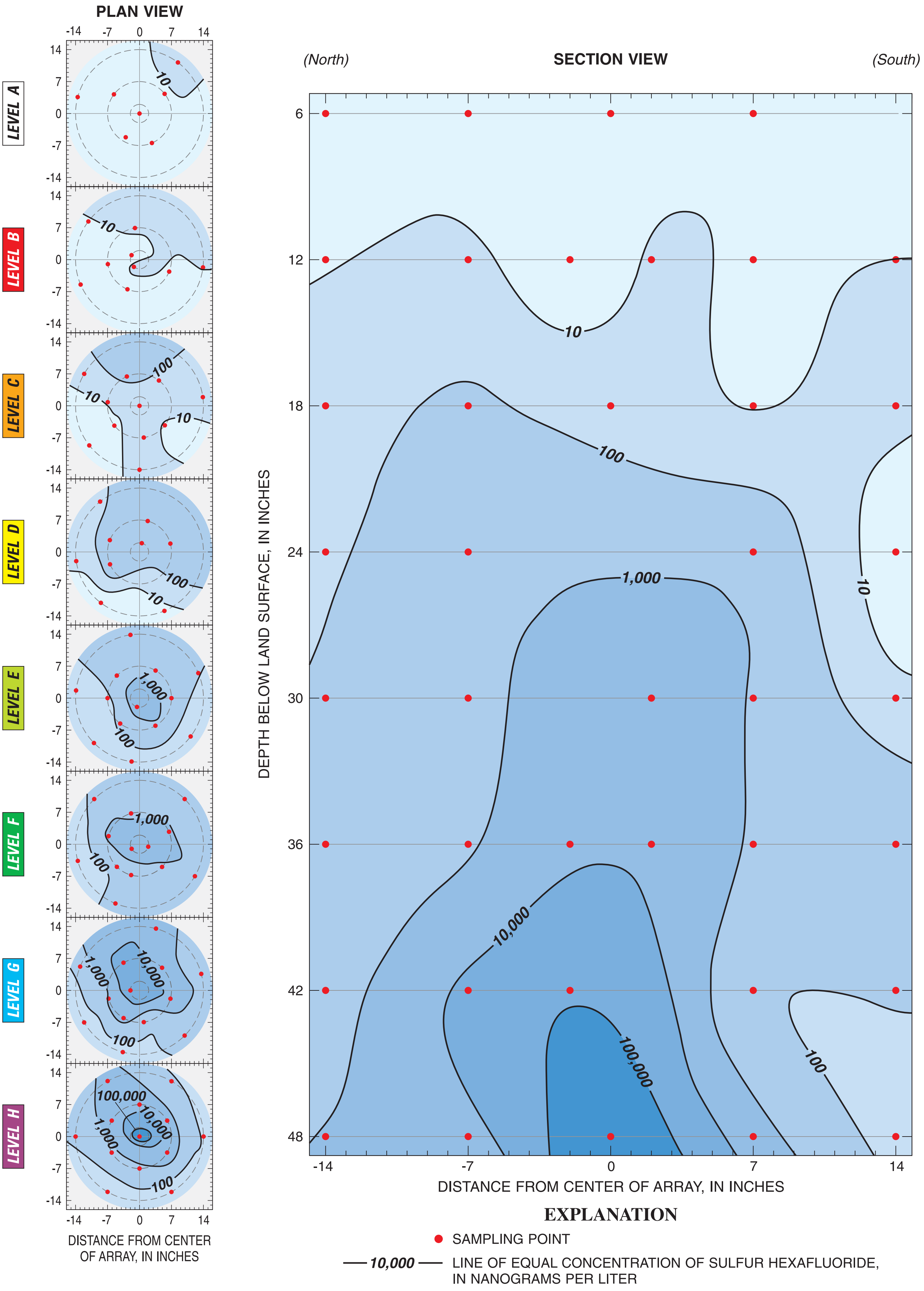


Figure 34a. Contour plots of sulfur hexafluoride concentration by layer and along a north-south cross section of the tracer array at time steps of 103-104 days after tracer injection.

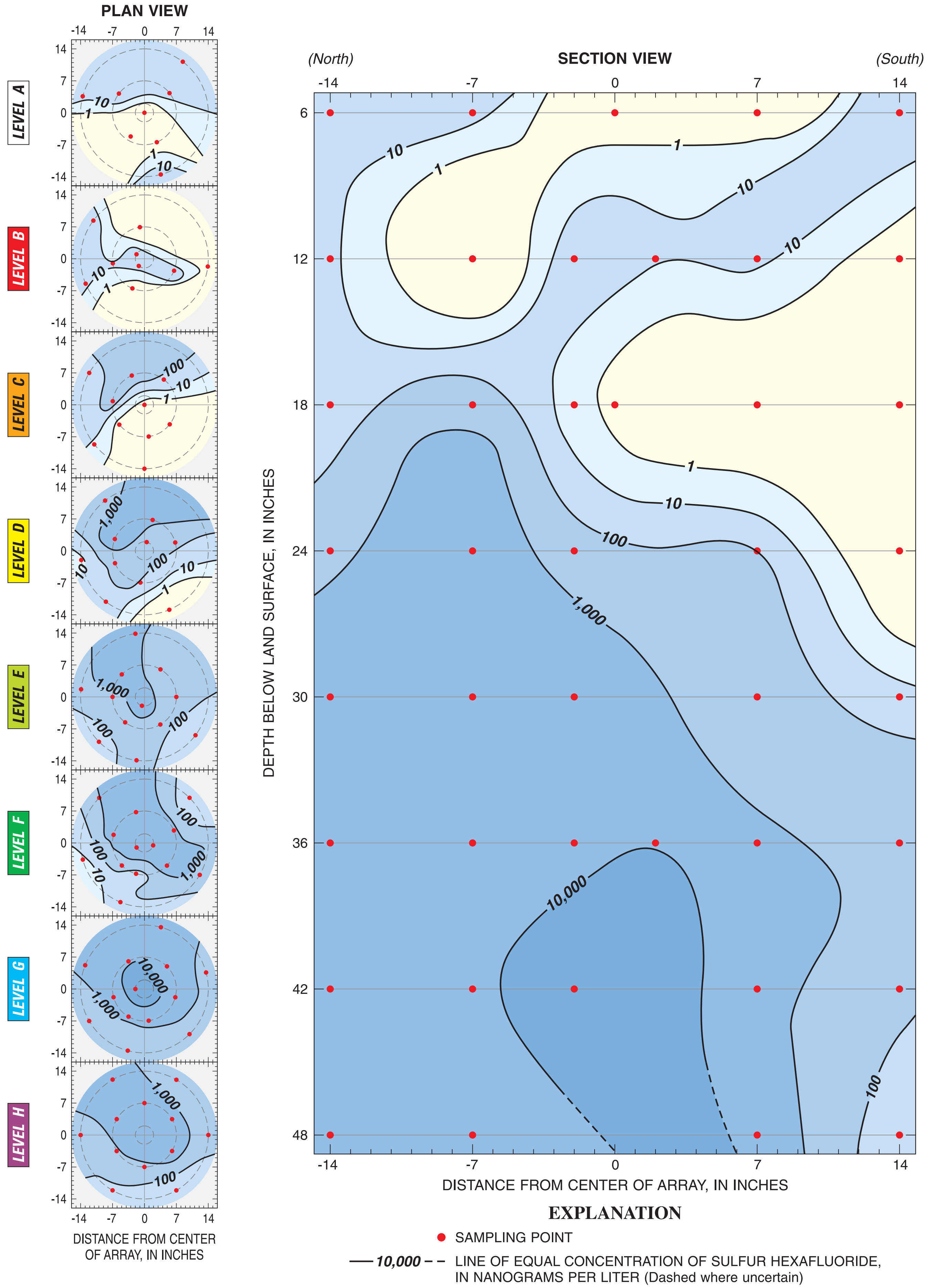


Figure 34b. Contour plots of sulfur hexafluoride concentration by layer and along a north-south cross section of the tracer array at time steps of 167-174 days after tracer injection.

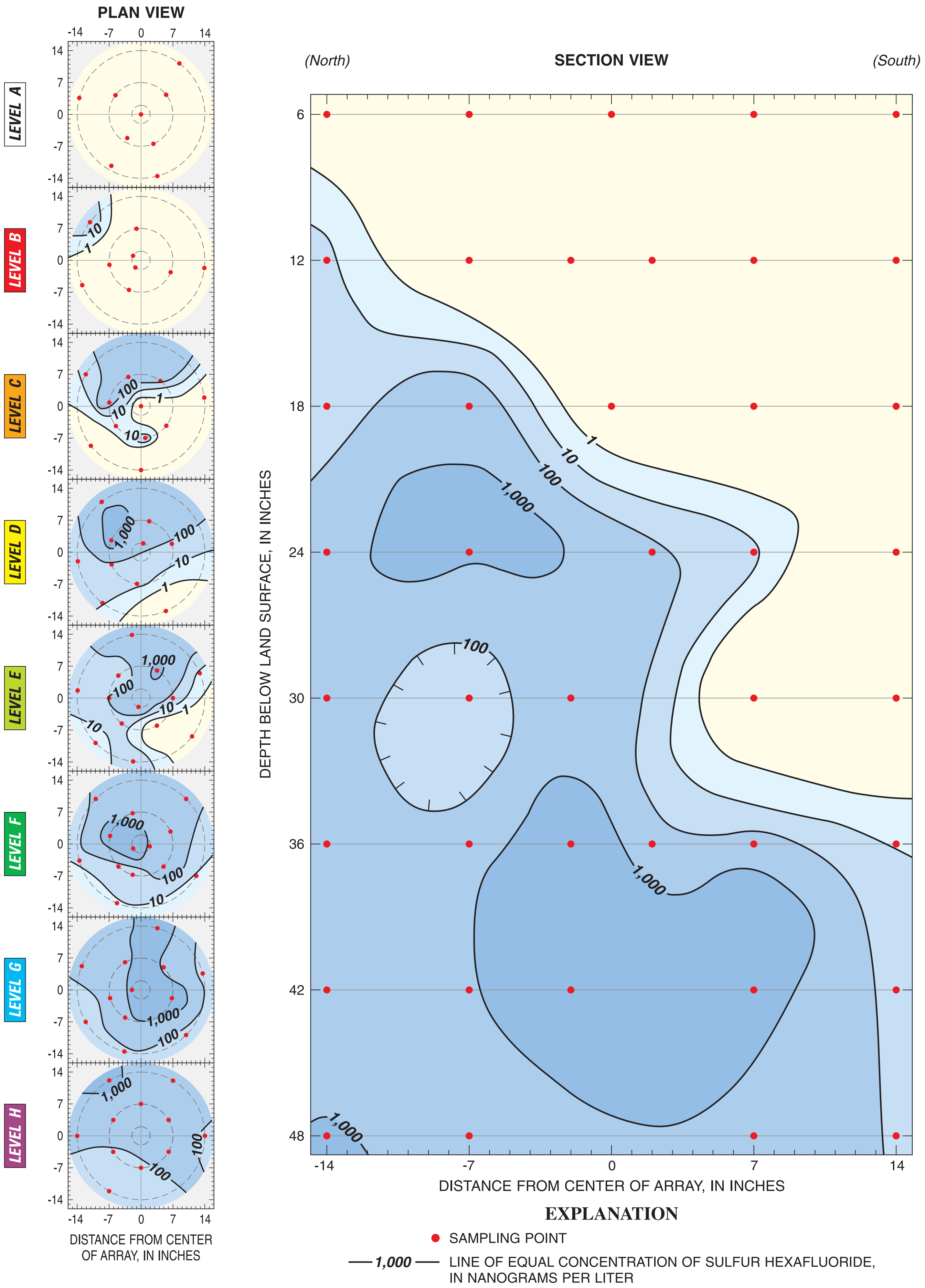


Figure 34c. Contour plots of sulfur hexafluoride concentration by layer and along a north-south cross section of the tracer array at time steps of 243-250 days after tracer injection.

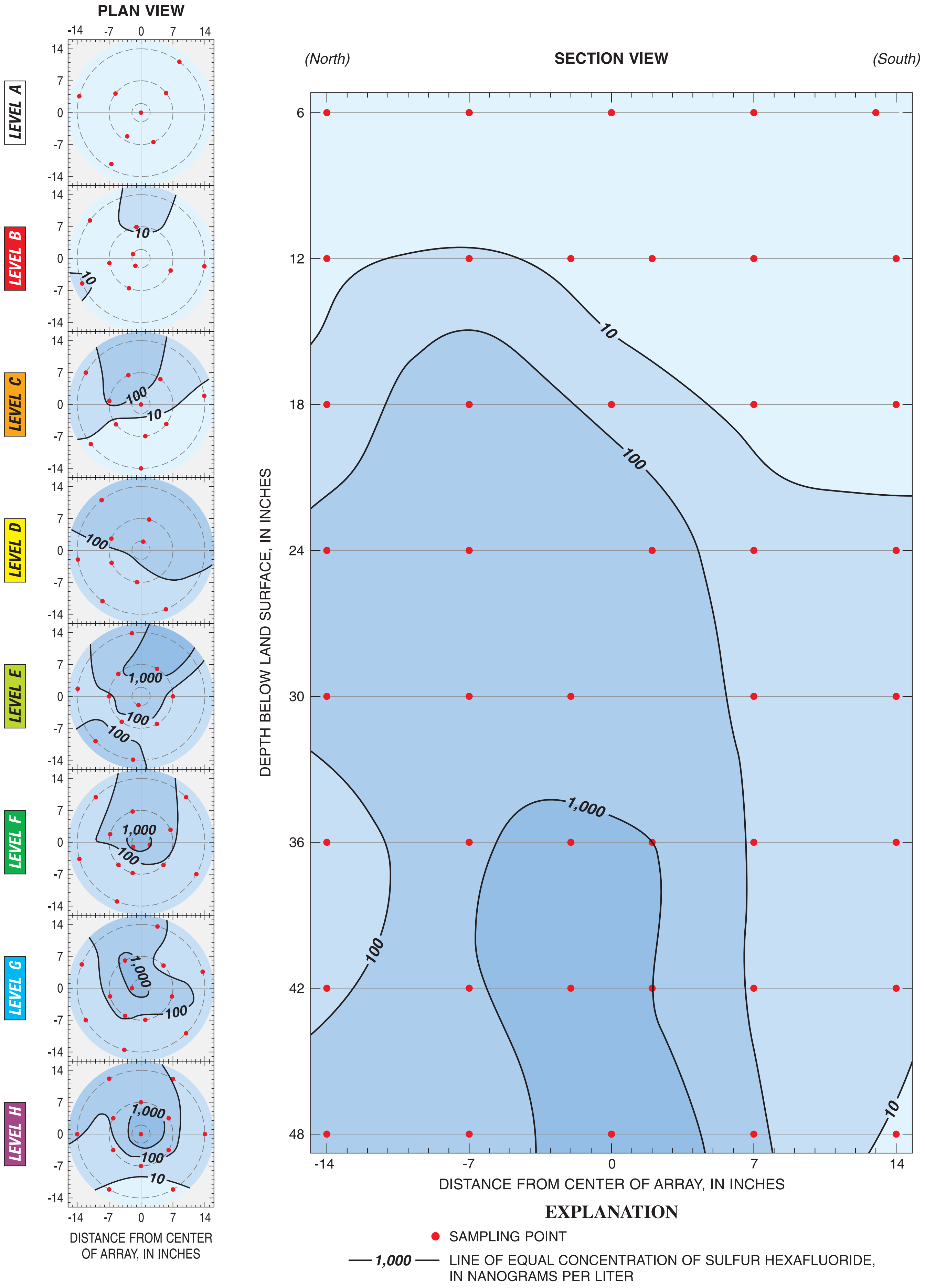


Figure 34d. Contour plots of sulfur hexafluoride concentration by layer and along a north-south cross section of the tracer array at time steps of 363-375 days after tracer injection.

mated mass would be 162,000 ng, which is about 5 percent of the initial injected mass.

For the fourth major sampling episode, sulfur hexafluoride samples were collected from 363–375 days after tracer injection (fig. 34d). The largest concentration detected during this time step was 8,195 ng/L, which is similar to the largest concentration that was detected during the third sampling episode. This concentration was detected at the injection point, which had not been sampled during the previous two sampling episodes. In contrast with the previous two episodes, concentrations of sulfur hexafluoride in all of the sampling locations during the fourth sampling episode were larger than 1 ng/L. A similar result was found for the bromide (figs. 33a–d), for which the concentrations in the upper layers of the array had increased between the third and fourth time steps. It is not clear why this occurred; however, it is possible that seasonal differences in temperature, rainfall, and evapotranspiration could have diluted the tracer concentrations in the near-surface layers of the array during the third sampling episode (May 1999), and subsequently increased concentrations during the fourth sampling episode (September 1999). The mean concentration of sulfur hexafluoride for the entire array during the fourth sampling round was 300 ng/L, which was smaller than the mean for the third sampling round. The tracer mass estimated from this mean was about 3 or 4 percent of the initial injected mass of sulfur hexafluoride, assuming an effective porosity of 0.40 or 0.55 (respectively) for the calculations of water volume in the array.

As was the case with the bromide tracer, qualitative interpretation of isoconcentration curves for sulfur hexafluoride (figs. 34a–d) indicates that a northward horizontal component of ground-water flow was present along with the vertical component. In addition, because the sulfur hexafluoride tracer did not move as a discrete pulse, it is difficult to accurately calculate the magnitude and direction of the velocity vector from these data.

Comparison of Tracers

After injection, the fluorescein showed much less spreading than the bromide and sulfur hexafluoride, and its center of mass remained near the injection point (figs. 32a–c). Even during the fourth major sampling episode (412–424 days after fluorescein-dye injection), the fluorescein-dye pulse had retained nearly the same position and shape as it had during the first major sampling episode. Because fluorescein dye is known to participate in sorption reactions with mineral surfaces and organic matter (Kasnavia and others, 1999; Sabatini and Austin, 1991), the transport of the dye should be similar to that of other solutes that participate in sorption reactions. The VOCs that are the major contaminants in the wetland study area are also known to sorb to organic matter in the sediments (Lorah and others, 1997, p. 83). The octanol-water partitioning coefficient, K_{OW}, is a measure of partitioning of a solute from aqueous solution into an organic phase (octanol) and can be used to evaluate the tendency of a solute in a ground-water system to adsorb to organic matter (Piwoni and Keeley, 1990). K_{OW} values typically vary over several orders of magnitude and therefore are expressed as logarithms. The $\log K_{OW}$ values for the VOCs of interest are slightly lower than the $\log K_{OW}$ for fluorescein; therefore, the transport of these VOCs would be expected to be retarded because of sorption, but to a lesser extent than would be seen for fluorescein. Of the VOCs listed below, vinyl chloride would be expected to exhibit the least amount of retardation because of sorption.

Breakthrough curves of bromide and sulfur hexafluoride concentrations with time were plotted for each sampling point to compare different spatial characteristics of tracer movement. Analysis of breakthrough data showed differences between the two tracers in almost every sampling level of the tracer array. In several instances, for example, anomalously large concentrations of one tracer were not matched by large concentrations of the other. One place this occurred

Substance	**$\log K_{OW}$ value(s)**	**Reference**
Fluorescein dye	3.35	Calculated using methods described by Meylan and Howard (1995)
1,1,2,2-Tetrachloroethane	2.56, 2.39	Reported by Montgomery and Welkom (1990)
1,1,2-Trichloroethane	2.18	Reported by Montgomery and Welkom (1990)
Trichloroethene	2.53, 2.29, 2.42, 2.60, 3.24, 3.30, 2.37, 3.03	Reported by Montgomery and Welkom (1990)
cis-1,2-Dichloroethene	1.41	Reported by Montgomery and Welkom (1990)
trans-1,2-Dichloroethene	2.09	Reported by Montgomery and Welkom (1990)
Vinyl chloride	0.60	Reported by Montgomery and Welkom (1990)

was at the injection point (H00-000), where the highest detection of sulfur hexafluoride was observed at the same time as a relatively low detection of bromide. This observation, made 104 days after tracer injection, indicates that the bromide tracer moved away from the injection point more efficiently than sulfur hexafluoride.

Isoconcentration contour plots for bromide (figs. 33a–c) and sulfur hexafluoride (figs. 34a–c) also showed that the bromide pulse generally moved away from the injection point more rapidly than the sulfur hexafluoride pulse; however, there were a few specific sampling points in the middle and upper levels of the tracer array in which a portion of the sulfur hexafluoride appeared to have outpaced the bromide. On October 1, 1998 (27 days after injection), site D07-165 had replicate samples with concentrations of 432 ng/L and 378 ng/L of sulfur hexafluoride, compared to concentrations of 1.7 mg/L and 1.4 mg/L of bromide.

To verify that these trends were not an artifact of the different initial concentrations and reporting limits for the bromide and sulfur hexafluoride, the comparison of tracer movement was considered in reference to the original injected concentrations by calculating dimensionless concentrations (C/C_0) by dividing the tracer concentration (C) for each measurement by the injected concentration (C_0). For site D07-165, at which sulfur hexafluoride was thought to have outpaced bromide, the dimensionless concentrations for replicate samples collected on October 1, 1998, were 0.000019 and 0.000016 for sulfur hexafluoride, compared to dimensionless concentrations of 0.000017 and 0.000014 for bromide. This indicates that although sulfur hexafluoride may have slightly outpaced bromide at this site, the relative concentrations are very similar, and any potential acceleration of sulfur hexafluoride compared to bromide is likely to have been localized and minor. Dimensionless concentrations were also used to verify the hypothesis that the bromide pulse as a whole had moved away from the injection point more rapidly than the sulfur hexafluoride pulse. A comparison of the relative movement of the bromide and sulfur hexafluoride using the dimensionless concentrations and the same vertical scales, for levels A through H of the array is shown in figure 35. The bromide peak is apparent in shallower depth intervals and earlier in the tracer test than the sulfur hexafluoride peak (fig. 35). In addition, a larger portion of the tracer mass is evident in the tracer array for the bromide compared to the sulfur hexafluoride, especially in the upper levels of the array.

As the comparison of tracers indicates that the bulk of the sulfur hexafluoride was somewhat retarded compared to the bromide, a sorption test was performed to evaluate the potential for the sulfur hexafluoride to adsorb to the organic-rich wetland sediments. The sorption test was conducted using replicate sets of serum vials containing a 1:6 ratio of deionized water to wetland sediment, which were spiked with a solution of sulfur hexafluoride to produce an expected concentration of approximately 400 ng/L, and then stored upside-down on a shaker table at approximately 22 °C. After 32 days of contact with the sediments, no significant decreases in sulfur hexafluoride concentrations were observed, and sorption was eliminated as a potential cause of the retardation of sulfur hexafluoride.

The early presence of sulfur hexafluoride at a few sites in the middle and upper levels of the tracer array and its persistence in the 6-in. depth throughout the duration of the experiment neither supports nor contradicts a hypothesis of volatilization from the saturated sediments into the overlying atmosphere. The wetland sediments had remained saturated throughout the tracer experiment, so dissolved sulfur hexafluoride in the ground water at the 6-in. depth would not have had the opportunity to come in direct contact with the atmosphere. Had all other hydrologic processes been assumed to be identical for bromide and sulfur hexafluoride, the absence or a rapid disappearance of sulfur hexafluoride from the 6-in. depth might have been assumed to be due to volatilization if the sediments had been unsaturated to that depth at any time, but this condition was not observed.

Interaction of the sulfur hexafluoride with natural marsh gases at depth could explain this tracer’s fate and transport. The major difference between bromide and sulfur hexafluoride is that sulfur hexafluoride can volatilize into any gas phase that is present (Wilson and MacKay, 1993). If no gas phase were present at depth, the sulfur hexafluoride would be expected to move in the same manner as bromide (conservatively). The early presence of sulfur hexafluoride at a few sampling points in the upper levels of the array and the apparent retardation of the bulk of the sulfur hexafluoride in the lower and middle levels of the array compared to bromide could have been due to volatilization of dissolved sulfur hexafluoride gas into small bubbles of marsh gases that are produced in the wetland sediments when concentrations of the marsh gases exceed saturation levels. Ebullition (formation of bubbles) of methane and other biogenic gases has been well documented in wetland environments (Fechner-Levy and Hemond, 1996), and in one study of gas exchange in a small lake in which sulfur hexafluoride was used as a tracer (Cole and Caraco, 1998), methane ebullition was evaluated as a potential source of tracer loss. Sulfur hexafluoride volatilization into naturally present gas bubbles within the tracer array could have provided two additional transport mechanisms that are not available to bromide: (1) upward movement associated with gas-bubble rise, and (2) retardation associated with gas-bubble trapping. These mechanisms could explain the early presence of sulfur hexafluoride at a few locations in the middle and upper levels of the array, and the lagging of the bulk of the sulfur hexafluoride near the injection point through the end of the tracer test. If small bubbles containing sulfur hexafluoride were formed shortly after tracer injection, these bubbles could have acted as a continuing source of sulfur hexafluoride near the tracer injection point, as the marsh gases could have re-dissolved at a later time, when concentrations decreased to below saturation levels. The occasional observation of effervescent ground-water samples during the tracer experiment supports this hypothesis. Like sulfur hexafluoride, the VOCs that are the major contaminants in the wetland study area could be

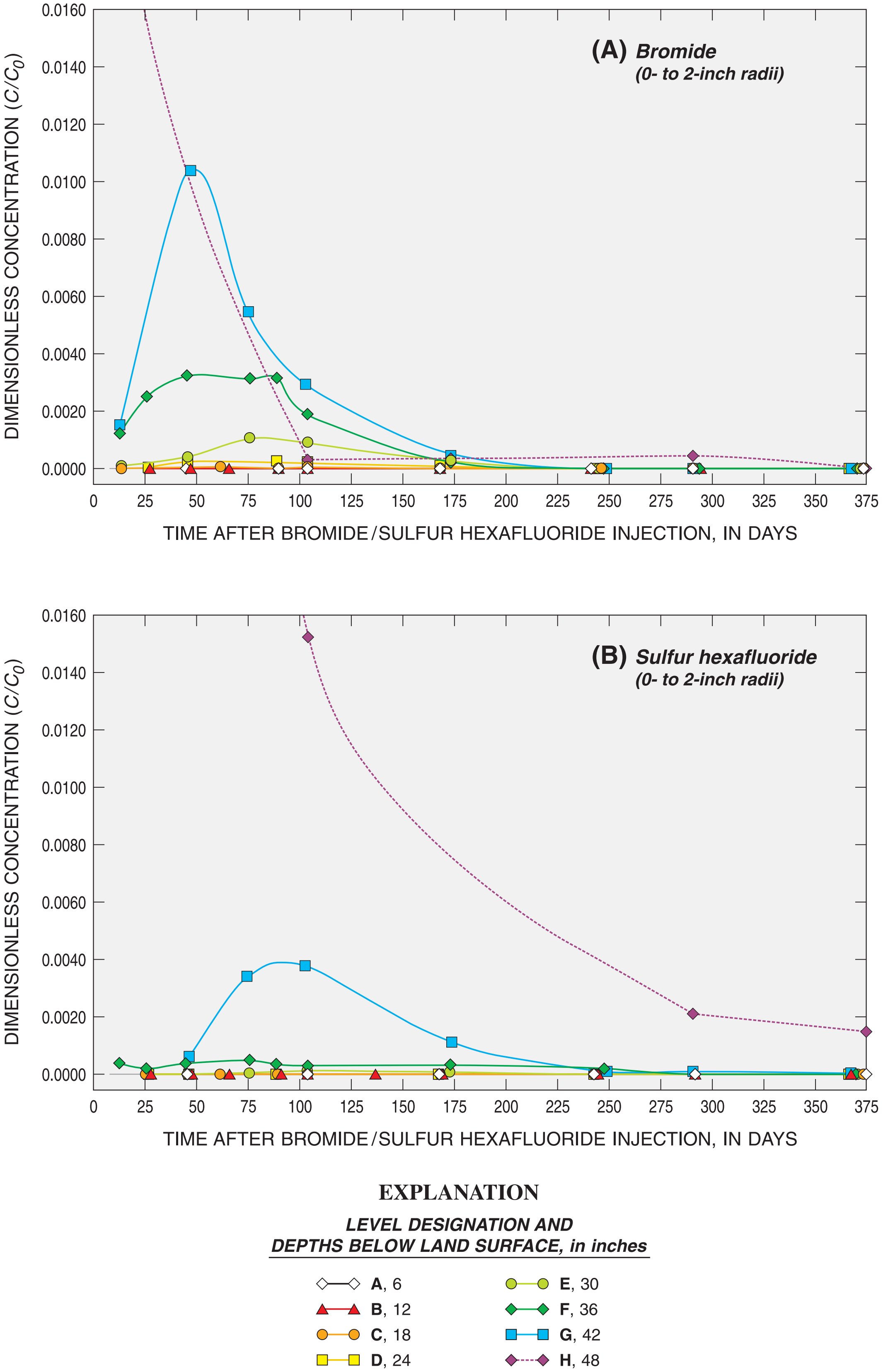


Figure 35. Comparison of tracers for the 0- to 2-inch radii by use of the dimensionless concentration [C/C_0], which is derived by dividing tracer concentration [C] by the injected concentration [C_0], for **(A)** bromide and **(B)** sulfur hexafluoride.

susceptible to volatilization into gas bubbles within the wetland sediments. If the volatilization hypothesis is correct, this transport mechanism could be an additional source of variability in VOC movement.

Summary and Conclusions

The U.S. Geological Survey, in cooperation with the U.S. Army, conducted a small-scale natural-gradient groundwater tracer test during a period of approximately 1 year. This tracer test was conducted within saturated sediments in a freshwater tidal wetland near West Branch Canal Creek, at Aberdeen Proving Ground, Maryland, as a part of ongoing studies of natural attenuation. The objectives of the test were to better characterize solute transport at the site, procure a dataset that could be used to more accurately determine the ground-water velocity in the upper wetland sediments, and compare a conservative, ionic tracer (bromide) to a conservative, volatile tracer (sulfur hexafluoride) to determine whether volatilization could affect the fate of volatile compounds in the ground water. The test was conducted using a cylindrical array of ninety-seven ¼-inch-diameter inverted-screen piezometers within approximately 25 cubic feet (2.3 cubic meters) of organic-rich wetland sediments, in an area with a vertically upward hydraulic gradient. Fluorescein dye was injected on July 17, 1998, as 0.025 liter of solution containing 50,000 milligrams per liter of sodium fluorescein, to test the hydrologic integrity of the tracer array prior to the injection of the conservative tracers. A solution of bromide ion saturated with sulfur hexafluoride (0.139 liter of solution containing 100,000 milligrams per liter of bromide ion and 23.3 milligrams per liter of sulfur hexafluoride) was injected 49 days later, on September 4, 1998. Tracer movement was monitored through September 14, 1999, with the collection of groundwater samples, including 644 samples that were analyzed for fluorescein, 617 samples that were analyzed for bromide with an ion-selective electrode, 213 samples that were analyzed for bromide with colorimetric methods, and 603 samples that were analyzed for sulfur hexafluoride. Additional samples for volatile organic compounds (96 samples) and methane (37 samples) were collected to determine the distribution of these contaminants and the extent of methanogenic conditions within the array.

Differences in the chemical properties of the three tracers and their movement throughout the experiment provide insights into contaminant fate and transport in the wetland sediments. Fluorescein dye proved to be a good tracer for evaluating the hydrologic integrity of the array of piezometers that were used in the tracer test. Fluorescein dye was also useful as a non-conservative tracer to illustrate the effects of sorption on retarding the movement of solutes that have similar octanol-water partitioning coefficients, including some volatile organic compounds. Bromide worked well as a conservative tracer for the ground-water system. Sulfur hexafluoride also proved to be useful as a conservative tracer and was detectable over the widest range of concentrations, eight orders of magnitude. Sulfur hexafluoride moved differently than bromide. Apparent simultaneous acceleration of some of the sulfur hexafluoride to discrete locations in the upper levels of the array and retardation of a portion of the sulfur hexafluoride pulse in the lower levels of the array could have been due to volatilization of the dissolved gas into small bubbles of ambient marsh gases that can be produced in the wetland sediments when concentrations of the gases exceed saturation levels.

Isoconcentration contour plots and breakthrough curves were constructed to aid in the analysis of tracer movement. Although bromide and sulfur hexafluoride were transported predominantly upward, the tracers also moved outward in all directions from the injection point. Concentration data at the lateral edges of the tracer array indicated that tracer mass was lost out of the sides of the array throughout the duration of the test. During the four major sampling episodes (103–104, 167–174, 243–250, and 363–375 days after tracer injection), the mass of each tracer was estimated by multiplying the mean concentration by the approximate volume of water in the array. Assuming an effective porosity of 0.40, the estimated mass of bromide ranged from about 68 percent (during the first sampling episode) to as low as 4 percent of the mass that was initially injected, whereas the estimated mass of sulfur hexafluoride ranged from about 51 percent to 3 percent of the initial mass. If an effective porosity of 0.55 was used, these tracer masses would be higher by a factor of 1.375. The loss of tracer mass from the array prevented a straightforward quantitative analysis of tracer transport and ground-water velocity. For these reasons, data analysis was limited to qualitative methods.

The distribution of bromide over time shows qualitatively that in addition to vertical flow, there is a slight northward horizontal component to ground-water flow in the area of the tracer array. This assumes that the lateral movement of bromide beyond the tracer array was similar to the direction of movement inferred by the concentration distribution observed within the array. Because it was possible that the tracer solution sank below the injection point at the beginning of the test due to density differences (the initial density of the tracer solution was calculated to be 1.097 grams per milliliter) and then did not move as a discrete pulse, calculations of the magnitude or direction of the velocity vector from these data cannot be performed without uncertainty. A comparison of bromide and sulfur hexafluoride concentrations relative to their respective injected concentrations indicates that a smaller proportion of the injected mass of sulfur hexafluoride moved up into the tracer array than bromide.

On the basis of the predominantly upward movement of the conservative tracers and the outward movement in all directions from the injection point, diffusion and advection are thought to be the major processes responsible for the tracer movement. Dilution, possibly enhanced by intermittent interaction with the overlying tidal surface water, likely decreased the concentrations of the tracers as they were transported upwards through the tracer array. Sorption was evaluated and eliminated as a potential source of retardation or mass loss for sulfur hexafluoride. Potential losses of sulfur hexafluoride due to volatilization from the surface of the water table could not be measured in the tracer array because the wetland sediments had remained saturated to land surface throughout the tracer test. A portion of the sulfur hexafluoride could have volatilized into ambient bubbles of biogenic marsh gases at depth; this process could explain the early presence of sulfur hexafluoride in a few sampling points in the upper levels of the tracer array (because of gas-bubble rise), and the retardation of the bulk of the sulfur hexafluoride (because of gas-bubble trapping) in the lower levels of the tracer array.

The tracer movement observed and the transport processes inferred from this movement are consistent with the concentration distribution of the volatile organic compounds detected in the array; however, the circumstances of the original introduction of the volatile organic compounds to the site are not known with certainty, so comparisons must be limited. Concentrations of volatile organic compounds were largest in the lowest depths of the array and decreased with decreasing depth. In addition to the transport processes that affect conservative solutes such as bromide, volatile organic compounds can also undergo sorption and degradation, both of which were observed in this experiment. The volatile organic compounds detected in low concentrations in the shallow levels of the tracer array (6–24 inches below land surface) were nearly exclusively daughter compounds, indicating that biodegradation was transforming these compounds and reducing their mass. Methane was detected at depths of 6–42 inches below land surface, with the largest concentrations in the shallowest levels, where biodegradation was most evident by the presence of daughter compounds. This is consistent with the pattern of methanogenic conditions that was documented previously for this site. Chemical and physical processes responsible for differences in the transport of fluorescein and sulfur hexafluoride compared to bromide, such as sorption (resulting in retardation of fluorescein) and volatilization into bubbles of marsh gases (resulting in bulk retardation of sulfur hexafluoride with isolated instances of accelerated upward movement) are likely to similarly affect the transport of volatile organic compounds in the upper wetland sediments in the area around West Branch Canal Creek.

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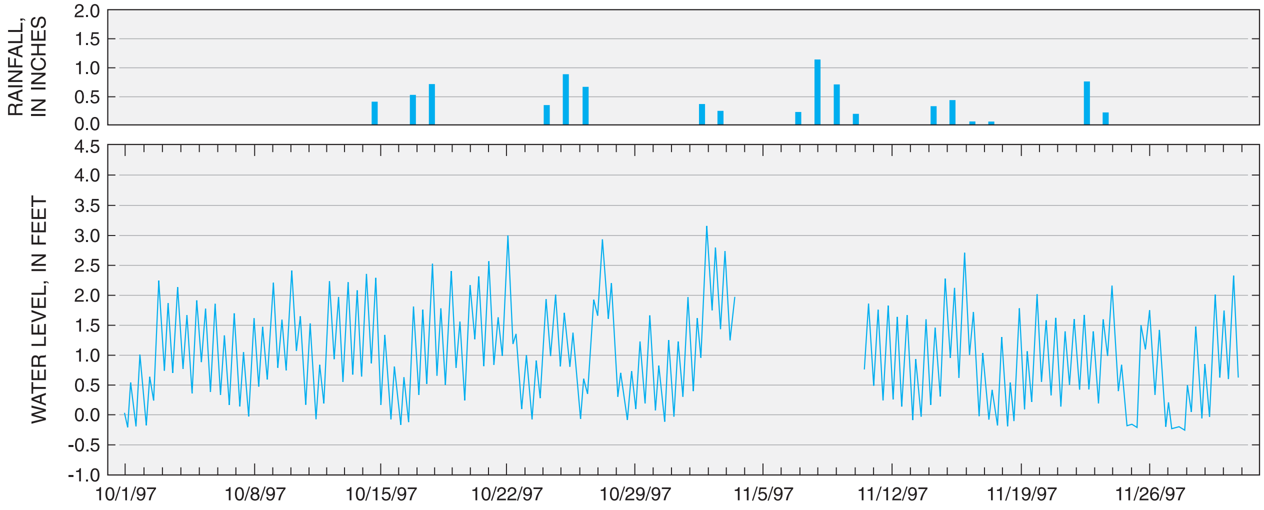
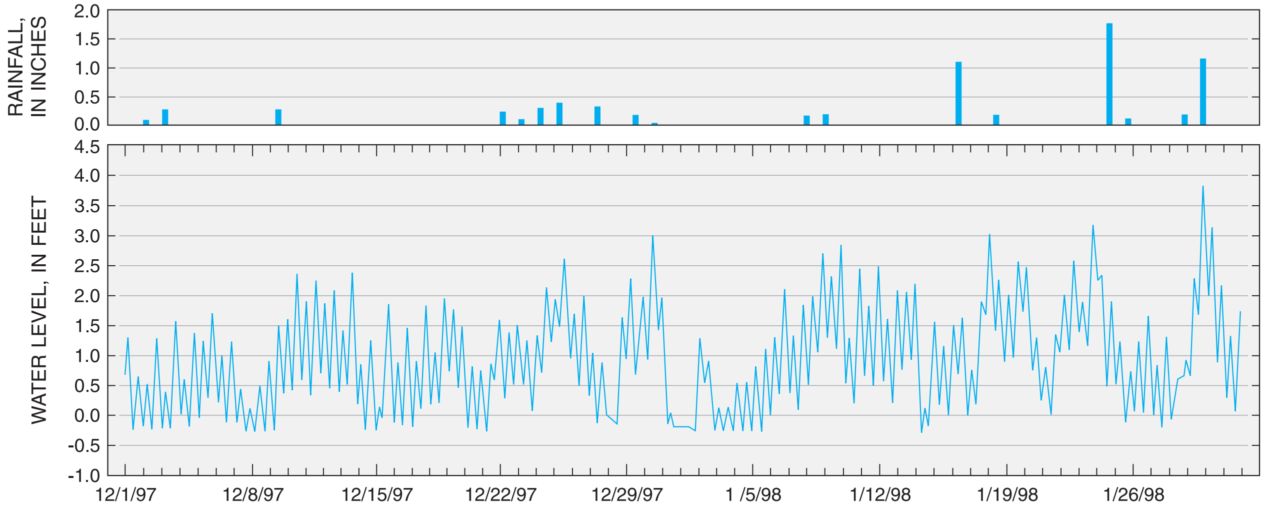
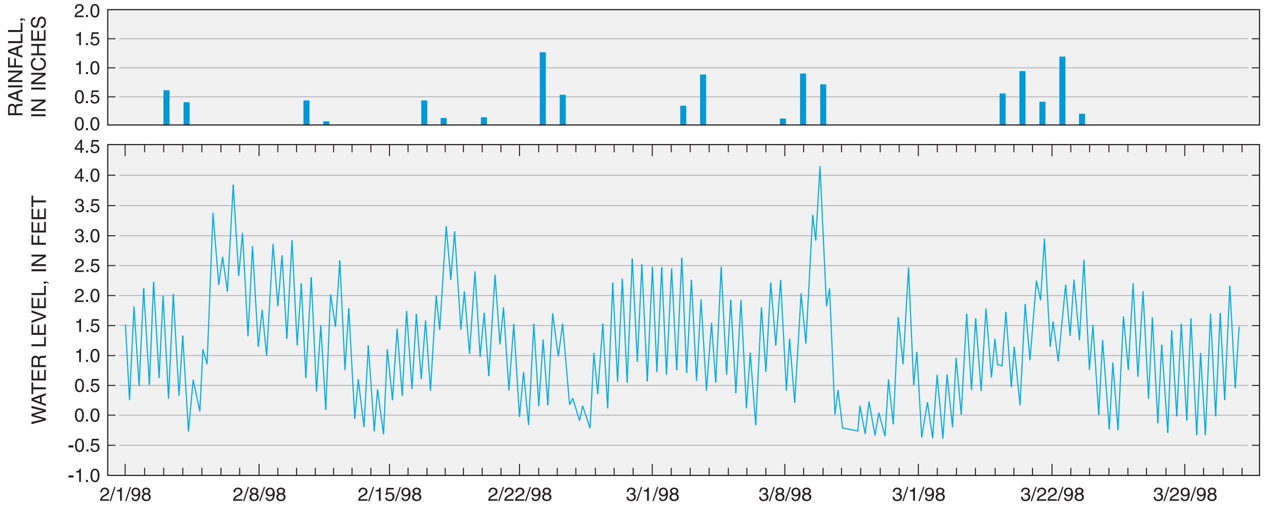
Appendixes--A through C follow

Appendix A. *Daily rainfall totals and fifteen-minute tidal water-level data from October 1997 through September 1999 for West Branch Canal Creek, Aberdeen Proving Ground, Maryland*

[Rainfall data from U.S. Army Aberdeen Test Center Meteorology Team]

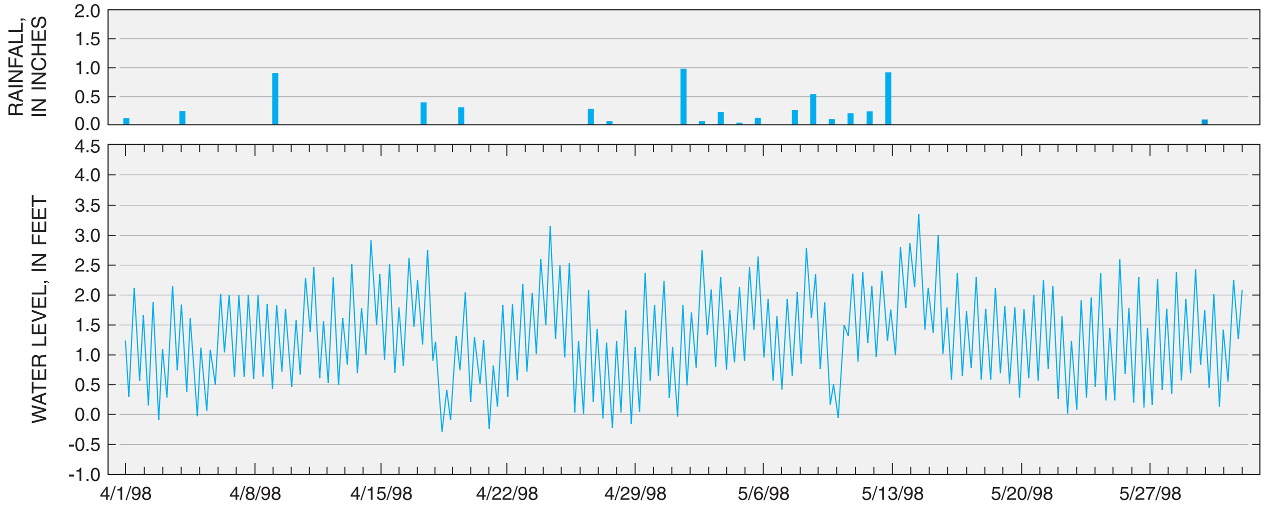


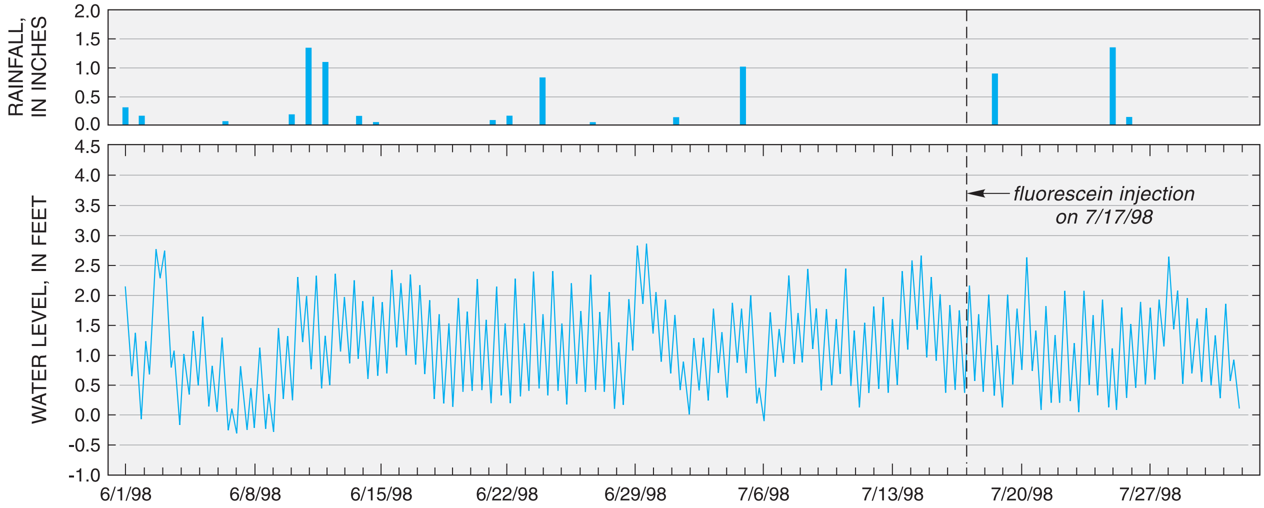




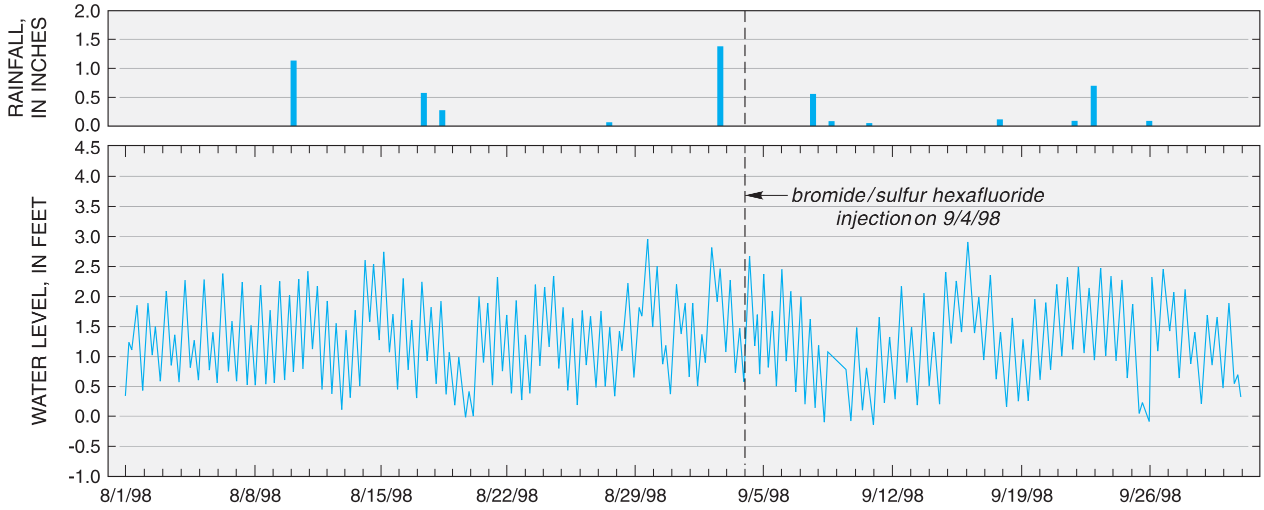
Appendix A. *Daily rainfall totals and fifteen-minute tidal water-level data from October 1997 through September 1999 for West Branch Canal Creek, Aberdeen Proving Ground, Maryland -- Continued*

[Rainfall data from U.S. Army Aberdeen Test Center Meteorology Team]





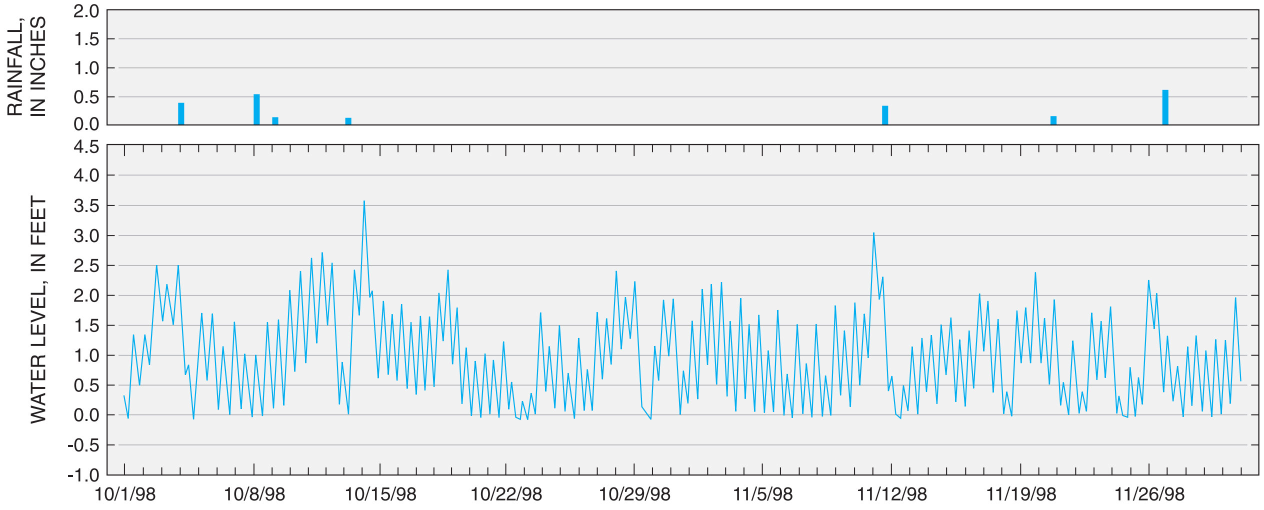
fluorescein injection on 7/17/98

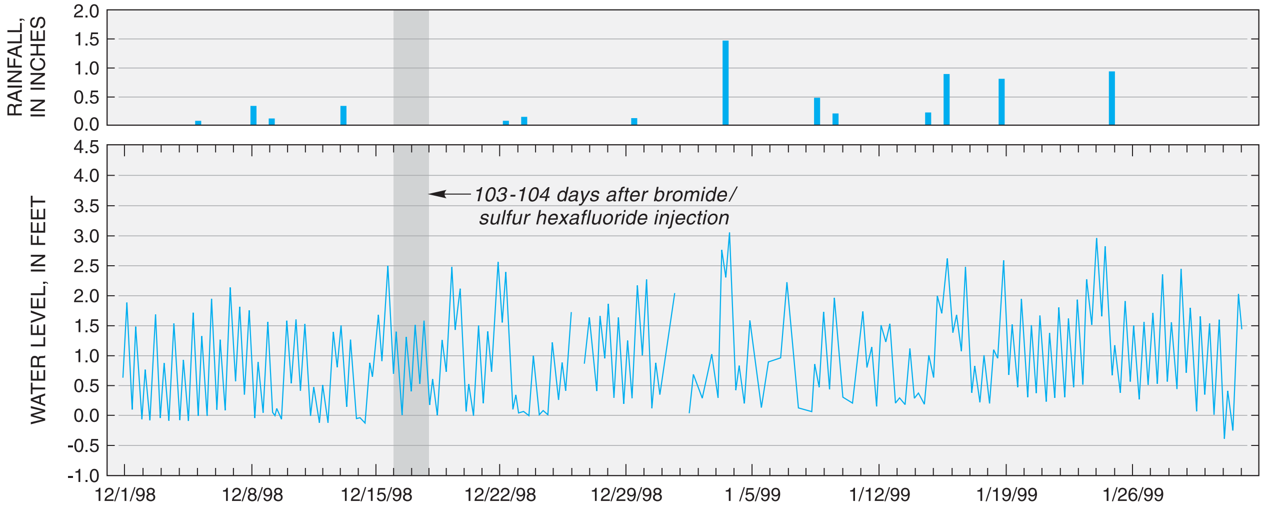


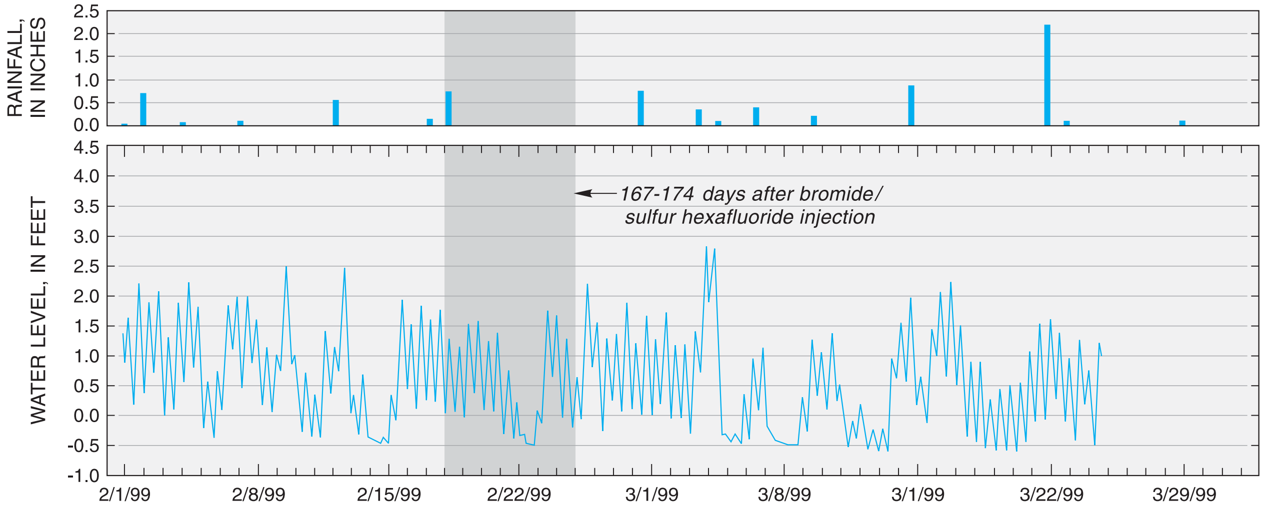
bromide/sulfur hexafluoride injection on 9/4/98

Appendix A. *Daily rainfall totals and fifteen-minute tidal water-level data from October 1997 through September 1999 for West Branch Canal Creek, Aberdeen Proving Ground, Maryland -- Continued*

[Rainfall data from U.S. Army Aberdeen Test Center Meteorology Team]

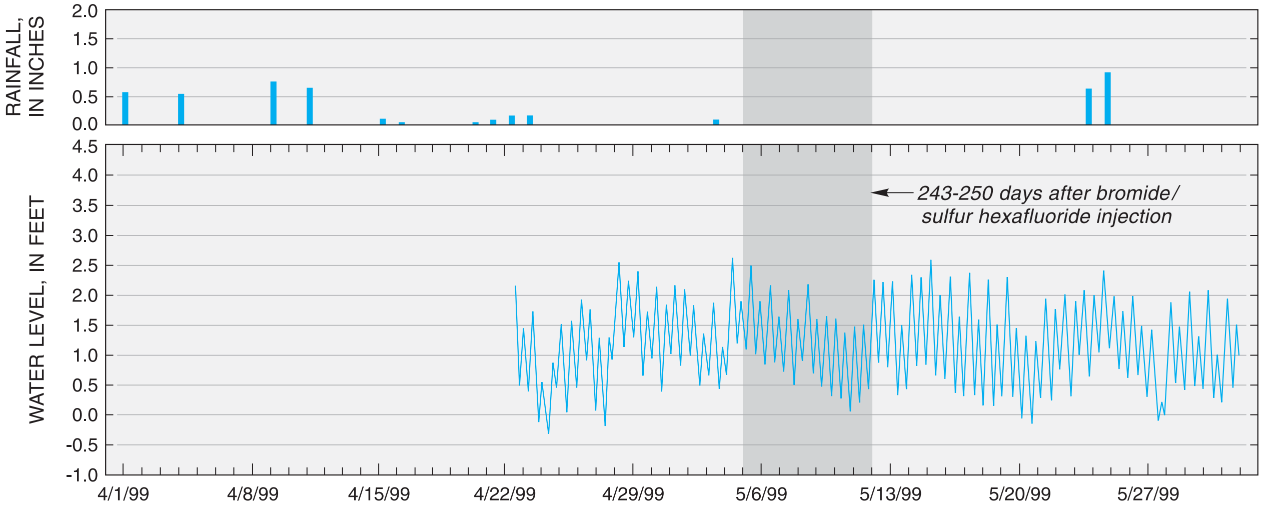


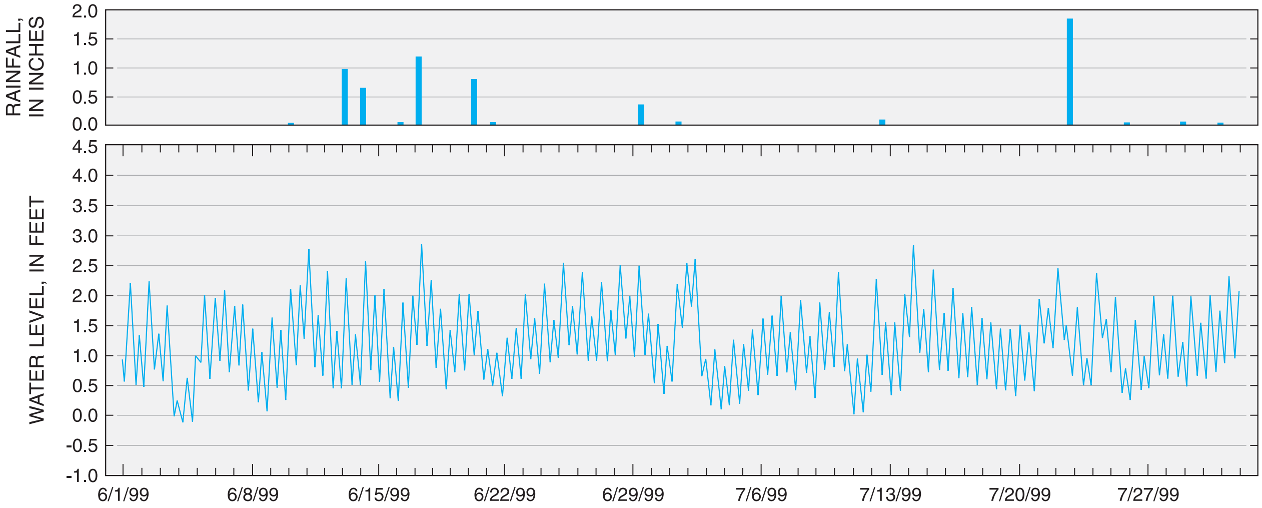


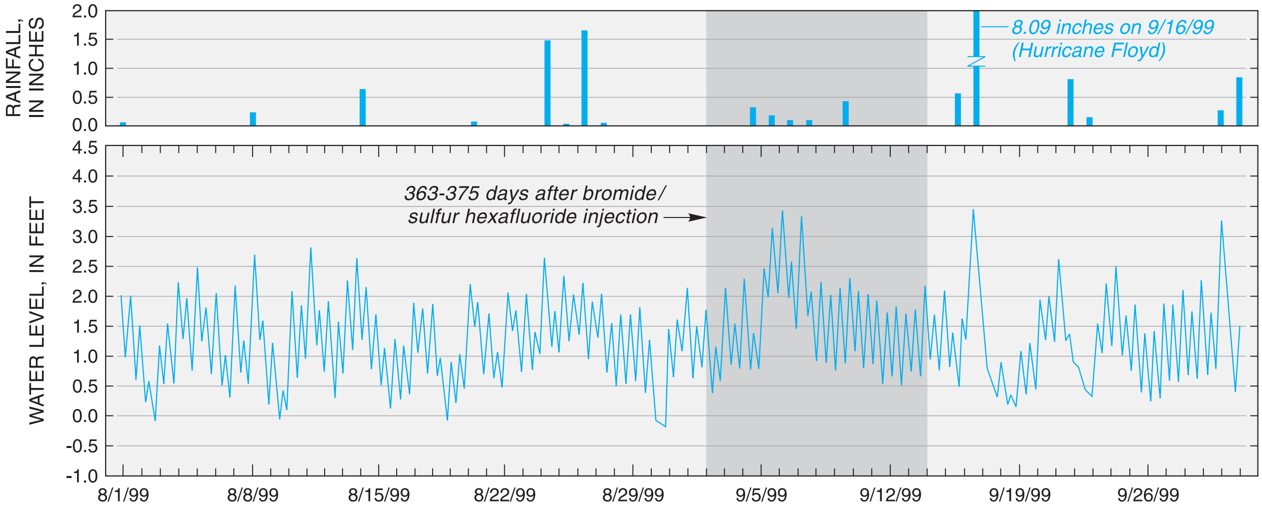


Appendix A. *Daily rainfall totals and fifteen-minute tidal water-level data from October 1997 through September 1999 for West Branch Canal Creek, Aberdeen Proving Ground, Maryland -- Continued*

[Rainfall data from U.S. Army Aberdeen Test Center Meteorology Team]







Appendix B1. *Site names and relative positions of tracer-test piezometers at West Branch Canal Creek, Aberdeen Proving Ground, Maryland*

[For radial coordinates, 0 degrees points toward the creek, angle theta increases in the clockwise direction, and magnetic north is at 52 degrees. For rectilinear coordinates, the origin is the tracer-injection site, H00-000. The X-axis is oriented perpendicular to the creek, positive on the side of the origin that is away from the creek, and negative on the side that is closest to the creek. The Y-axis is parallel to the creek, positive on the upstream side of the origin, and negative on the downstream side. The Z-axis is elevation and is positive in the upward direction.]

Site name	Distance from injection point, calculated (inches)	Radial Coordinates			Rectilinear Coordinates: Distance in X, Y, and Z directions from the origin (injection point)			Site identification number
		Depth below land surface (inches)	Radius from central axis (inches)	Angle theta from creek (degrees)	X (inches)	Y (inches)	Z (inches)	
A00-300	42.00	6	0	300	-0.09	-0.16	42	392347076183801
A06-300	42.43	6	6	300	-3.00	-5.20	42	392347076183802
A07-037	42.58	6	7	37	-5.59	4.21	42	392347076183803
A07-142	42.58	6	7	142	5.52	4.31	42	392347076183804
A07-247	42.58	6	7	247	2.74	-6.44	42	392347076183805
A13-300	43.97	6	13	300	-6.50	-11.26	42	392347076183806
A14-015	44.27	6	14	15	-13.52	3.62	42	392347076183807
A14-127	44.27	6	14	127	8.43	11.18	42	392347076183808
A14-255	44.27	6	14	255	3.62	-13.52	42	392347076183809
B02-030	36.06	12	2	30	-1.73	1.00	36	392347076183810
B02-307	36.06	12	2	307	-1.20	-1.60	36	392347076183811
B07-082	36.67	12	7	82	-0.97	6.93	36	392347076183812
B07-202	36.67	12	7	202	6.49	-2.62	36	392347076183813
B07-292	36.67	12	7	292	-2.62	-6.49	36	392347076183814
B07-352	36.67	12	7	352	-6.93	-0.97	36	392347076183815
B14-037	38.63	12	14	37	-11.18	8.43	36	392347076183816
B14-187	38.63	12	14	187	13.90	-1.71	36	392347076183817
B14-337	38.63	12	14	337	-12.89	-5.47	36	392347076183818
C00-000	30.00	18	0	0	-0.18	0.00	30	392347076183819
C07-007	30.81	18	7	7	-6.95	0.85	30	392347076183820
C07-067	30.81	18	7	67	-2.74	6.44	30	392347076183821
C07-127	30.81	18	7	127	4.21	5.59	30	392347076183822
C07-217	30.81	18	7	217	5.59	-4.21	30	392347076183823
C07-262	30.81	18	7	262	0.97	-6.93	30	392347076183824
C07-322	30.81	18	7	322	-5.52	-4.31	30	392347076183825
C14-030	33.11	18	14	30	-12.12	7.00	30	392347076183826
C14-172	33.11	18	14	172	13.86	1.95	30	392347076183827
C14-270	33.11	18	14	270	0.00	-14.00	30	392347076183828
C14-322	33.11	18	14	322	-11.03	-8.62	30	392347076183829
D02-105	24.08	24	2	105	0.52	1.93	24	392347076183830
D07-022	25.00	24	7	22	-6.49	2.62	24	392347076183831
D07-105	25.00	24	7	105	1.81	6.76	24	392347076183832
D07-165	25.00	24	7	165	6.76	1.81	24	392347076183833
D07-277	25.00	24	7	277	-0.85	-6.95	24	392347076183835
D07-337	25.00	24	7	337	-6.44	-2.74	24	392347076183834

Appendix B1. *Site names and relative positions of tracer-test piezometers at West Branch Canal Creek, Aberdeen Proving Ground, Maryland--Continued*

Site name	Distance from injection point, calculated (inches)	Radial Coordinates			Rectilinear Coordinates Distance in X, Y, and Z directions from the origin (injection point)			Site identification number
		Depth below land surface (inches)	Radius from central axis (inches)	Angle theta from creek (degrees)	X (inches)	Y (inches)	Z (inches)	
D14-052	27.78	24	14	52	-8.62	11.03	24	392347076183836
D14-247	27.78	24	14	247	5.47	-12.89	24	392347076183837
D14-307	27.78	24	14	307	-8.43	-11.18	24	392347076183838
D14-352	27.78	24	14	352	-13.86	-1.95	24	392347076183839
D24-045	33.94	24	24	45	-16.97	16.97	24	none assigned
E02-285	18.11	30	2	285	-0.52	-1.93	18	392347076183840
E07-000	19.31	30	7	0	-7.00	0.00	18	392347076183841
E07-045	19.31	30	7	45	-4.95	4.95	18	392347076183842
E07-120	19.31	30	7	120	3.50	6.06	18	392347076183843
E07-180	19.31	30	7	180	7.00	0.00	18	392347076183844
E07-240	19.31	30	7	240	3.50	-6.06	18	392347076183845
E07-307	19.31	30	7	307	-4.21	-5.59	18	392347076183846
E14-007	22.80	30	14	7	-13.90	1.71	18	392347076183847
E14-082	22.80	30	14	82	-1.95	13.86	18	392347076183848
E14-157	22.80	30	14	157	12.89	5.47	18	392347076183849
E14-217	22.80	30	14	217	11.18	-8.43	18	392347076183850
E14-277	22.80	30	14	277	-1.71	-13.90	18	392347076183851
E14-315	22.80	30	14	315	-9.90	-9.90	18	392347076183852
F02-195	12.17	36	2	195	1.93	-0.52	12	392347076183853
F02-330	12.17	36	2	330	-1.73	-1.00	12	392347076183854
F07-015	13.89	36	7	15	-6.76	1.81	12	392347076183855
F07-075	13.89	36	7	75	-1.81	6.76	12	392347076183856
F07-157	13.89	36	7	157	6.44	2.74	12	392347076183857
F07-225	13.89	36	7	225	4.95	-4.95	12	392347076183858
F07-285	13.89	36	7	285	-1.81	-6.76	12	392347076183859
F07-315	13.89	36	7	315	-4.95	-4.95	12	392347076183860
F14-045	18.44	36	14	45	-9.90	9.90	12	392347076183861
F14-135	18.44	36	14	135	9.90	9.90	12	392347076183862
F14-210	18.44	36	14	210	12.12	-7.00	12	392347076183863
F14-292	18.44	36	14	292	-5.24	-12.98	12	392347076183864
F14-345	18.44	36	14	345	-13.52	-3.62	12	392347076183865
G02-000	6.32	42	2	0	-2.00	0.00	6.0	392347076183866
G07-060	9.22	42	7	60	-3.50	6.06	6.0	392347076183867
G07-135	9.22	42	7	135	4.95	4.95	6.0	392347076183868
G07-195	9.22	42	7	195	6.76	-1.81	6.0	392347076183869

Appendix B1. *Site names and relative positions of tracer-test piezometers at West Branch Canal Creek, Aberdeen Proving Ground, Maryland--Continued*

		Radial Coordinates			Rectilinear Coordinates			
					Distance in X, Y, and Z directions from the origin (injection point)			
Site name	Distance from injection point, calculated (inches)	Depth below land surface (inches)	Radius from central axis (inches)	Angle theta from creek (degrees)	X (inches)	Y (inches)	Z (inches)	Site identification number
G07-255	9.22	42	7	255	1.81	-6.76	6.0	392347076183870
G07-300	9.22	42	7	300	-3.50	-6.06	6.0	392347076183871
G07-345	9.22	42	7	345	-6.76	-1.81	6.0	392347076183872
G14-022	15.23	42	14	22	-12.98	5.24	6.0	392347076183873
G14-105	15.23	42	14	105	3.62	13.52	6.0	392347076183874
G14-165	15.23	42	14	165	13.52	3.62	6.0	392347076183875
G14-225	15.23	42	14	225	9.90	-9.90	6.0	392347076183876
G14-285	15.23	42	14	285	-3.62	-13.52	6.0	392347076183877
G14-330	15.23	42	14	330	-12.12	-7.00	6.0	392347076183878
G18-180	18.97	42	18	180	18.00	0.00	6.0	392347076183800
H00-000	0.00	48	0	0	0.00	0.00	0.0	392347076183879
H07-030	7.00	48	7	30	-6.06	3.50	0.0	392347076183880
H07-090	7.00	48	7	90	0.00	7.00	0.0	392347076183881
H07-150	7.00	48	7	150	6.06	3.50	0.0	392347076183882
H07-210	7.00	48	7	210	6.06	-3.50	0.0	392347076183883
H07-270	7.00	48	7	270	0.00	-7.00	0.0	392347076183884
H07-330	7.00	48	7	330	-6.06	-3.50	0.0	392347076183885
H14-000	14.00	48	14	0	-14.00	0.00	0.0	392347076183886
H14-060	14.00	48	14	60	-7.00	12.12	0.0	392347076183887
H14-120	14.00	48	14	120	7.00	12.12	0.0	392347076183888
H14-180	14.00	48	14	180	14.00	0.00	0.0	392347076183889
H14-240	14.00	48	14	240	7.00	-12.12	0.0	392347076183890
H14-300	14.00	48	14	300	-7.00	-12.12	0.0	392347076183891
I06-285	8.49	54	6	285	-1.55	-5.80	-6.0	392347076183893
I07-112	9.22	54	7	112	2.62	6.49	-6.0	392347076183894
J06-000	13.42	60	6	0	-6.00	0.00	-12.0	392347076183895
J07-187	13.89	60	7	187	6.95	-0.85	-12.0	392347076183896

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999*

[SF_6, sulfur hexafluoride; µg/L, micrograms per liter; mg/L, milligrams per liter; ng/L, nanograms per liter; mL, milliliters; NR, no replicate was collected for this sample; --, not analyzed; <, less than; purge, analysis was performed on purge water]

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluorescein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colorimetric method (mg/L)	Sulfur hexafluoride (ng/L)	Water volume removed (mL)
A00-300	NR	07/14/1998	-3	-52	--	--	--	--	45.0
A00-300	NR	09/18/1998	63	14	--	--	--	--	19.0
A00-300	NR	10/20/1998	95	46	< 5.0	2.3	--	--	10.4
A00-300	NR	10/21/1998	96	47	--	--	--	0.40	3.8
A00-300	NR	12/03/1998	139	90	< 5.0	3.8	--	--	14.2
A00-300	NR	12/17/1998	153	104	< 5.0	5.8	--	3.52	12.8
A00-300	NR	02/19/1999	217	168	--	5.9	--	< .16	17.6
A00-300	NR	05/05/1999	292	243	< 5.0	--	1.02	< .02	53.0
A00-300	NR	06/23/1999	341	292	< 5.0	5.4	--	11.2	12.8
A00-300	NR	09/14/1999	424	375	13.7	7.7	--	1.63	25.6
A06-300	NR	07/14/1998	-3	-52	--	--	--	--	38.0
A06-300	NR	08/04/1998	18	-31	5.5	3.2	--	< .01	13.2
A06-300	NR	08/05/1998	19	-30	--	--	0.18	--	26.4
A06-300	NR	08/31/1998	45	-4	15.7	--	--	--	10.5
A06-300	NR	10/01/1998	76	27	< 5.0	1.4	--	--	7.0
A06-300	NR	11/19/1998	125	76	< 5.0	2.3	--	26.3	17.2
A06-300	NR	12/17/1998	153	104	< 5.0	6.6	--	4.73	11.4
A06-300	NR	02/19/1999	217	168	--	4.8	--	< .02	24.8
A06-300	NR	05/05/1999	292	243	< 5.0	--	0.88	< .02	44.0
A06-300	NR	09/13/1999	423	374	< 5.0	8.3	--	1.37	24.0
A07-037	NR	07/14/1998	-3	-52	--	--	--	--	40.0
A07-037	NR	08/31/1998	45	-4	< 5.0	--	--	--	9.2
A07-037	NR	10/21/1998	96	47	< 5.0	2.1	--	0.91	10.6
A07-037	NR	12/03/1998	139	90	< 5.0	2.8	--	--	8.5
A07-037	NR	12/17/1998	153	104	< 5.0	4.3	--	4.54	12.4
A07-037	NR	02/19/1999	217	168	--	5.6	--	52.6	23.0
A07-037	NR	05/05/1999	292	243	< 5.0	--	0.97	< .02	38.8
A07-037	NR	09/13/1999	423	374	13.4	5.8	--	2.23	20.3
A07-142	NR	07/14/1998	-3	-52	--	--	--	--	7.0
A07-142	NR	08/20/1998	34	-15	< 5.0	--	--	--	5.5
A07-142	NR	10/21/1998	96	47	< 5.0	2.1	--	--	7.2
A07-142	NR	11/19/1998	125	76	< 5.0	2.7	--	186	14.8
A07-142	NR	12/17/1998	153	104	< 5.0	8.1	--	9.13	11.4

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF$_6$ injection, 09/04/1998	Fluore-scein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colori-metric method (mg/L)	Sulfur hexa-fluoride (ng/L)	Water volume removed (mL)
A07-142	NR	01/07/1999	174	125	--	--	--	--	3.4
A07-142	NR	01/19/1999	186	137	--	9.4	--	10.5	12.4
A07-142	NR	02/19/1999	217	168	--	7.1	--	12.0	14.1
A07-142	NR	05/05/1999	292	243	< 5.0	--	0.83	< .02	50.0
A07-142	NR	09/13/1999	423	374	13.9	--	--	2.06	10.2
A07-247	NR	07/14/1998	-3	-52	--	--	--	--	6.0
A07-247	NR	08/20/1998	34	-15	5.4	--	--	--	9.0
A07-247	NR	10/01/1998	76	27	5.2	< 1.0	0.37	--	26.9
A07-247	NR	11/05/1998	111	62	< 5.0	2.3	--	--	9.8
A07-247	NR	12/17/1998	153	104	< 5.0	7.0	--	2.03	15.0
A07-247	NR	02/19/1999	217	168	--	5.4	--	< .16	16.0
A07-247	NR	05/05/1999	292	243	--	--	0.90	< .02	24.2
A07-247	NR	09/13/1999	423	374	7.2	9.3	--	2.13	21.6
A13-300	NR	07/14/1998	-3	-52	--	--	--	--	6.0
A13-300	NR	08/04/1998	18	-31	--	--	0.20	--	19.0
A13-300	NR	08/05/1998	19	-30	--	--	--	--	4.2
A13-300	NR	08/20/1998	34	-15	< 5.0	--	--	--	7.6
A13-300	NR	10/01/1998	76	27	--	--	--	--	6.3
A13-300	NR	10/21/1998	96	47	< 5.0	1.5	--	--	7.7
A13-300	NR	12/03/1998	139	90	--	--	--	--	3.8
A13-300	NR	12/17/1998	153	104	< 5.0	2.7	--	--	1.6
A13-300	NR	02/19/1999	217	168	--	6.5	--	--	7.4
A13-300	NR	05/05/1999	292	243	--	--	0.90	< .02	22.0
A13-300	NR	09/13/1999	423	374	5.2	9.3	--	1.63	13.2
A14-015	NR	07/14/1998	-3	-52	--	--	--	--	22.0
A14-015	NR	08/20/1998	34	-15	< 5.0	--	--	--	9.0
A14-015	NR	09/18/1998	63	14	< 5.0	1.9	--	1.11	5.6
A14-015	NR	12/03/1998	139	90	< 5.0	2.0	--	--	8.2
A14-015	NR	12/17/1998	153	104	< 5.0	4.1	--	5.33	10.2
A14-015	NR	02/19/1999	217	168	--	4.6	--	13.0	15.6
A14-015	NR	05/05/1999	292	243	< 5.0	--	0.95	< .02	40.6
A14-015	NR	09/13/1999	423	374	7.4	10.8	--	5.44	14.4
A14-127	NR	07/15/1998	-2	-51	--	--	--	--	7.0
A14-127	NR	08/04/1998	18	-31	--	--	0.34	--	38.9
A14-127	NR	10/01/1998	76	27	< 5.0	3.1	--	--	8.0

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluore-scein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colori-metric method (mg/L)	Sulfur hexa-fluoride (ng/L)	Water volume removed (mL)
A14-127	NR	10/21/1998	96	47	< 5.0	2.9	--	--	17.9
A14-127	NR	12/17/1998	153	104	< 5.0	8.6	--	12.5	13.4
A14-127	NR	02/19/1999	217	168	--	5.7	--	33.4	18.6
A14-127	NR	05/05/1999	292	243	< 5.0	--	1.02	< .02	42.2
A14-127	NR	09/13/1999	423	374	6.2	9.7	--	2.61	25.2
A14-255	NR	07/15/1998	-2	-51	17.7	--	--	--	11.0
A14-255	NR	09/18/1998	63	14	< 5.0	< 1.0	--	--	7.1
A14-255	NR	11/19/1998	125	76	7.6	3.3	--	--	6.2
A14-255	NR	12/03/1998	139	90	--	--	--	--	2.6
A14-255	NR	12/17/1998	153	104	< 5.0	8.3	--	--	9.7
A14-255	NR	01/19/1999	186	137	--	7.6	--	--	7.4
A14-255	NR	02/19/1999	217	168	--	--	--	33.7	5.9
A14-255	NR	05/05/1999	292	243	< 5.0	--	--	< .02	17.7
A14-255	NR	09/13/1999	423	374	--	--	--	--	2.5
B02-030	NR	07/14/1998	-3	-52	--	--	--	--	28.0
B02-030	NR	08/20/1998	34	-15	< 5.0	--	--	--	8.2
B02-030	NR	08/31/1998	45	-4	< 5.0	--	--	--	17.0
B02-030	NR	10/01/1998	76	27	< 5.0	1.2	--	2.57	11.6
B02-030	NR	11/09/1998	115	66	--	--	0.21	2.28	27.2
B02-030	NR	12/03/1998	139	90	< 5.0	2.3	--	9.62	12.5
B02-030	NR	12/17/1998	153	104	< 5.0	3.9	--	1.94	11.3
B02-030	NR	01/19/1999	186	137	--	--	--	13.6	7.7
B02-030	NR	02/19/1999	217	168	--	7.4	--	34.5	14.7
B02-030	NR	05/05/1999	292	243	< 5.0	--	0.89	< .02	37.9
B02-030	NR	06/23/1999	341	292	< 5.0	5.2	--	55.7	14.5
B02-030	NR	09/13/1999	423	374	< 5.0	9.5	--	5.22	26.6
B02-307	NR	07/14/1998	-3	-52	--	--	--	--	45.0
B02-307	NR	08/03/1998	17	-32	< 5.0	1.9	--	< .01	19.8
B02-307	NR	10/01/1998	76	27	< 5.0	< 1.0	--	2.13	13.2
B02-307	NR	10/20/1998	95	46	--	--	--	--	6.0
B02-307	1	10/21/1998	96	47	< 5.0	2.4	--	5.60	10.7
B02-307	2	10/21/1998	96	47	--	1.3	--	--	--
B02-307	NR	11/09/1998	115	66	--	--	--	--	6.0
B02-307	NR	12/03/1998	139	90	< 5.0	2.8	--	0.39	14.1
B02-307	NR	12/17/1998	153	104	< 5.0	6.1	--	15.0	17.1

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluore-scein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colori-metric method (mg/L)	Sulfur hexa-fluoride (ng/L)	Water volume removed (mL)
B02-307	NR	02/19/1999	217	168	--	6.8	--	10.2	16.4
B02-307	NR	05/05/1999	292	243	< 5.0	--	0.82	< .02	35.7
B02-307	NR	09/13/1999	423	374	7.2	6.8	--	2.84	26.4
B07-082	NR	07/14/1998	-3	-52	--	--	--	--	10.0
B07-082	NR	08/20/1998	34	-15	< 5.0	--	--	--	8.4
B07-082	NR	10/01/1998	76	27	< 5.0	1.2	--	--	9.5
B07-082	NR	10/21/1998	96	47	< 5.0	2.2	--	0.78	11.8
B07-082	NR	11/19/1998	125	76	< 5.0	3.4	--	3.53	15.6
B07-082	NR	12/17/1998	153	104	< 5.0	4.2	--	12.9	11.8
B07-082	NR	02/19/1999	217	168	--	6.7	--	< .02	14.0
B07-082	NR	05/05/1999	292	243	< 5.0	--	0.91	< .02	34.5
B07-082	NR	09/13/1999	423	374	< 5.0	6.4	--	11.2	25.0
B07-202	NR	07/14/1998	-3	-52	--	--	--	--	9.0
B07-202	NR	08/04/1998	18	-31	--	--	0.05	--	24.8
B07-202	NR	08/05/1998	19	-30	< 5.0	1.5	--	--	10.0
B07-202	1	09/18/1998	63	14	< 5.0	< 1.0	0.06	2.63	42.7
B07-202	2	09/18/1998	63	14	--	--	0.05	1.01	--
B07-202	NR	11/09/1998	115	66	--	--	0.35	4.86	27.0
B07-202	NR	12/17/1998	153	104	< 5.0	5.6	--	7.29	14.0
B07-202	NR	02/19/1999	217	168	--	7.8	--	24.5	15.4
B07-202	NR	05/05/1999	292	243	< 5.0	--	0.70	< .02	49.0
B07-202	NR	09/13/1999	423	374	6.3	7.6	--	3.86	25.8
B07-292	NR	07/14/1998	-3	-52	--	--	--	--	7.0
B07-292	NR	08/20/1998	34	-15	< 5.0	--	--	--	2.0
B07-292	NR	10/01/1998	76	27	--	--	--	--	0.6
B07-292	NR	10/21/1998	96	47	< 5.0	< 1.0	--	--	3.2
B07-292	NR	11/19/1998	125	76	< 5.0	2.1	--	0.87	13.4
B07-292	NR	12/03/1998	139	90	< 5.0	2.6	--	--	8.4
B07-292	NR	12/17/1998	153	104	< 5.0	5.0	--	1.89	9.8
B07-292	NR	01/19/1999	186	137	--	8.6	--	8.29	11.8
B07-292	NR	02/19/1999	217	168	--	7.4	--	< .16	12.3
B07-292	NR	05/05/1999	292	243	< 5.0	--	0.75	< .06	31.2
B07-292	NR	09/13/1999	423	374	< 5.0	8.9	--	4.16	25.6
B07-352	NR	07/14/1998	-3	-52	--	--	--	--	8.0
B07-352	1	09/18/1998	63	14	< 5.0	1.1	0.13	3.73	33.0

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluore-scein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colori-metric method (mg/L)	Sulfur hexa-fluoride (ng/L)	Water volume removed (mL)
B07-352	2	09/18/1998	63	14	< 5.0	1.3	--	--	--
B07-352	NR	11/05/1998	111	62	< 5.0	1.5	--	--	10.4
B07-352	NR	12/17/1998	153	104	< 5.0	2.2	--	3.83	12.6
B07-352	NR	02/19/1999	217	168	--	6.6	--	10.1	14.4
B07-352	NR	05/05/1999	292	243	< 5.0	--	0.88	< .02	44.5
B07-352	NR	09/13/1999	423	374	< 5.0	5.0	--	4.92	17.0
B14-037	NR	07/14/1998	-3	-52	< 5.0	--	--	--	25.0
B14-037	NR	08/04/1998	18	-31	--	--	0.27	--	26.1
B14-037	NR	08/05/1998	19	-30	--	--	--	--	9.6
B14-037	NR	11/05/1998	111	62	< 5.0	2.0	--	--	9.6
B14-037	NR	12/17/1998	153	104	< 5.0	4.7	--	9.51	12.2
B14-037	NR	02/19/1999	217	168	--	6.6	--	24.6	15.8
B14-037	NR	05/05/1999	292	243	< 5.0	--	0.64	24.7	37.1
B14-037	NR	09/13/1999	423	374	< 5.0	5.3	--	9.44	24.6
B14-187	NR	07/15/1998	-2	-51	--	--	--	--	6.0
B14-187	NR	08/20/1998	34	-15	< 5.0	--	--	--	10.2
B14-187	NR	10/20/1998	95	46	< 5.0	1.2	--	--	11.2
B14-187	NR	11/19/1998	125	76	< 5.0	2.2	--	3.10	13.5
B14-187	NR	12/17/1998	153	104	< 5.0	4.6	--	10.0	12.9
B14-187	NR	01/19/1999	186	137	--	7.7	--	--	8.8
B14-187	NR	02/19/1999	217	168	--	8.0	--	< .16	22.8
B14-187	NR	05/06/1999	293	244	< 5.0	--	1.80	< .03	34.8
B14-187	NR	09/13/1999	423	374	< 5.0	9.4	--	4.80	14.6
B14-337	NR	07/15/1998	-2	-51	--	--	--	--	22.0
B14-337	NR	10/01/1998	76	27	< 5.0	1.7	--	--	10.9
B14-337	NR	10/21/1998	96	47	< 5.0	2.6	--	--	44.1
B14-337	NR	12/03/1998	139	90	< 5.0	3.0	--	--	13.6
B14-337	NR	12/17/1998	153	104	< 5.0	5.4	--	2.09	18.4
B14-337	NR	02/19/1999	217	168	--	5.1	--	9.05	27.0
B14-337	NR	05/06/1999	293	244	< 5.0	--	0.85	< .04	38.6
B14-337	NR	09/13/1999	423	374	< 5.0	8.4	--	13.1	38.6
C00-000	NR	07/14/1998	-3	-52	--	--	--	--	30.0
C00-000	NR	08/03/1998	17	-32	< 5.0	1.2	--	< .01	19.1
C00-000	NR	08/20/1998	34	-15	< 5.0	--	--	--	17.1
C00-000	NR	09/18/1998	63	14	--	--	0.12	--	25.0

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluorescein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colorimetric method (mg/L)	Sulfur hexafluoride (ng/L)	Water volume removed (mL)
C00-000	NR	10/01/1998	76	27	--	--	--	13.8	11.2
C00-000	NR	11/05/1998	111	62	--	--	6.01	73.2	30.2
C00-000	NR	12/03/1998	139	90	--	--	2.13	49.7	22.4
C00-000	NR	12/17/1998	153	104	< 5.0	4.1	--	38.8	16.4
C00-000	NR	02/19/1999	217	168	--	6.2	--	< .33	20.0
C00-000	NR	05/06/1999	293	244	< 5.0	--	1.80	< .05	39.6
C00-000	NR	06/23/1999	341	292	< 5.0	4.2	--	62.8	17.6
C00-000	1	09/13/1999	423	374	< 5.0	5.3	--	39.5	17.1
C00-000	2	09/13/1999	423	374	< 5.0	3.9	--	--	--
C07-007	NR	07/14/1998	-3	-52	--	--	--	--	108.0
C07-007	NR	09/18/1998	63	14	--	--	--	--	16.6
C07-007	NR	11/05/1998	111	62	< 5.0	17.1	--	--	17.2
C07-007	1	12/03/1998	139	90	< 5.0	14.8	12.12	167	37.0
C07-007	2	12/03/1998	139	90	--	14.9	--	--	--
C07-007	NR	12/17/1998	153	104	< 5.0	12.4	--	10.5	19.8
C07-007	NR	02/19/1999	217	168	--	6.6	--	201	29.8
C07-007	NR	05/06/1999	293	244	< 5.0	--	1.13	135	77.4
C07-007	NR	09/13/1999	423	374	< 5.0	4.4	--	124	36.6
C07-067	NR	07/14/1998	-3	-52	--	--	--	--	87.0
C07-067	NR	08/20/1998	34	-15	< 5.0	--	--	--	21.8
C07-067	NR	10/21/1998	96	47	< 5.0	13.2	--	28.6	17.6
C07-067	NR	11/19/1998	125	76	< 5.0	47.7	--	51.9	19.0
C07-067	NR	12/17/1998	153	104	< 5.0	18.0	--	150	18.6
C07-067	NR	02/19/1999	217	168	--	7.4	--	613	18.6
C07-067	NR	05/06/1999	293	244	< 5.0	--	1.57	760	48.4
C07-067	NR	09/13/1999	423	374	7.4	4.1	--	573	38.7
C07-127	NR	07/14/1998	-3	-52	--	--	--	--	11.0
C07-127	NR	08/31/1998	45	-4	6.7	--	--	--	14.4
C07-127	NR	10/01/1998	76	27	--	--	--	--	3.6
C07-127	NR	11/05/1998	111	62	< 5.0	3.9	--	--	13.3
C07-127	NR	12/03/1998	139	90	< 5.0	3.0	2.28	5.07	27.8
C07-127	NR	12/17/1998	153	104	< 5.0	2.8	--	58.6	17.2
C07-127	1	01/19/1999	186	137	--	5.5	--	40.5	23.2
C07-127	2	01/19/1999	186	137	--	5.3	--	34.2	--
C07-127	NR	02/19/1999	217	168	--	6.4	--	96.2	26.9

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluorescein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colorimetric method (mg/L)	Sulfur hexafluoride (ng/L)	Water volume removed (mL)
C07-127	NR	05/06/1999	293	244	< 5.0	--	1.08	101	56.2
C07-127	NR	09/13/1999	423	374	< 5.0	4.4	--	95.7	24.8
C07-217	NR	07/14/1998	-3	-52	--	--	--	--	15.0
C07-217	NR	10/01/1998	76	27	< 5.0	< 1.0	--	26.0	17.6
C07-217	NR	10/20/1998	95	46	< 5.0	1.3	--	8.56	13.8
C07-217	NR	11/19/1998	125	76	--	--	0.50	45.6	22.3
C07-217	NR	12/17/1998	153	104	< 5.0	4.3	--	9.50	17.3
C07-217	purge	01/19/1999	186	137	--	4.2	--	--	6.0
C07-217	NR	01/19/1999	186	137	--	7.5	--	11.1	8.6
C07-217	NR	02/19/1999	217	168	--	6.1	--	< .02	19.2
C07-217	1	05/06/1999	293	244	< 5.0	--	0.62	< .02	42.8
C07-217	2	05/06/1999	293	244	< 5.0	--	--	--	--
C07-217	NR	09/13/1999	423	374	< 5.0	5.3	--	6.67	31.6
C07-262	NR	07/14/1998	-3	-52	--	--	--	--	67.0
C07-262	NR	08/20/1998	34	-15	< 5.0	--	--	--	15.5
C07-262	NR	11/05/1998	111	62	< 5.0	< 2.0	--	--	13.4
C07-262	NR	12/02/1998	138	89	--	--	0.76	4.14	21.5
C07-262	NR	12/17/1998	153	104	< 5.0	3.6	--	66.5	16.7
C07-262	NR	02/19/1999	217	168	--	5.1	--	< .32	18.7
C07-262	NR	05/06/1999	293	244	< 5.0	--	0.61	21.0	40.6
C07-262	1	09/13/1999	423	374	< 5.0	4.6	--	2.10	23.8
C07-262	2	09/13/1999	423	374	< 5.0	4.0	--	--	--
C07-322	NR	07/14/1998	-3	-52	--	--	--	--	9.0
C07-322	NR	10/01/1998	76	27	< 5.0	1.1	0.24	--	28.4
C07-322	NR	10/20/1998	95	46	< 5.0	1.3	--	--	8.2
C07-322	1	11/19/1998	125	76	--	--	1.27	14.1	32.8
C07-322	2	11/19/1998	125	76	--	--	1.65	--	--
C07-322	NR	12/02/1998	138	89	< 5.0	3.3	1.29	--	21.6
C07-322	NR	12/17/1998	153	104	< 5.0	4.1	--	5.43	12.0
C07-322	NR	02/19/1999	217	168	--	6.2	--	< .34	13.7
C07-322	1	05/06/1999	293	244	< 5.0	--	0.73	< .02	36.5
C07-322	2	05/06/1999	293	244	--	--	--	5.63	--
C07-322	NR	09/13/1999	423	374	< 5.0	7.0	--	7.37	27.9
C14-030	NR	07/14/1998	-3	-52	--	--	--	--	19.0
C14-030	NR	10/01/1998	76	27	< 5.0	1.4	--	--	10.6

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluorescein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colorimetric method (mg/L)	Sulfur hexafluoride (ng/L)	Water volume removed (mL)
C14-030	NR	11/19/1998	125	76	< 5.0	9.9	--	--	13.9
C14-030	NR	12/17/1998	153	104	< 5.0	8.0	--	27.3	16.6
C14-030	NR	01/19/1999	186	137	--	9.1	6.38	82.8	25.9
C14-030	NR	02/19/1999	217	168	--	6.8	--	22.4	13.0
C14-030	NR	05/06/1999	293	244	< 5.0	--	1.11	19.0	37.7
C14-030	NR	09/13/1999	423	374	< 5.0	5.4	--	18.2	39.9
C14-172	NR	07/15/1998	-2	-51	--	--	--	--	9.0
C14-172	NR	08/05/1998	19	-30	--	--	0.03	--	23.2
C14-172	NR	08/20/1998	34	-15	< 5.0	--	--	--	13.8
C14-172	NR	09/18/1998	63	14	< 5.0	< 1.0	--	2.31	13.2
C14-172	NR	10/21/1998	96	47	--	1.3	--	--	26.6
C14-172	NR	11/05/1998	111	62	< 5.0	1.0	--	--	7.8
C14-172	NR	12/17/1998	153	104	< 5.0	3.3	--	30.0	11.8
C14-172	NR	02/19/1999	217	168	--	5.8	--	--	6.0
C14-172	NR	05/06/1999	293	244	--	--	0.72	< .02	23.1
C14-172	NR	09/13/1999	423	374	< 5.0	3.5	--	4.10	10.4
C14-270	NR	07/15/1998	-2	-51	--	--	--	--	10.0
C14-270	NR	09/18/1998	63	14	< 5.0	< 1.0	--	7.83	16.8
C14-270	NR	11/05/1998	111	62	< 5.0	< 1.0	0.08	--	60.7
C14-270	NR	12/02/1998	138	89	< 5.0	1.1	--	--	8.4
C14-270	NR	12/17/1998	153	104	< 5.0	2.7	--	21.9	18.9
C14-270	NR	02/19/1999	217	168	--	4.6	--	< .02	17.8
C14-270	NR	05/06/1999	293	244	< 5.0	--	0.69	< .02	42.5
C14-270	1	09/13/1999	423	374	< 5.0	4.5	--	4.75	38.3
C14-270	2	09/13/1999	423	374	< 5.0	4.9	--	--	--
C14-322	NR	07/14/1998	-3	-52	10.6	--	--	--	20.0
C14-322	NR	08/04/1998	18	-31	--	--	0.06	--	33.0
C14-322	NR	08/05/1998	19	-30	--	--	--	--	12.8
C14-322	NR	08/20/1998	34	-15	< 5.0	--	--	--	16.8
C14-322	NR	10/01/1998	76	27	< 5.0	< 1.0	--	--	12.0
C14-322	NR	10/20/1998	95	46	< 5.0	1.1	--	--	26.8
C14-322	NR	11/02/1998	108	59	--	--	--	--	33.6
C14-322	NR	12/17/1998	153	104	< 5.0	3.9	--	2.10	14.9
C14-322	NR	02/19/1999	217	168	--	5.1	--	9.91	14.6
C14-322	NR	05/06/1999	293	244	< 5.0	--	0.89	< .02	35.5

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF$_6$ injection, 09/04/1998	Fluore-scein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colori-metric method (mg/L)	Sulfur hexa-fluoride (ng/L)	Water volume removed (mL)
C14-322	1	09/13/1999	423	374	< 5.0	5.2	--	7.67	31.4
C14-322	2	09/13/1999	423	374	< 5.0	4.9	--	7.48	--
D02-105	NR	07/14/1998	-3	-52	--	--	--	--	45.0
D02-105	NR	08/05/1998	19	-30	14.2	1.4	--	--	6.4
D02-105	NR	08/20/1998	34	-15	< 5.0	--	--	--	17.4
D02-105	NR	10/01/1998	76	27	< 5.0	4.9	--	474	15.1
D02-105	NR	10/20/1998	95	46	--	--	23.3	54.4	28.6
D02-105	NR	12/02/1998	138	89	--	--	24.1	136	24.8
D02-105	NR	12/17/1998	153	104	< 5.0	19.5	--	--	18.1
D02-105	NR	02/19/1999	217	168	--	10.3	--	409	15.2
D02-105	NR	05/06/1999	293	244	< 5.0	--	1.82	175	35.5
D02-105	NR	09/10/1999	420	371	< 5.0	3.2	--	476	33.7
D07-022	NR	07/14/1998	-3	-52	--	--	--	--	9.0
D07-022	NR	08/04/1998	18	-31	--	--	--	--	15.8
D07-022	NR	08/05/1998	19	-30	--	--	0.04	--	31.1
D07-022	NR	08/20/1998	34	-15	< 5.0	--	--	--	20.7
D07-022	1	10/20/1998	95	46	--	--	38.3	67.5	40.9
D07-022	2	10/20/1998	95	46	--	--	--	53.0	--
D07-022	NR	11/19/1998	125	76	--	--	92.7	60.3	22.3
D07-022	NR	12/17/1998	153	104	< 5.0	119	--	364	17.0
D07-022	NR	02/19/1999	217	168	--	28.9	--	2,970	14.4
D07-022	1	05/06/1999	293	244	7.5	--	4.18	1,430	58.8
D07-022	2	05/06/1999	293	244	--	--	3.83	1,387	--
D07-022	1	06/23/1999	341	292	< 5.0	4.2	--	458	15.9
D07-022	2	06/23/1999	341	292	--	--	--	424	--
D07-022	NR	09/10/1999	420	371	8.4	3.0	--	246	26.8
D07-105	NR	07/14/1998	-3	-52	6.4	--	--	--	18.0
D07-105	NR	09/18/1998	63	14	< 5.0	< 1.0	1.19	8.52	31.8
D07-105	NR	10/01/1998	76	27	< 5.0	3.3	--	6.72	18.0
D07-105	NR	11/05/1998	111	62	--	--	46.9	31.1	22.0
D07-105	NR	12/02/1998	138	89	< 5.0	55.5	--	876	16.6
D07-105	NR	12/17/1998	153	104	< 5.0	33.2	--	660	15.3
D07-105	NR	02/19/1999	217	168	--	13.3	--	1,350	26.6
D07-105	NR	05/06/1999	293	244	10.5	--	3.69	794	32.8
D07-105	NR	09/10/1999	420	371	12.3	3.6	--	487	23.2

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluorescein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colorimetric method (mg/L)	Sulfur hexafluoride (ng/L)	Water volume removed (mL)
D07-165	NR	07/14/1998	-3	-52	--	--	--	--	19.0
D07-165	NR	08/20/1998	34	-15	< 5.0	--	--	--	18.2
D07-165	1	10/01/1998	76	27	< 5.0	1.3	2.18	432	44.1
D07-165	2	10/01/1998	76	27	< 5.0	1.4	--	378	--
D07-165	1	10/20/1998	95	46	< 5.0	5.2	--	--	20.0
D07-165	2	10/20/1998	95	46	< 5.0	5.4	--	--	--
D07-165	NR	11/19/1998	125	76	< 5.0	3.4	--	--	15.6
D07-165	NR	12/17/1998	153	104	< 5.0	6.6	--	606	16.4
D07-165	NR	02/19/1999	217	168	--	6.1	--	151	23.8
D07-165	1	05/06/1999	293	244	< 5.0	--	0.63	82.1	81.8
D07-165	2	05/06/1999	293	244	--	--	0.65	--	--
D07-165	NR	09/09/1999	419	370	--	--	--	--	11.6
D07-277	NR	07/14/1998	-3	-52	--	--	--	--	9.0
D07-277	NR	08/04/1998	18	-31	--	--	<0.02	--	39.0
D07-277	1	08/20/1998	34	-15	< 5.0	--	--	--	26.0
D07-277	2	08/20/1998	34	-15	< 5.0	--	--	--	--
D07-277	NR	10/20/1998	95	46	--	--	5.09	16.3	25.9
D07-277	NR	12/02/1998	138	89	--	--	10.8	9.60	20.3
D07-277	NR	12/17/1998	153	104	< 5.0	8.1	--	--	15.1
D07-277	NR	02/19/1999	217	168	--	7.2	--	--	15.6
D07-277	NR	02/25/1999	223	174	--	--	--	100	2.6
D07-277	NR	05/06/1999	293	244	--	--	1.21	10.4	28.0
D07-277	NR	09/10/1999	420	371	9.8	--	--	26.1	18.0
D07-337	NR	07/14/1998	-3	-52	--	--	--	--	12.0
D07-337	NR	08/31/1998	45	-4	5.3	--	--	--	16.2
D07-337	NR	10/01/1998	76	27	< 5.0	14.3	--	--	8.9
D07-337	NR	11/05/1998	111	62	--	--	49.1	--	15.4
D07-337	NR	11/19/1998	125	76	< 5.0	50.5	--	--	8.8
D07-337	NR	12/17/1998	153	104	< 5.0	27.7	--	303	11.4
D07-337	NR	01/19/1999	186	137	--	17.0	12.7	145	29.1
D07-337	NR	02/19/1999	217	168	--	9.9	--	225	10.2
D07-337	NR	05/07/1999	294	245	< 5.0	--	1.16	65.5	36.8
D07-337	NR	06/23/1999	341	292	< 5.0	4.8	--	2.75	10.2
D07-337	NR	09/10/1999	420	371	< 5.0	2.9	--	32.0	26.6
D14-052	NR	07/14/1998	-3	-52	--	--	--	--	11.0

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluorescein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colorimetric method (mg/L)	Sulfur hexafluoride (ng/L)	Water volume removed (mL)
D14-052	NR	08/20/1998	34	-15	< 5.0	--	--	--	12.1
D14-052	NR	10/01/1998	76	27	< 5.0	< 1.0	--	--	12.9
D14-052	NR	10/21/1998	96	47	< 5.0	2.6	--	--	20.0
D14-052	NR	11/19/1998	125	76	< 5.0	25.2	--	69.0	11.8
D14-052	NR	12/17/1998	153	104	< 5.0	58.8	--	80.5	12.8
D14-052	NR	01/19/1999	186	137	--	37.9	--	2,080	11.6
D14-052	NR	02/19/1999	217	168	--	22.0	--	632	13.5
D14-052	NR	05/07/1999	294	245	< 5.0	8.3	7.11	966	33.6
D14-052	1	06/23/1999	341	292	< 5.0	11.1	--	29.8	20.7
D14-052	2	06/23/1999	341	292	< 5.0	8.9	--	--	--
D14-052	NR	09/10/1999	420	371	< 5.0	4.1	--	255	22.6
D14-247	NR	07/15/1998	-2	-51	--	--	--	--	12.0
D14-247	NR	08/20/1998	34	-15	--	--	--	--	3.8
D14-247	NR	08/31/1998	45	-4	--	--	--	--	3.0
D14-247	NR	09/18/1998	63	14	< 5.0	< 1.0	0.15	1.28	26.8
D14-247	NR	10/20/1998	95	46	< 5.0	1.3	--	1.69	16.7
D14-247	NR	12/02/1998	138	89	--	--	--	9.03	8.6
D14-247	NR	12/17/1998	153	104	< 5.0	1.1	--	--	13.2
D14-247	NR	02/19/1999	217	168	--	4.1	--	< .02	11.4
D14-247	NR	05/07/1999	294	245	< 5.0	--	0.80	< .02	30.7
D14-247	NR	09/10/1999	420	371	< 5.0	3.0	--	21.5	20.6
D14-307	NR	07/15/1998	-2	-51	--	--	--	--	10.0
D14-307	NR	10/01/1998	76	27	< 5.0	< 1.0	--	--	9.7
D14-307	NR	10/21/1998	96	47	< 5.0	1.1	--	--	31.4
D14-307	NR	11/19/1998	125	76	< 5.0	1.6	--	3.67	12.3
D14-307	NR	12/17/1998	153	104	< 5.0	1.7	--	1.82	16.4
D14-307	NR	01/19/1999	186	137	--	4.7	--	20.0	14.8
D14-307	NR	02/19/1999	217	168	--	4.9	--	58.5	17.4
D14-307	1	05/07/1999	294	245	< 5.0	--	1.03	10.7	51.6
D14-307	2	05/07/1999	294	245	--	--	1.01	--	--
D14-307	NR	06/23/1999	341	292	< 5.0	5.5	--	16.3	15.6
D14-307	NR	09/10/1999	420	371	< 5.0	2.2	--	66.4	34.4
D14-352	NR	07/15/1998	-2	-51	--	--	--	--	19.0
D14-352	NR	09/18/1998	63	14	< 5.0	1.4	--	8.14	16.5
D14-352	NR	11/05/1998	111	62	< 5.0	1.4	--	--	19.4

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluore-scein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colori-metric method (mg/L)	Sulfur hexa-fluoride (ng/L)	Water volume removed (mL)
D14-352	NR	12/02/1998	138	89	--	--	1.04	1.00	23.6
D14-352	NR	12/17/1998	153	104	< 5.0	3.3	--	13.8	15.6
D14-352	NR	02/19/1999	217	168	--	5.5	--	9.83	19.0
D14-352	1	05/07/1999	294	245	< 5.0	--	1.14	19.3	67.2
D14-352	2	05/07/1999	294	245	--	--	1.16	--	--
D14-352	1	06/23/1999	341	292	< 5.0	6.9	--	23.2	25.6
D14-352	2	06/23/1999	341	292	< 5.0	7.4	--	22.7	--
D14-352	NR	09/10/1999	420	371	< 5.0	11.9	--	36.8	56.9
D24-045	NR	09/02/1999	412	363	--	--	--	--	17.0
D24-045	NR	09/03/1999	413	364	< 5.0	< 1.0	--	9.25	19.2
D24-045	1	09/10/1999	420	371	< 5.0	2.3	--	64.5	41.2
D24-045	2	09/10/1999	420	371	< 5.0	2.5	--	--	--
E02-285	NR	07/14/1998	-3	-52	--	--	--	--	21.0
E02-285	NR	08/03/1998	17	-32	< 5.0	1.4	--	0.03	22.7
E02-285	1	08/11/1998	25	-24	< 5.0	1.6	--	--	24.7
E02-285	2	08/11/1998	25	-24	< 5.0	1.3	--	--	--
E02-285	NR	08/31/1998	45	-4	< 5.0	--	--	--	24.7
E02-285	NR	09/18/1998	63	14	--	--	7.62	--	21.0
E02-285	NR	10/01/1998	76	27	--	--	--	828	9.0
E02-285	NR	10/20/1998	95	46	< 5.0	38.6	--	72.4	14.7
E02-285	1	11/19/1998	125	76	< 5.0	106	--	1,490	13.0
E02-285	2	11/19/1998	125	76	--	--	--	1,140	--
E02-285	NR	12/17/1998	153	104	< 5.0	88.9	--	2,960	19.3
E02-285	NR	02/24/1999	222	173	--	26.2	--	1,900	19.3
E02-285	NR	05/07/1999	294	245	< 5.0	--	1.65	426	36.1
E02-285	NR	09/09/1999	419	370	< 5.0	1.3	--	467	27.9
E07-000	NR	07/14/1998	-3	-52	--	--	--	--	15.0
E07-000	NR	09/18/1998	63	14	< 5.0	< 1.0	--	4.26	24.0
E07-000	NR	11/05/1998	111	62	< 5.0	13.2	--	--	17.7
E07-000	NR	12/02/1998	138	89	--	--	23.9	46.3	17.9
E07-000	NR	12/17/1998	153	104	< 5.0	35.0	--	57.7	12.3
E07-000	NR	02/24/1999	222	173	--	10.8	--	411	12.4
E07-000	NR	05/07/1999	294	245	< 5.0	2.4	1.61	116	31.8
E07-000	NR	06/23/1999	341	292	< 5.0	--	--	165	14.6
E07-000	1	09/10/1999	420	371	< 5.0	1.7	--	79.4	33.2

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluore-scein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colori-metric method (mg/L)	Sulfur hexa-fluoride (ng/L)	Water volume removed (mL)
E07-000	2	09/10/1999	420	371	< 5.0	1.6	--	--	--
E07-045	NR	07/14/1998	-3	-52	--	--	--	--	15.0
E07-045	NR	07/15/1998	-2	-51	< 5.0	--	--	--	10.0
E07-045	NR	10/01/1998	76	27	< 5.0	1.1	--	--	13.0
E07-045	NR	11/05/1998	111	62	--	--	56.5	12.9	17.6
E07-045	NR	12/17/1998	153	104	< 5.0	112	--	625	11.6
E07-045	1	01/07/1999	174	125	--	97.1	--	3,400	21.2
E07-045	2	01/07/1999	174	125	--	96.3	--	2,480	--
E07-045	NR	02/25/1999	223	174	--	51.8	--	5,610	20.0
E07-045	NR	05/10/1999	297	248	< 5.0	9.9	10.5	22.4	44.0
E07-045	NR	06/23/1999	341	292	< 5.0	8.9	--	--	6.8
E07-045	NR	09/09/1999	419	370	14.3	3.3	--	681	16.0
E07-120	NR	07/14/1998	-3	-52	--	--	--	--	23.0
E07-120	NR	08/20/1998	34	-15	< 5.0	--	--	--	23.1
E07-120	NR	09/18/1998	63	14	< 5.0	< 1.0	--	16.6	14.9
E07-120	NR	10/20/1998	95	46	--	--	22.4	63.6	30.4
E07-120	NR	11/19/1998	125	76	< 5.0	53.9	--	255	19.2
E07-120	NR	12/17/1998	153	104	< 5.0	68.1	--	647	20.2
E07-120	NR	02/24/1999	222	173	--	21.3	--	115	15.8
E07-120	1	05/10/1999	297	248	< 5.0	6.4	6.64	1,230	71.0
E07-120	2	05/10/1999	297	248	--	--	5.70	1,060	--
E07-120	NR	09/09/1999	419	370	< 5.0	1.7	--	2,250	34.0
E07-180	NR	07/14/1998	-3	-52	--	--	--	--	16.0
E07-180	NR	08/31/1998	45	-4	5.2	--	--	--	24.5
E07-180	NR	10/01/1998	76	27	< 5.0	1.0	0.87	16.5	33.4
E07-180	NR	10/21/1998	96	47	< 5.0	1.4	--	79.5	15.2
E07-180	NR	12/02/1998	138	89	< 5.0	7.4	7.86	7.05	29.5
E07-180	NR	12/17/1998	153	104	< 5.0	8.8	--	364	14.4
E07-180	NR	02/24/1999	222	173	--	4.1	--	293	21.8
E07-180	1	05/10/1999	297	248	< 5.0	--	0.96	43.9	36.5
E07-180	2	05/10/1999	297	248	--	--	--	43.6	--
E07-180	NR	09/09/1999	419	370	< 5.0	1.2	--	59.3	37.2
E07-240	NR	07/14/1998	-3	-52	--	--	--	--	14.0
E07-240	NR	09/18/1998	63	14	< 5.0	1.4	--	13.2	13.6
E07-240	1	11/19/1998	125	76	--	--	26.2	799	38.0

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluorescein (μg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colorimetric method (mg/L)	Sulfur hexafluoride (ng/L)	Water volume removed (mL)
E07-240	2	11/19/1998	125	76	--	--	--	704	--
E07-240	NR	12/17/1998	153	104	< 5.0	22.9	--	771	11.0
E07-240	NR	01/07/1999	174	125	--	14.8	18.5	1,030	27.1
E07-240	NR	02/24/1999	222	173	--	6.6	--	209	12.2
E07-240	NR	05/10/1999	297	248	< 5.0	--	1.02	< .02	29.4
E07-240	NR	09/09/1999	419	370	< 5.0	1.3	--	68.8	23.4
E07-307	NR	07/14/1998	-3	-52	--	--	--	--	18.0
E07-307	NR	08/20/1998	34	-15	< 5.0	--	--	--	19.4
E07-307	NR	10/01/1998	76	27	< 5.0	3.5	--	3.89	18.7
E07-307	NR	11/05/1998	111	62	--	--	24.2	38.9	29.9
E07-307	1	12/02/1998	138	89	--	--	30.2	92.9	24.2
E07-307	2	12/02/1998	138	89	--	--	--	115	--
E07-307	NR	12/17/1998	153	104	< 5.0	25.4	--	176	13.0
E07-307	NR	02/24/1999	222	173	--	5.7	--	288	16.2
E07-307	NR	05/10/1999	297	248	< 5.0	--	0.80	13.6	43.2
E07-307	1	06/23/1999	341	292	< 5.0	4.7	--	28.9	26.2
E07-307	2	06/23/1999	341	292	< 5.0	4.6	--	25.8	--
E07-307	NR	09/09/1999	419	370	< 5.0	< 1.0	--	74.0	33.8
E14-007	NR	07/14/1998	-3	-52	--	--	--	--	16.0
E14-007	NR	08/20/1998	34	-15	< 5.0	< 1.0	--	--	12.0
E14-007	NR	10/20/1998	95	46	< 5.0	< 1.0	--	--	15.7
E14-007	NR	12/17/1998	153	104	5.3	8.4	--	--	10.5
E14-007	NR	01/07/1999	174	125	--	17.9	--	113	13.8
E14-007	NR	02/24/1999	222	173	--	13.9	--	393	24.2
E14-007	NR	05/10/1999	297	248	--	--	4.13	38.3	38.4
E14-007	NR	06/23/1999	341	292	5.5	7.8	--	--	7.8
E14-007	NR	09/09/1999	419	370	< 5.0	2.1	--	39.2	9.4
E14-082	NR	07/14/1998	-3	-52	--	--	--	--	11.0
E14-082	NR	09/30/1998	75	26	< 5.0	< 1.0	0.32	--	28.6
E14-082	NR	11/19/1998	125	76	< 5.0	14.6	--	--	14.3
E14-082	NR	12/17/1998	153	104	< 5.0	33.0	--	123	17.4
E14-082	NR	02/24/1999	222	173	--	23.9	--	1,280	19.0
E14-082	NR	05/10/1999	297	248	< 5.0	--	15.7	408	31.8
E14-082	NR	06/23/1999	341	292	< 5.0	14.3	--	752	13.4
E14-082	NR	09/09/1999	419	370	< 5.0	6.5	--	601	29.6

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluorescein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colorimetric method (mg/L)	Sulfur hexafluoride (ng/L)	Water volume removed (mL)
E14-157	NR	07/15/1998	-2	-51	--	--	--	--	11.0
E14-157	NR	08/04/1998	18	-31	--	--	--	--	5.4
E14-157	NR	08/05/1998	19	-30	--	--	0.06	--	32.2
E14-157	NR	08/20/1998	34	-15	< 5.0	--	--	--	17.6
E14-157	NR	11/05/1998	111	62	< 5.0	< 1.0	--	--	10.4
E14-157	NR	12/17/1998	153	104	< 5.0	5.0	--	117	12.3
E14-157	NR	05/10/1999	297	248	< 5.0	--	0.60	6.08	39.6
E14-217	NR	07/15/1998	-2	-51	--	--	--	--	13.0
E14-217	NR	10/01/1998	76	27	< 5.0	< 1.0	--	1.91	22.7
E14-217	NR	10/20/1998	95	46	< 5.0	1.2	--	--	26.8
E14-217	NR	12/02/1998	138	89	< 5.0	2.6	--	16.4	21.6
E14-217	NR	12/17/1998	153	104	< 5.0	2.4	--	21.7	17.4
E14-217	NR	02/24/1999	222	173	--	2.1	--	25.2	26.2
E14-217	NR	05/10/1999	297	248	< 5.0	--	0.73	< .02	34.9
E14-217	NR	09/09/1999	419	370	< 5.0	1.9	--	--	13.0
E14-277	NR	07/15/1998	-2	-51	--	--	--	--	14.0
E14-277	NR	08/20/1998	34	-15	< 5.0	--	--	--	9.0
E14-277	NR	11/05/1998	111	62	< 5.0	2.2	--	--	14.0
E14-277	NR	12/02/1998	138	89	< 5.0	4.4	5.15	171	23.5
E14-277	NR	12/17/1998	153	104	< 5.0	3.9	--	41.3	14.4
E14-277	NR	01/07/1999	174	125	--	3.0	--	103	17.2
E14-277	NR	02/25/1999	223	174	--	214	--	185	31.1
E14-277	NR	05/10/1999	297	248	< 5.0	2.6	1.27	44.3	35.9
E14-277	1	09/08/1999	418	369	5.7	1.7	--	127	31.0
E14-277	2	09/08/1999	418	369	< 5.0	1.7	--	--	--
E14-315	NR	07/15/1998	-2	-51	--	--	--	--	13.0
E14-315	NR	08/05/1998	19	-30	--	--	0.08	--	27.8
E14-315	NR	10/20/1998	95	46	< 5.0	< 1.0	--	--	13.4
E14-315	1	11/19/1998	125	76	< 5.0	3.4	--	--	14.2
E14-315	2	11/19/1998	125	76	< 5.0	3.3	--	--	--
E14-315	NR	12/17/1998	153	104	< 5.0	6.4	--	8.62	17.9
E14-315	NR	02/24/1999	222	173	--	3.4	--	46.2	13.0
E14-315	NR	05/10/1999	297	248	< 5.0	--	0.87	4.94	36.6
E14-315	NR	06/23/1999	341	292	< 5.0	3.7	--	25.8	19.6
E14-315	NR	09/08/1999	418	369	< 5.0	1.1	--	166	30.0

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluore-scein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colori-metric method (mg/L)	Sulfur hexa-fluoride (ng/L)	Water volume removed (mL)
F02-195	NR	07/14/1998	-3	-52	--	--	--	--	51.0
F02-195	NR	08/03/1998	17	-32	895	1.3	--	1.27	22.3
F02-195	1	08/11/1998	25	-24	800	< 1.0	--	--	27.4
F02-195	2	08/11/1998	25	-24	907	< 4.0	--	--	--
F02-195	NR	09/17/1998	62	13	257	87.6	161	8,870	35.2
F02-195	NR	10/19/1998	94	45	250	279	--	8,540	21.7
F02-195	NR	11/19/1998	125	76	148	315	--	11,300	20.2
F02-195	NR	12/17/1998	153	104	134	176	--	5,460	13.2
F02-195	NR	02/24/1999	222	173	--	18.4	--	10,000	26.2
F02-195	NR	05/10/1999	297	248	65.9	--	1.67	309	41.4
F02-195	NR	09/08/1999	418	369	80.5	< 1.0	--	1,010	34.1
F02-330	NR	07/14/1998	-3	-52	--	--	--	--	23.5
F02-330	NR	08/03/1998	17	-32	6.6	1.3	--	0.16	17.4
F02-330	purge	08/11/1998	25	-24	27.7	1.1	--	--	21.0
F02-330	NR	08/11/1998	25	-24	75.6	1.4	--	--	6.0
F02-330	NR	09/30/1998	75	26	37.3	251	--	4,740	32.3
F02-330	NR	10/19/1998	94	45	45.7	354	389	--	24.3
F02-330	NR	11/18/1998	124	75	--	--	303	--	28.4
F02-330	1	12/02/1998	138	89	52.2	317	--	8,810	30.1
F02-330	2	12/02/1998	138	89	--	--	--	7,460	--
F02-330	NR	12/17/1998	153	104	58.9	200	--	7,990	23.0
F02-330	NR	02/24/1999	222	173	--	24.7	--	5,810	25.2
F02-330	NR	05/10/1999	297	248	65.0	1.9	1.63	8,260	39.0
F02-330	NR	06/23/1999	341	292	43.0	3.1	--	362	22.2
F02-330	1	09/08/1999	418	369	113	1.0	--	3,010	36.4
F02-330	2	09/08/1999	418	369	--	--	--	199	--
F07-015	NR	07/14/1998	-3	-52	--	--	--	--	21.0
F07-015	NR	08/03/1998	17	-32	14.3	1.5	0.04	< .01	39.5
F07-015	NR	09/17/1998	62	13	< 5.0	1.0	7.98	34.9	42.9
F07-015	NR	11/05/1998	111	62	--	--	103	396	37.3
F07-015	1	12/02/1998	138	89	19.7	137	--	216	21.2
F07-015	2	12/02/1998	138	89	19.2	155	--	--	--
F07-015	NR	12/17/1998	153	104	179	140	--	1,610	22.9
F07-015	NR	02/24/1999	222	173	--	40.1	--	1,930	24.0
F07-015	NR	05/10/1999	297	248	11.4	3.8	4.57	6,550	52.4

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluorescein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colorimetric method (mg/L)	Sulfur hexafluoride (ng/L)	Water volume removed (mL)
F07-015	NR	06/22/1999	340	291	--	--	--	3,750	18.6
F07-015	NR	06/23/1999	341	292	16.4	4.5	--	--	18.6
F07-015	1	09/08/1999	418	369	29.1	1.5	--	308	36.8
F07-015	2	09/08/1999	418	369	--	--	--	280	--
F07-075	NR	07/14/1998	-3	-52	--	--	--	--	40.0
F07-075	NR	08/20/1998	34	-15	111	--	--	--	23.9
F07-075	NR	10/19/1998	94	45	68.2	36.6	--	7.13	24.6
F07-075	NR	11/18/1998	124	75	33.0	137	--	64.6	25.4
F07-075	NR	12/17/1998	153	104	19.2	185	--	704	26.0
F07-075	NR	02/25/1999	223	174	--	--	--	5,440	21.2
F07-075	NR	05/10/1999	297	248	--	--	15.1	383	41.8
F07-075	NR	06/22/1999	340	291	19.5	7.9	--	2,910	15.0
F07-075	NR	09/08/1999	418	369	67.6	--	--	688	34.6
F07-157	NR	07/14/1998	-3	-52	--	--	--	--	22.0
F07-157	purge	08/11/1998	25	-24	< 5.0	1.2	--	--	19.5
F07-157	NR	08/11/1998	25	-24	< 5.0	1.2	--	--	7.2
F07-157	NR	09/30/1998	75	26	< 5.0	7.6	10.4	--	39.0
F07-157	NR	11/05/1998	111	62	--	--	73.9	185	34.6
F07-157	NR	12/01/1998	137	88	< 5.0	92.8	--	--	16.4
F07-157	NR	12/16/1998	152	103	< 5.0	72.8	--	1,270	20.4
F07-157	NR	02/24/1999	222	173	--	11.3	--	1,500	27.1
F07-157	NR	05/10/1999	297	248	< 5.0	--	1.74	329	45.6
F07-157	NR	09/08/1999	418	369	< 5.0	1.1	--	123	24.7
F07-225	NR	07/14/1998	-3	-52	--	--	--	--	16.0
F07-225	NR	08/20/1998	34	-15	< 5.0	--	--	--	22.7
F07-225	NR	09/30/1998	75	26	< 5.0	65.7	--	--	12.4
F07-225	NR	11/18/1998	124	75	--	--	165	3,410	17.3
F07-225	NR	12/16/1998	152	103	< 5.0	129	--	949	18.3
F07-225	NR	01/19/1999	186	137	--	52.3	36.7	3,440	34.8
F07-225	NR	02/24/1999	222	173	--	8.6	--	2,150	13.4
F07-225	NR	05/10/1999	297	248	< 5.0	--	1.02	357	38.1
F07-225	NR	09/08/1999	418	369	< 5.0	< 1.0	--	91.2	32.4
F07-285	NR	07/14/1998	-3	-52	--	--	--	--	23.0
F07-285	NR	08/31/1998	45	-4	< 5.0	--	--	--	35.6
F07-285	NR	09/30/1998	75	26	< 5.0	31.6	--	27.3	24.4

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF$_6$ injection, 09/04/1998	Fluorescein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colorimetric method (mg/L)	Sulfur hexafluoride (ng/L)	Water volume removed (mL)
F07-285	NR	10/19/1998	94	45	< 5.0	36.7	--	--	16.0
F07-285	NR	10/21/1998	96	47	--	--	--	4.16	4.0
F07-285	NR	11/05/1998	111	62	--	--	47.9	138	32.0
F07-285	NR	12/01/1998	137	88	< 5.0	46.5	--	77.1	18.8
F07-285	NR	12/17/1998	153	104	< 5.0	23.5	--	270	24.2
F07-285	NR	02/24/1999	222	173	--	9.0	--	31.2	18.8
F07-285	1	05/11/1999	298	249	< 5.0	--	0.82	28.9	59.4
F07-285	2	05/12/1999	299	250	--	--	0.59	--	--
F07-285	NR	09/08/1999	418	369	< 5.0	1.0	--	32.9	37.6
F07-315	NR	07/14/1998	-3	-52	--	--	--	--	37.0
F07-315	NR	08/20/1998	34	-15	< 5.0	--	--	--	30.4
F07-315	NR	10/19/1998	94	45	--	--	17.3	--	17.5
F07-315	NR	11/18/1998	124	75	< 5.0	35.2	--	59.3	27.4
F07-315	NR	12/17/1998	153	104	< 5.0	15.2	--	190	22.6
F07-315	NR	02/24/1999	222	173	--	3.4	--	232	18.0
F07-315	NR	05/11/1999	298	249	7.4	--	0.65	68.4	41.6
F07-315	NR	06/22/1999	340	291	< 5.0	2.2	--	108	20.6
F07-315	NR	09/08/1999	418	369	< 5.0	1.0	--	16.3	35.6
F14-045	NR	07/14/1998	-3	-52	--	--	--	--	17.0
F14-045	NR	08/04/1998	18	-31	--	--	0.09	--	25.4
F14-045	NR	08/05/1998	19	-30	--	--	--	--	11.6
F14-045	purge	08/11/1998	25	-24	< 5.0	--	--	--	20.4
F14-045	NR	08/11/1998	25	-24	< 5.0	1.9	--	--	6.0
F14-045	1	09/30/1998	75	26	< 5.0	1.3	--	--	24.9
F14-045	2	09/30/1998	75	26	< 5.0	1.0	--	--	--
F14-045	NR	11/18/1998	124	75	< 5.0	8.2	--	--	19.0
F14-045	NR	12/16/1998	152	103	< 5.0	43.3	--	168	14.2
F14-045	NR	02/24/1999	222	173	--	59.8	--	943	15.9
F14-045	NR	05/11/1999	298	249	< 5.0	--	9.68	244	31.3
F14-045	NR	06/22/1999	340	291	< 5.0	6.0	--	316	15.8
F14-045	NR	09/08/1999	418	369	< 5.0	1.5	--	14.3	26.4
F14-135	NR	07/15/1998	-2	-51	--	--	--	--	15.0
F14-135	NR	08/20/1998	34	-15	< 5.0	--	--	--	19.2
F14-135	1	10/19/1998	94	45	< 5.0	20.3	--	--	36.0
F14-135	2	10/19/1998	94	45	--	19.3	--	--	--

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF$_6$ injection, 09/04/1998	Fluorescein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colorimetric method (mg/L)	Sulfur hexafluoride (ng/L)	Water volume removed (mL)
F14-135	1	11/05/1998	111	62	< 5.0	30.4	--	--	24.1
F14-135	2	11/05/1998	111	62	< 5.0	26.6	--	--	--
F14-135	NR	12/16/1998	152	103	< 5.0	20.8	--	140	19.3
F14-135	NR	01/19/1999	186	137	--	9.8	10.3	205	34.1
F14-135	NR	02/25/1999	223	174	--	--	--	12.4	14.0
F14-135	NR	05/11/1999	298	249	--	--	1.62	202	39.4
F14-135	NR	09/07/1999	417	368	< 5.0	<1.0	--	74.8	35.0
F14-210	NR	07/15/1998	-2	-51	--	--	--	--	21.0
F14-210	NR	09/17/1998	62	13	--	--	--	--	12.4
F14-210	NR	10/21/1998	96	47	5.2	1.2	--	--	24.9
F14-210	1	12/01/1998	137	88	5.3	< 1.0	--	394	31.3
F14-210	2	12/01/1998	137	88	5.3	< 1.0	--	363	--
F14-210	NR	12/16/1998	152	103	< 5.0	1.0	--	518	27.3
F14-210	NR	02/24/1999	222	173	--	1.0	--	915	30.1
F14-210	NR	05/11/1999	298	249	< 5.0	--	0.17	9.94	43.6
F14-210	NR	09/07/1999	417	368	< 5.0	< 1.0	--	21.9	50.6
F14-292	NR	07/14/1998	-3	-52	< 5.0	--	--	--	26.0
F14-292	NR	08/04/1998	18	-31	--	--	0.08	--	36.8
F14-292	NR	09/30/1998	75	26	< 5.0	2.6	--	--	22.8
F14-292	1	11/18/1998	124	75	< 5.0	11.8	--	--	27.4
F14-292	2	11/18/1998	124	75	< 5.0	11.9	--	--	--
F14-292	NR	12/16/1998	152	103	< 5.0	10.4	--	284	25.2
F14-292	NR	02/24/1999	222	173	--	3.8	--	25.7	16.1
F14-292	NR	05/11/1999	298	249	< 5.0	--	0.65	7.40	46.4
F14-292	1	09/07/1999	417	368	< 5.0	1.2	--	44.0	59.6
F14-292	2	09/07/1999	417	368	< 5.0	< 1.0	--	42.9	--
F14-345	NR	07/15/1998	-2	-51	--	--	--	--	19.0
F14-345	NR	08/20/1998	34	-15	< 5.0	--	--	--	13.4
F14-345	NR	11/05/1998	111	62	< 5.0	1.1	--	--	10.3
F14-345	NR	12/01/1998	137	88	< 5.0	5.2	5.21	--	23.8
F14-345	NR	12/17/1998	153	104	< 5.0	7.6	--	18.0	24.8
F14-345	NR	01/07/1999	174	125	--	12.1	--	44.0	15.8
F14-345	NR	02/24/1999	222	173	--	8.6	--	4.91	12.8
F14-345	NR	05/11/1999	298	249	< 5.0	--	1.97	19.4	29.6
F14-345	NR	06/22/1999	340	291	5.8	5.7	--	84.8	27.4

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF$_6$ injection, 09/04/1998	Fluorescein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colorimetric method (mg/L)	Sulfur hexafluoride (ng/L)	Water volume removed (mL)
F14-345	NR	09/07/1999	417	368	< 5.0	1.5	--	42.5	25.4
G02-000	NR	07/14/1998	-3	-52	--	--	--	--	26.0
G02-000	NR	08/03/1998	17	-32	3,460	1.2	--	< .01	14.3
G02-000	NR	08/19/1998	33	-16	5,120	< 1.0	--	--	22.6
G02-000	NR	09/17/1998	62	13	--	--	151	--	16.6
G02-000	NR	10/21/1998	96	47	5,770	991	1,090	14,000	16.5
G02-000	NR	11/18/1998	124	75	2,370	548	--	79,400	29.0
G02-000	NR	12/16/1998	152	103	2,030	296	--	87,400	23.1
G02-000	NR	02/25/1999	223	174	--	48.1	--	25,500	24.3
G02-000	NR	05/11/1999	298	249	523	4.4	2.55	2,470	37.5
G02-000	NR	06/22/1999	340	291	448	2.5	--	2,880	24.6
G02-000	1	09/07/1999	417	368	1,020	< 1.0	--	1,140	27.6
G02-000	2	09/07/1999	417	368	--	--	--	1,240	--
G07-060	NR	07/14/1998	-3	-52	--	--	--	--	45.0
G07-060	NR	08/05/1998	19	-30	3,790	2.2	--	--	8.0
G07-060	NR	08/19/1998	33	-16	1,500	< 1.0	--	--	29.2
G07-060	NR	11/05/1998	111	62	--	--	180	15,900	30.9
G07-060	1	12/01/1998	137	88	2,280	189	--	11,600	35.6
G07-060	2	12/01/1998	137	88	1,870	186	--	4,770	--
G07-060	purge	12/16/1998	152	103	1,160	151	--	--	11.0
G07-060	NR	12/16/1998	152	103	1,660	107	--	23,600	20.1
G07-060	NR	02/25/1999	223	174	--	28.0	--	9,020	28.0
G07-060	NR	05/11/1999	298	249	391	4.0	3.55	885	47.3
G07-060	NR	06/22/1999	340	291	252	2.1	--	135	27.6
G07-060	1	09/07/1999	417	368	377	<1.0	--	1,050	51.0
G07-060	2	09/07/1999	417	368	296	<1.0	--	--	--
G07-135	NR	07/14/1998	-3	-52	--	--	--	--	26.0
G07-135	purge	08/11/1998	25	-24	< 5.0	1.3	--	--	17.5
G07-135	NR	08/11/1998	25	-24	< 5.0	1.6	--	--	8.0
G07-135	NR	08/31/1998	45	-4	< 5.0	--	--	--	29.8
G07-135	NR	09/30/1998	75	26	< 5.0	46.2	49.1	--	33.7
G07-135	NR	10/19/1998	94	45	< 5.0	84.5	--	--	19.4
G07-135	NR	11/18/1998	124	75	--	--	127	--	23.6
G07-135	NR	12/16/1998	152	103	< 5.0	88.3	--	2,570	16.3
G07-135	1	01/07/1999	174	125	--	59.5	--	6,260	19.4

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluore-scein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colori-metric method (mg/L)	Sulfur hexa-fluoride (ng/L)	Water volume removed (mL)
G07-135	2	01/07/1999	174	125	--	--	--	5,900	--
G07-135	NR	02/25/1999	223	174	--	9.8	--	2,680	18.6
G07-135	NR	05/11/1999	298	249	< 5.0	--	2.32	819	37.0
G07-135	1	09/07/1999	417	368	< 5.0	<1.0	--	45.1	21.6
G07-135	2	09/07/1999	417	368	< 5.0	<1.0	--	--	--
G07-195	NR	07/14/1998	-3	-52	5.9	--	--	--	21.0
G07-195	NR	08/03/1998	17	-32	< 5.0	1.3	--	< .01	20.3
G07-195	NR	08/19/1998	33	-16	29.8	--	--	--	20.0
G07-195	NR	09/17/1998	62	13	12.8	76.5	121	2,910	26.7
G07-195	NR	11/05/1998	111	62	--	--	287	8,350	27.2
G07-195	NR	12/01/1998	137	88	16.0	211	--	--	18.6
G07-195	NR	12/16/1998	152	103	18.4	119	--	6,220	18.8
G07-195	NR	02/25/1999	223	174	--	11.3	--	5,610	27.0
G07-195	NR	05/11/1999	298	249	7.8	--	1.81	2,260	37.7
G07-195	1	09/07/1999	417	368	28.7	1.1	--	459	35.8
G07-195	2	09/07/1999	417	368	--	--	--	722	--
G07-255	NR	07/14/1998	-3	-52	--	--	--	--	18.0
G07-255	purge	08/11/1998	25	-24	< 5.0	1.4	--	--	18.0
G07-255	NR	08/11/1998	25	-24	5.3	1.3	--	--	6.0
G07-255	NR	09/30/1998	75	26	< 5.0	286	293	--	32.6
G07-255	NR	10/19/1998	94	45	--	--	341	2,420	21.9
G07-255	NR	11/18/1998	124	75	< 5.0	275	--	2,310	29.7
G07-255	NR	12/16/1998	152	103	16.0	110	--	134	24.2
G07-255	NR	01/07/1999	174	125	--	42.4	--	8,500	19.1
G07-255	NR	02/25/1999	223	174	--	8.1	--	2,270	20.3
G07-255	NR	09/07/1999	417	368	37.7	<1.0	--	90.1	24.4
G07-300	NR	07/14/1998	-3	-52	--	--	--	--	60.0
G07-300	purge	08/11/1998	25	-24	< 5.0	1.1	--	--	22.7
G07-300	NR	08/11/1998	25	-24	12.7	1.2	--	--	7.0
G07-300	NR	08/19/1998	33	-16	< 5.0	--	--	--	29.7
G07-300	NR	09/30/1998	75	26	< 5.0	133	--	585	25.3
G07-300	NR	11/05/1998	111	62	--	--	197	2,390	32.0
G07-300	NR	12/01/1998	137	88	< 5.0	150	--	1,640	26.0
G07-300	NR	12/16/1998	152	103	< 5.0	72.8	--	2,370	29.0
G07-300	NR	02/25/1999	223	174	--	23.8	--	1,690	15.8

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluore-scein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colori-metric method (mg/L)	Sulfur hexa-fluoride (ng/L)	Water volume removed (mL)
G07-300	1	05/11/1999	298	249	< 5.0	4.0	2.90	866	65.4
G07-300	2	05/11/1999	298	249	--	5.2	1.29	--	--
G07-300	NR	06/22/1999	340	291	< 5.0	2.3	--	77.8	23.8
G07-300	NR	09/07/1999	417	368	5.1	<1.0	--	181	36.3
G07-345	NR	07/14/1998	-3	-52	--	--	--	--	20.0
G07-345	NR	08/03/1998	17	-32	< 5.0	1.1	--	< .01	14.0
G07-345	NR	09/17/1998	62	13	< 5.0	4.3	--	30.6	22.4
G07-345	NR	10/19/1998	94	45	< 5.0	38.1	--	--	26.7
G07-345	NR	10/21/1998	96	47	--	--	--	23.0	2.7
G07-345	NR	11/18/1998	124	75	--	--	82.2	--	25.8
G07-345	NR	12/16/1998	152	103	8.5	71.1	--	1,000	24.6
G07-345	purge	01/07/1999	174	125	--	66.9	--	--	13.6
G07-345	NR	01/07/1999	174	125	--	55.8	--	2,730	10.9
G07-345	NR	02/25/1999	223	174	--	19.2	--	2,430	12.8
G07-345	NR	05/11/1999	298	249	< 5.0	3.7	4.23	185	43.0
G07-345	NR	06/22/1999	340	291	< 5.0	3.6	--	73.5	23.8
G07-345	NR	09/07/1999	417	368	< 5.0	1.1	--	137	39.6
G14-022	NR	07/14/1998	-3	-52	--	--	--	--	18.0
G14-022	NR	08/19/1998	33	-16	< 5.0	--	--	--	15.2
G14-022	NR	09/30/1998	75	26	< 5.0	2.2	--	--	14.0
G14-022	NR	11/05/1998	111	62	< 5.0	7.9	--	--	17.2
G14-022	NR	12/16/1998	152	103	< 5.0	30.3	--	352	12.0
G14-022	NR	01/07/1999	174	125	--	49.2	--	1,920	17.6
G14-022	purge	02/25/1999	223	174	--	34.1	--	1,000	11.4
G14-022	NR	02/25/1999	223	174	--	22.8	--	2,100	8.4
G14-022	NR	05/11/1999	298	249	< 5.0	--	4.12	205	34.8
G14-022	NR	06/22/1999	340	291	< 5.0	2.9	--	--	22.4
G14-022	NR	09/07/1999	417	368	< 5.0	< 1.0	--	57.6	30.4
G14-105	NR	07/15/1998	-2	-51	--	--	--	--	18.0
G14-105	purge	08/11/1998	25	-24	871	< 1.0	--	--	22.0
G14-105	NR	08/11/1998	25	-24	1,120	1.9	--	--	6.2
G14-105	NR	09/17/1998	62	13	713	32.5	--	312	27.0
G14-105	NR	10/19/1998	94	45	402	95.8	--	--	20.3
G14-105	1	11/18/1998	124	75	--	--	122	3,720	46.2
G14-105	2	11/18/1998	124	75	--	--	134	3,230	--

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluore-scein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colori-metric method (mg/L)	Sulfur hexa-fluoride (ng/L)	Water volume removed (mL)
G14-105	NR	12/16/1998	152	103	703	73.3	--	3,550	20.2
G14-105	NR	02/18/1999	216	167	--	26.2	--	4,620	21.8
G14-105	1	05/11/1999	298	249	145	4.8	4.52	1,760	57.8
G14-105	2	05/11/1999	298	249	--	--	4.12	--	--
G14-105	NR	09/07/1999	417	368	147	1.1	--	170	40.7
G14-165	NR	07/15/1998	-2	-51	--	--	--	--	19.0
G14-165	NR	08/04/1998	18	-31	--	--	0.07	--	40.3
G14-165	NR	08/19/1998	33	-16	< 5.0	--	--	--	28.6
G14-165	NR	09/30/1998	75	26	< 5.0	9.8	--	--	24.0
G14-165	NR	11/18/1998	124	75	--	--	21.2	270	39.4
G14-165	1	12/16/1998	152	103	< 5.0	15.5	--	256	35.4
G14-165	2	12/16/1998	152	103	< 5.0	16.3	--	--	--
G14-165	NR	02/18/1999	216	167	--	3.4	--	592	24.6
G14-165	1	05/11/1999	298	249	< 5.0	--	0.40	37.5	57.4
G14-165	2	05/11/1999	298	249	--	--	0.44	--	--
G14-165	NR	09/03/1999	413	364	< 5.0	< 1.0	--	10.8	24.7
G14-225	NR	07/15/1998	-2	-51	--	--	--	--	14.0
G14-225	NR	08/19/1998	33	-16	< 5.0	--	--	--	11.2
G14-225	NR	10/20/1998	95	46	< 5.0	18.2	--	--	23.2
G14-225	1	12/01/1998	137	88	--	--	24.0	89.7	34.6
G14-225	2	12/01/1998	137	88	--	--	30.3	--	--
G14-225	1	12/16/1998	152	103	< 5.0	19.4	--	140	28.4
G14-225	2	12/16/1998	152	103	< 5.0	--	--	--	--
G14-225	NR	02/18/1999	216	167	--	2.6	--	202	33.7
G14-225	1	05/11/1999	298	249	< 5.0	--	0.26	63.6	50.8
G14-225	2	05/11/1999	298	249	--	--	0.22	--	--
G14-225	NR	09/03/1999	413	364	< 5.0	< 1.0	--	17.8	33.2
G14-285	NR	07/15/1998	-2	-51	--	--	--	--	17.0
G14-285	purge	08/11/1998	25	-24	< 5.0	1.7	--	--	20.2
G14-285	NR	08/11/1998	25	-24	< 5.0	1.4	--	--	6.0
G14-285	NR	11/05/1998	111	62	< 5.0	4.8	--	--	20.8
G14-285	1	12/16/1998	152	103	< 5.0	8.9	--	70.4	28.4
G14-285	2	12/16/1998	152	103	--	--	--	63.6	--
G14-285	NR	01/07/1999	174	125	--	6.3	--	114	21.1
G14-285	NR	02/18/1999	216	167	--	2.3	--	178	38.2

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluore-scein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colori-metric method (mg/L)	Sulfur hexa-fluoride (ng/L)	Water volume removed (mL)
G14-285	NR	05/11/1999	298	249	< 5.0	--	0.56	80.6	37.2
G14-285	NR	09/03/1999	413	364	< 5.0	< 1.0	--	17.4	17.4
G14-330	NR	07/17/1998	0	-49	--	--	0.03	--	20.0
G14-330	NR	08/05/1998	19	-30	--	--	--	--	6.4
G14-330	NR	08/19/1998	33	-16	--	--	--	--	4.0
G14-330	NR	08/31/1998	45	-4	< 5.0	--	--	--	7.0
G14-330	NR	10/20/1998	95	46	< 5.0	4.1	--	26.0	40.8
G14-330	NR	11/18/1998	124	75	< 5.0	7.4	--	--	14.6
G14-330	NR	12/16/1998	152	103	< 5.0	9.1	--	30.7	25.2
G14-330	NR	02/18/1999	216	167	--	6.2	--	156	19.0
G14-330	1	05/11/1999	298	249	< 5.0	--	1.21	46.4	41.6
G14-330	2	05/11/1999	298	249	< 5.0	--	--	--	--
G14-330	NR	06/22/1999	340	291	< 5.0	2.4	--	14.1	24.0
G14-330	1	09/03/1999	413	364	< 5.0	< 1.0	--	16.0	35.0
G14-330	2	09/03/1999	413	364	< 5.0	< 1.0	--	--	--
G18-180	NR	08/19/1998	33	-16	< 5.0	--	--	--	31.4
G18-180	NR	11/05/1998	111	62	< 5.0	1.7	--	--	24.4
G18-180	NR	12/16/1998	152	103	< 5.0	1.0	--	49.0	21.9
G18-180	NR	02/18/1999	216	167	--	< 1.0	--	211	33.6
G18-180	1	05/11/1999	298	249	< 5.0	--	0.06	45.4	69.6
G18-180	2	05/11/1999	298	249	--	--	0.05	--	--
G18-180	NR	09/02/1999	412	363	< 5.0	< 1.0	--	30.9	32.0
H00-000	NR	07/14/1998	-3	-52	< 5.0	--	--	--	51.0
H00-000	1	07/17/1998	0	-49	< 5.0	--	--	--	45.0
H00-000	2	07/17/1998	0	-49	< 5.0	--	--	--	--
H00-000	purge	12/17/1998	153	104	--	--	--	222,000	20.0
H00-000	NR	12/17/1998	153	104	35,800 E	28.2	--	356,000	3.0
H00-000	purge	06/22/1999	340	291	1,460	3.7	2.69	--	26.0
H00-000	NR	06/22/1999	340	291	1,560	42.6	--	48,300	26.6
H00-000	1, purge	09/14/1999	424	375	1,920	1.9	--	60,600	18.6
H00-000	2, purge	09/14/1999	424	375	1,940	--	--	--	--
H00-000	NR	09/14/1999	424	375	2,830	< 1.0	--	8,190	14.6
H07-030	NR	07/14/1998	-3	-52	7.7	--	--	--	21.0
H07-030	purge	08/11/1998	25	-24	268	1.3	--	--	22.6
H07-030	NR	08/11/1998	25	-24	433	1.5	--	--	7.0

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF$_6$ injection, 09/04/1998	Fluore-scein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colori-metric method (mg/L)	Sulfur hexa-fluoride (ng/L)	Water volume removed (mL)
H07-030	NR	09/17/1998	62	13	267	104	397	3,700	27.8
H07-030	NR	09/30/1998	75	26	46.3	225	286	1,970	27.1
H07-030	NR	11/05/1998	111	62	98.2	148	144	--	24.7
H07-030	NR	12/01/1998	137	88	690	100	--	2,580	26.4
H07-030	NR	12/16/1998	152	103	49.9	67.5	--	3,670	18.6
H07-030	NR	01/07/1999	174	125	--	40.9	--	1,300	14.9
H07-030	NR	02/18/1999	216	167	--	17.0	--	1,920	21.6
H07-030	NR	05/11/1999	298	249	25.7	2.3	1.65	342	32.0
H07-030	NR	06/22/1999	340	291	< 5.0	2.1	--	351	12.8
H07-030	NR	09/02/1999	412	363	10.6	--	--	102	23.9
H07-090	NR	07/14/1998	-3	-52	--	--	--	--	35.0
H07-090	NR	08/03/1998	17	-32	92.4	1.0	--	< .02	13.0
H07-090	NR	08/19/1998	33	-16	1,650	--	--	--	24.1
H07-090	NR	10/19/1998	94	45	134	239	--	4,660	30.7
H07-090	NR	11/18/1998	124	75	202	185	87.7	1,880	54.8
H07-090	purge	12/16/1998	152	103	134	116	--	--	17.8
H07-090	NR	12/16/1998	152	103	129	80.3	--	5,440	9.8
H07-090	1, purge	01/07/1999	174	125	--	57.0	--	--	18.1
H07-090	2, purge	01/07/1999	174	125	--	56.7	--	--	--
H07-090	NR	01/07/1999	174	125	--	37.5	--	13,000	12.1
H07-090	NR	02/18/1999	216	167	--	17.4	--	6,220	27.7
H07-090	NR	05/11/1999	298	249	114	--	1.34	895	40.2
H07-090	NR	06/22/1999	340	291	139	2.0	--	493	26.0
H07-090	NR	09/02/1999	412	363	450	< 1.0	--	589	32.6
H07-150	NR	07/14/1998	-3	-52	--	--	--	--	39.0
H07-150	purge	08/11/1998	25	-24	< 5.0	--	--	--	31.2
H07-150	NR	08/11/1998	25	-24	114	1.2	--	--	6.0
H07-150	NR	08/19/1998	33	-16	83.4	--	--	--	28.0
H07-150	NR	09/17/1998	62	13	17.6	123	--	658	29.9
H07-150	NR	10/19/1998	94	45	--	--	118	2,880	36.5
H07-150	NR	11/18/1998	124	75	7.5	84.1	--	3,200	33.2
H07-150	NR	12/16/1998	152	103	10.1	39.6	--	1,900	28.5
H07-150	NR	02/18/1999	216	167	--	16.9	--	4,380	16.6
H07-150	1	05/12/1999	299	250	14.7	--	1.28	948	70.4
H07-150	2	05/12/1999	299	250	--	--	0.80	--	--

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluore-scein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colori-metric method (mg/L)	Sulfur hexa-fluoride (ng/L)	Water volume removed (mL)
H07-150	NR	09/02/1999	412	363	19.9	< 1.0	--	320	43.0
H07-210	NR	07/14/1998	-3	-52	--	--	--	--	34.0
H07-210	purge	08/11/1998	25	-24	9.6	1.7	--	--	22.8
H07-210	NR	08/11/1998	25	-24	832	1.9	--	--	6.0
H07-210	NR	09/17/1998	62	13	106	194	265	2,210	26.7
H07-210	NR	09/30/1998	75	26	130	297	319	5,300	29.4
H07-210	NR	11/05/1998	111	62	--	--	200	5,470	28.7
H07-210	NR	12/01/1998	137	88	298	130	--	3,160	25.4
H07-210	purge	12/16/1998	152	103	--	--	--	3,570	20.0
H07-210	NR	12/16/1998	152	103	594	52.9	--	3,480	9.4
H07-210	NR	02/18/1999	216	167	--	7.5	--	5,950	27.5
H07-210	NR	05/12/1999	299	250	52.4	--	0.55	453	53.2
H07-210	NR	09/02/1999	412	363	63.5	< 1.0	--	197	24.0
H07-270	NR	07/14/1998	-3	-52	--	--	--	--	58.0
H07-270	NR	08/03/1998	17	-32	< 5.0	1.1	--	< .03	11.0
H07-270	NR	08/19/1998	33	-16	9.7	--	--	--	29.8
H07-270	NR	10/19/1998	94	45	< 5.0	58.7	--	492	31.0
H07-270	1	11/18/1998	124	75	< 5.0	38.3	--	413	35.6
H07-270	2	11/18/1998	124	75	< 5.0	38.0	--	--	--
H07-270	purge	12/16/1998	152	103	8.5	27.9	--	1,750	26.1
H07-270	NR	12/16/1998	152	103	11.7	15.5	--	922	10.2
H07-270	NR	02/18/1999	216	167	--	4.9	--	695	26.0
H07-270	1	05/12/1999	299	250	6.2	--	0.25	74.6	68.9
H07-270	2	05/12/1999	299	250	--	--	0.25	--	--
H07-270	NR	09/02/1999	412	363	5.2	< 1.0	--	41.7	44.2
H07-330	NR	07/14/1998	-3	-52	--	--	--	--	24.0
H07-330	NR	08/11/1998	25	-24	< 5.0	1.3	--	--	7.6
H07-330	NR	09/17/1998	62	13	--	--	--	--	5.6
H07-330	1	09/30/1998	75	26	11.8	82.9	155	542	55.4
H07-330	2	09/30/1998	75	26	12.5	81.1	119	425	--
H07-330	NR	11/04/1998	110	61	--	--	78.0	1,190	32.6
H07-330	NR	12/01/1998	137	88	< 5.0	43.4	--	985	29.6
H07-330	1	12/16/1998	152	103	< 5.0	20.7	--	1,020	32.4
H07-330	2	12/16/1998	152	103	32.8	18.9	--	879	--
H07-330	NR	02/18/1999	216	167	--	1.9	--	809	26.4

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF$_6$ injection, 09/04/1998	Fluore-scein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colori-metric method (mg/L)	Sulfur hexa-fluoride (ng/L)	Water volume removed (mL)
H07-330	NR	05/12/1999	299	250	19.2	--	0.57	88.3	48.8
H07-330	NR	06/22/1999	340	291	44.9	1.7	--	52.5	31.8
H07-330	NR	09/02/1999	412	363	47.8	< 1.0	--	48.8	30.6
H14-000	NR	07/14/1998	-3	-52	--	--	--	--	50.0
H14-000	NR	07/15/1998	-2	-51	--	--	--	--	53.0
H14-000	NR	08/04/1998	18	-31	--	--	0.04	--	38.1
H14-000	NR	08/19/1998	33	-16	10.7	< 1.0	--	--	28.0
H14-000	NR	10/19/1998	94	45	--	--	43.7	4.22	47.2
H14-000	NR	11/18/1998	124	75	< 5.0	1.7	--	--	31.8
H14-000	purge	12/16/1998	152	103	28.2	2.0	--	77.4	11.2
H14-000	NR	12/16/1998	152	103	9.6	7.3	--	206	41.0
H14-000	NR	02/18/1999	216	167	--	3.3	--	451	33.1
H14-000	1	05/12/1999	299	250	9.4	--	0.85	238	76.2
H14-000	2	05/12/1999	299	250	--	--	0.79	232	--
H14-000	NR	06/22/1999	340	291	45.8	1.6	0.36	166	56.6
H14-000	NR	09/02/1999	412	363	< 5.0	< 1.0	--	119	44.2
H14-060	NR	07/14/1998	-3	-52	--	--	--	--	150.0
H14-060	purge	08/11/1998	25	-24	6.4	--	--	--	25.0
H14-060	NR	08/11/1998	25	-24	6.4	--	--	--	8.0
H14-060	NR	08/31/1998	45	-4	5.1	--	--	--	28.5
H14-060	NR	10/19/1998	94	45	< 5.0	3.3	--	--	49.0
H14-060	NR	12/01/1998	137	88	23.5	19.4	--	489	24.1
H14-060	purge	12/16/1998	152	103	38.4	16.9	--	358	28.6
H14-060	1	12/16/1998	152	103	76.9	28.0	--	1,580	17.0
H14-060	2	12/16/1998	152	103	75.3	28.4	--	1,170	--
H14-060	NR	02/18/1999	216	167	--	11.8	--	5,890	48.3
H14-060	1	05/12/1999	299	250	51.9	--	1.50	1,760	62.8
H14-060	2	05/12/1999	299	250	36.5	--	--	1,470	--
H14-060	NR	06/22/1999	340	291	36.5	2.1	0.67	1,490	56.6
H14-060	NR	09/02/1999	412	363	46.5	< 1.0	--	584	44.2
H14-120	NR	07/15/1998	-2	-51	20.6	--	--	--	35.0
H14-120	NR	08/19/1998	33	-16	< 5.0	--	--	--	37.2
H14-120	NR	09/30/1998	75	26	< 5.0	12.3	--	--	24.4
H14-120	1	11/18/1998	124	75	--	--	18.7	53.5	48.4
H14-120	2	11/18/1998	124	75	--	--	18.0	--	--

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluorescein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colorimetric method (mg/L)	Sulfur hexafluoride (ng/L)	Water volume removed (mL)
H14-120	purge	12/16/1998	152	103	< 5.0	16.2	--	--	20.0
H14-120	1	12/16/1998	152	103	< 5.0	12.6	--	113	13.0
H14-120	2	12/16/1998	152	103	--	--	--	105	--
H14-120	NR	02/18/1999	216	167	--	6.5	--	224	29.1
H14-120	1	05/12/1999	299	250	< 5.0	--	1.33	540	46.0
H14-120	2	05/12/1999	299	250	--	--	--	300	--
H14-120	NR	09/02/1999	412	363	< 5.0	< 1.0	--	92.2	30.8
H14-180	NR	07/15/1998	-2	-51	--	--	--	--	25.0
H14-180	NR	08/04/1998	18	-31	--	--	--	--	7.2
H14-180	NR	08/05/1998	19	-30	378	2.0	--	--	34.5
H14-180	NR	08/19/1998	33	-16	284	--	--	--	9.3
H14-180	NR	11/04/1998	110	61	--	--	13.9	74.3	20.9
H14-180	NR	12/01/1998	137	88	83.1	12.0	--	7.8	31.2
H14-180	NR	12/16/1998	152	103	68.7	7.8	--	99.9	15.5
H14-180	NR	01/07/1999	174	125	--	4.3	--	359	17.6
H14-180	NR	02/18/1999	216	167	--	1.2	--	190	14.3
H14-180	NR	05/12/1999	299	250	52.1	--	0.18	90.9	29.4
H14-180	NR	09/02/1999	412	363	19.2	< 1.0	--	16.3	44.3
H14-240	NR	07/15/1998	-2	-51	--	--	--	--	23.0
H14-240	purge	08/11/1998	25	-24	6.4	1.0	--	--	23.0
H14-240	NR	08/11/1998	25	-24	5.3	--	--	--	6.5
H14-240	NR	09/17/1998	62	13	< 5.0	2.5	--	1.45	35.5
H14-240	NR	09/30/1998	75	26	< 5.0	7.3	--	--	29.4
H14-240	NR	10/20/1998	95	46	--	--	32.8	1.52	118.3
H14-240	NR	11/04/1998	110	61	--	--	11.9	16.1	22.8
H14-240	NR	11/18/1998	124	75	--	--	--	--	7.8
H14-240	NR	12/01/1998	137	88	--	6.9	--	--	24.7
H14-240	purge	12/16/1998	152	103	7.5	6.5	--	8.04	19.0
H14-240	NR	12/16/1998	152	103	17.3	4.7	--	31.9	7.9
H14-240	NR	02/18/1999	216	167	--	< 1.0	--	16.8	30.0
H14-240	NR	05/12/1999	299	250	9.3	--	--	--	24.0
H14-240	NR	09/02/1999	412	363	< 5.0	< 1.0	--	6.19	47.3
H14-300	NR	07/15/1998	-2	-51	--	--	--	--	100.0
H14-300	NR	08/19/1998	33	-16	15.1	< 1.0	--	--	27.0
H14-300	NR	08/31/1998	45	-4	43.4	--	--	--	34.9

Appendix B2. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 14, 1998 through September 14, 1999--Continued*

Site name	Replicate	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluore-scein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colori-metric method (mg/L)	Sulfur hexa-fluoride (ng/L)	Water volume removed (mL)
H14-300	1	10/19/1998	94	45	< 5.0	10.1	--	--	84.6
H14-300	2	10/19/1998	94	45	< 5.0	12.0	--	--	--
H14-300	NR	11/18/1998	124	75	< 5.0	6.6	--	--	28.8
H14-300	purge	12/16/1998	152	103	14.1	4.2	--	22.0	26.4
H14-300	1	12/16/1998	152	103	24.8	3.1	--	29.7	17.4
H14-300	2	12/16/1998	152	103	26.1	3.1	--	--	--
H14-300	NR	02/18/1999	216	167	--	1.1	--	92.2	48.8
H14-300	1	05/12/1999	299	250	< 5.0	--	0.21	12.6	65.9
H14-300	2	05/12/1999	299	250	--	--	0.21	--	--
H14-300	NR	06/22/1999	340	291	37.4	1.4	--	3.42	25.6
H14-300	1	09/02/1999	412	363	< 5.0	< 1.0	--	9.95	58.4
H14-300	2	09/02/1999	412	363	--	< 1.0	--	--	--
I06-285	NR	05/12/1999	299	250	--	--	--	--	22.0
I06-285	NR	09/02/1999	412	363	< 5.0	< 1.0	--	11.8	27.0
I07-112	NR	05/12/1999	299	250	< 5.0	--	--	90.2	52.3
I07-112	1	09/03/1999	413	364	< 5.0	< 1.0	--	6.48	73.3
I07-112	2	09/03/1999	413	364	< 5.0	< 1.0	--	--	--
J06-000	NR	05/12/1999	299	250	< 5.0	--	--	19.9	60.4
J06-000	NR	06/22/1999	340	291	37.4	1.2	--	1.55	49.0
J06-000	1	09/03/1999	413	364	< 5.0	< 1.0	--	2.84	51.8
J06-000	2	09/03/1999	413	364	< 5.0	< 1.0	--	0.86	--
J07-187	NR	05/12/1999	299	250	< 5.0	--	--	20.2	67.0
J07-187	NR	09/02/1999	412	363	< 5.0	< 1.0	--	3.29	49.6

Appendix B3. *Concentrations of volatile organic compounds in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, August 4, 1998 through September 13, 1999*

[µg/L, micrograms per liter; NR, no replicate was collected for this sample; <, less than; - -, no data; E, estimated value]

			Chlorinated Ethanes					**Chlorinated**		
Site name	**Replicate**	**Date sampled**	**1,1,2,2-Tetra-chloro-ethane (µg/L)**	**1,1,2-Tri-chloro-ethane (µg/L)**	**1,2-Di-chloro-ethane (µg/L)**	**1,1-Di-chloro-ethane (µg/L)**	**Chloro-ethane (µg/L)**	**Tetra-chloro-ethene (µg/L)**	**Tri-chloro-ethene (µg/L)**	***cis* -1,2-Di-chloro-ethene (µg/L)**
A00-300	NR	05/05/1999	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
A06-300	NR	02/19/1999	< .5	< .5	0.7	< .5	< .5	< .5	< .5	0.6
A06-300	NR	05/05/1999	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5
A06-300	NR	09/13/1999	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0
A07-037	NR	02/19/1999	< .5	< .5	< .5	< .5	< .5	< .5	< .5	1.3
A07-142	NR	05/05/1999	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5
A07-247	NR	09/13/1999	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0
A13-300	NR	08/12/1998	< .5	0.5	< .5	< .5	< .5	< .5	0.5	< .5
A14-127	NR	08/04/1998	0.6	< .5	< .5	< .5	< .5	< .5	< .5	1.0
A14-127	NR	10/21/1998	< .5	< .5	< .5	< .5	< .5	< .5	< .5	0.7
B07-202	NR	08/04/1998	< .5	< .5	1.0	< .5	< .5	< .5	0.5	1.7
B07-202	NR	05/05/1999	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5
B07-352	NR	05/05/1999	< .5	< .5	< .5	< .5	< .5	< .5	< .5	1.2
B14-037	NR	08/12/1998	< .5	< .5	< .5	< .5	< .5	< .5	0.8	3.3
B14-037	NR	09/09/1999	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0
B14-187	NR	02/19/1999	< .5	< .5	< .5	< .5	< .5	< .5	< .5	0.8
B14-337	NR	10/21/1998	3.1	2.5	1.2	< .5	< .5	< .5	1.5	6.3
B14-337	NR	02/19/1999	< .5	< .5	0.8	< .5	< .5	< .5	< .5	1.9
B14-337	NR	09/13/1999	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0
C07-007	NR	02/19/1999	< .5	< .5	< .5	4.9	5.3	< .5	< .5	24.0
C07-007	1	05/06/1999	< .5	< .5	< .5	< .5	< .5	< .5	< .5	24.9
C07-007	2	05/06/1999	< .5	< .5	< .5	< .5	< .5	< .5	< .5	26.5
C07-067	NR	09/13/1999	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	26.0
C07-127	NR	02/19/1999	< .5	< .5	< .5	< .5	< .5	< .5	< .5	25.7
C07-127	1	05/06/1999	< .5	< .5	< .5	< .5	< .5	< .5	< .5	28.0
C07-127	2	05/06/1999	< .5	< .5	< .5	< .5	< .5	< .5	< .5	20.9
C07-262	NR	09/13/1999	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	7.4
C14-172	NR	10/21/1998	< .5	1.1	< .5	< .5	< .5	< .5	2.1 E	16.2
C14-322	NR	08/05/1998	< .5	< .5	0.5	< .5	< .5	< .5	0.9	55.9
C14-322	NR	10/21/1998	< .5	< .5	0.5	< .5	< .5	< .5	1.9 E	34.3
D07-022	1	08/05/1998	< .5	< .5	< .5	< .5	< .5	< .5	0.8	80.8
D07-022	2	08/04/1998	< .5	< .5	< .5	< .5	< .5	< .5	0.9	51.4
D07-105	NR	02/19/1999	< .5	< .5	< .5	< .5	< .5	< .5	< .5	33.6
D07-165	NR	02/19/1999	< .5	< .5	< .5	< .5	< .5	< .5	< .5	48.1
D07-165	1	05/06/1999	< .5	< .5	< .5	< .5	< .5	< .5	< .5	40.9

Ethenes			Additional Volatile Organic Compounds							
trans -1,2-Dichloroethene (µg/L)	1,1-Dichloroethene (µg/L)	Vinyl chloride (µg/L)	Chloroform (µg/L)	Chloromethane (µg/L)	Bromomethane (µg/L)	Dibromochloromethane (µg/L)	Dichlorodifluoromethane (µg/L)	Toluene (µg/L)	Trichlorofluoromethane (µg/L)	Site name
< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	0.8	< 0.5	< 0.5	< 0.5	< 0.5	A00-300
0.6	< .5	< .5	< .5	< .5	0.7	< .5	< .5	< .5	< .5	A06-300
< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	A06-300
< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	2.2	A06-300
1.7	< .5	< .5	< .5	< .5	< .5	< .5	0.7	< .5	< .5	A07-037
< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	0.5	A07-142
< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	3.2	A07-247
< .5	< .5	< .5	< .5	1.0	0.6	< .5	0.9	< .5	3.1	A13-300
0.7	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	2.8	A14-127
0.6	< .5	0.6	< .5	< .5	< .5	< .5	< .5	< .5	< .5	A14-127
< .5	< .5	5.3	< .5	< .5	< .5	< .5	< .5	0.9	1.0	B07-202
< .5	< .5	2.4	< .5	< .5	< .5	< .5	< .5	< .5	0.6	B07-202
< .5	< .5	24.4	< .5	< .5	< .5	< .5	< .5	< .5	< .5	B07-352
2.4	< .5	15.7	< .5	< .5	0.8	< .5	< .5	1.4	1.1	B14-037
< 2.0	< 2.0	7.4	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	2.3	B14-037
< .5	< .5	< .5	< .5	< .5	0.9	< .5	0.7	< .5	< .5	B14-187
9.8	< .5	17.3	1.2	< .5	< .5	< .5	< .5	< .5	< .5	B14-337
1.2	< .5	< .5	< .5	< .5	< .5	< .5	1.4	2.5	< .5	B14-337
< 2.0	< 2.0	4.6	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	2.6	B14-337
21.1	< .5	9.3	< .5	< .5	0.8	< .5	0.8	< .5	< .5	C07-007
22.1	< .5	87.9	< .5	< .5	< .5	< .5	< .5	< .5	< .5	C07-007
16.7	< .5	94.8	< .5	< .5	< .5	< .5	< .5	< .5	< .5	C07-007
2.9	< 2.0	92.1	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	C07-067
17.5	< .5	19.8	< .5	< .5	0.8	< .5	0.8	< .5	< .5	C07-127
13.5	< .5	68.7	< .5	< .5	< .5	< .5	< .5	< .5	< .5	C07-127
12.9	< .5	47.0	< .5	< .5	< .5	< .5	< .5	< .5	< .5	C07-127
< 2.0	< 2.0	34.9	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	3.0	C07-262
4.6	< .5	19.4	< .5	< .5	< .5	< .5	< .5	< .5	< .5	C14-172
74.5	< .5	86.4	< .5	< .5	< .5	< .5	< .5	< .5	0.8	C14-322
34.5	< .5	24.9	< .5	< .5	< .5	< .5	< .5	< .5	0.5	C14-322
126	< .5	66.5	< .5	< .5	< .5	< .5	< .5	< .5	0.9	D07-022
78.4	< .5	40.7	< .5	< .5	< .5	< .5	< .5	< .5	2.1	D07-022
39.2	< .5	33.6	< .5	< .5	0.6	< .5	< .5	< .5	< .5	D07-105
47.7	< .5	51.8	< .5	< .5	0.5	< .5	< .5	< .5	< .5	D07-165
32.6	< .5	92.6	< .5	< .5	< .5	< .5	< .5	< .5	< .5	D07-165

Appendix B3. *Concentrations of volatile organic compounds in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, August 4, 1998 through September 13, 1999--Continued*

			Chlorinated Ethanes					**Chlorinated**		
Site name	**Replicate**	**Date sampled**	**1,1,2,2-Tetra-chloro-ethane (µg/L)**	**1,1,2-Tri-chloro-ethane (µg/L)**	**1,2-Di-chloro-ethane (µg/L)**	**1,1-Di-chloro-ethane (µg/L)**	**Chloro-ethane (µg/L)**	**Tetra-chloro-ethene (µg/L)**	**Tri-chloro-ethene (µg/L)**	***cis* -1,2-Di-chloro-ethene (µg/L)**
D07-165	2	05/06/1999	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	35.3
D14-052	NR	09/10/1999	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	62.4
D14-247	NR	09/10/1999	2.4	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	59.2
D14-352	NR	05/07/1999	< .5	< .5	< .5	< .5	< .5	< .5	< .5	7.2
D24-045	NR	09/03/1999	4.1	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	9.9	49.2
E07-000	NR	09/10/1999	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	80.5
E07-120	NR	05/07/1999	< .5	< .5	< .5	< .5	< .5	< .5	1.6	59.1
E07-307	NR	05/10/1999	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	43.9
E14-007	NR	10/20/1998	< .5	< .5	< .5	< .5	< .5	< .5	4.3	62.6
E14-082	NR	09/07/1999	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	86.9
E14-157	NR	08/05/1998	< .5	< .5	< .5	< .5	< .5	< .5	6.4	98.2
E14-217	NR	10/20/1998	1.1	< .5	< .5	< .5	< .5	< .5	2.5	80.6
E14-217	NR	02/16/1999	< .5	< .5	< .5	< .5	34.9	< .5	< .5	67.7
E14-277	NR	02/16/1999	< .5	< .5	< .5	< .5	23.6	< .5	< .5	45.8
E14-315	NR	08/12/1998	< .5	< .5	0.6	< .5	< .5	< .5	4.0	58.7
E14-315	NR	09/08/1999	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	5.8	82.5
F07-015	NR	02/16/1999	< .5	< .5	< .5	< .5	13.6	< .5	2.6	79.7
F07-015	NR	05/10/1999	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	2.7	63.4
F07-157	NR	02/16/1999	1.2	< .5	< .5	< .5	< .5	< .5	2.2	71.1
F07-157	NR	05/10/1999	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	2.6	56.6
F14-045	NR	08/05/1998	4.7	< .5	< .5	< .5	< .5	< .5	12.8	47.8
F14-135	NR	10/19/1998	< .5	< .5	< .5	< .5	< .5	< .5	18.8	62.7
F14-135	NR	09/07/1999	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	14.1	67.2
F14-210	NR	09/07/1999	2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	2.5	77.0
F14-292	NR	08/04/1998	< .5	< .5	< .5	< .5	< .5	< .5	11.0	< .5
F14-292	NR	09/07/1999	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	3.0	94.0
G14-022	NR	09/07/1999	22.3	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	13.9	48.3
G14-165	NR	08/04/1998	6.4	4.1	< .5	< .5	< .5	1.9	20.8	43.1
G14-225	NR	10/21/1998	< .5	< .5	< .5	< .5	< .5	< .5	4.4	29.6
G14-225	NR	02/18/1999	1.3	< .5	< .5	< .5	< .5	< .5	5.4	57.7
G14-225	NR	09/03/1999	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	9.6	54.3
G14-285	NR	02/18/1999	3.2	< .7	< .7	< .7	< .7	< .7	7.0	52.7
G14-330	NR	10/20/1998	20.2	2.4	< .5	< .5	< .5	1.4	18.7	46.5
G14-330	NR	09/03/1999	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	2.2	17.8	55.5
G18-180	NR	02/18/1999	130	4.6	< .5	< .5	< .5	1.8	13.5	29.0

Ethenes			Additional Volatile Organic Compounds							
trans -1,2-Di-chloro-ethene (µg/L)	1,1-Di-chloro-ethene (µg/L)	Vinyl chloride (µg/L)	Chloro-form (µg/L)	Chloro-methane (µg/L)	Bromo-methane (µg/L)	Di-bromo-chloro-methane (µg/L)	Di-chloro-difluoro-methane (µg/L)	Toluene (µg/L)	Tri-chloro-fluoro-methane (µg/L)	Site name
32.1	< 0.5	79.8	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	D07-165
57.7	< 2.0	111	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	2.8	D14-052
42.9	< 2.0	97.9	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	3.4	D14-247
2.3	< .5	56.2	< .5	< .5	< .5	< .5	< .5	2.3	< .5	D14-352
126	< 2.0	65.5	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	D24-045
140	< 2.0	35.9	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	2.2	E07-000
128	< .5	37.6	< .5	< .5	< .5	< .5	< .5	< .5	< .5	E07-120
76.9	< 2.0	22.1	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	E07-307
143	< .5	43.2	< .5	< .5	< .5	< .5	1.0	< .5	4.0	E14-007
175	< 2.0	36.8	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	2.4	E14-082
210	< .5	20.5	< .5	< .5	< .5	< .5	< .5	< .5	3.3	E14-157
123	< .5	26.4	< .5	< .5	< .5	< .5	< .5	< .5	2.4	E14-217
95.7	< .5	63.4	< .5	< .5	1.6	< .5	< .5	< .5	< .5	E14-217
71.8	< .5	44.4	< .5	< .5	1.8	< .5	< .5	< .5	< .5	E14-277
151	< .5	17.6	< .5	< .5	< .5	< .5	< .5	0.6	0.9	E14-315
156	< 2.0	49.8	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	2.3	E14-315
173	< .5	23.7	< .5	1.2	1.3	< .5	< .5	< .5	0.6	F07-015
125	< 2.0	19.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	F07-015
157	< .5	24.9	< .5	< .5	1.3	< .5	< .5	< .5	< .5	F07-157
130	< 2.0	13.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	F07-157
196	< .5	7.4	< .5	< .5	< .5	< .5	< .5	< .5	1.0	F14-045
184	< .5	7.7	< .5	< .5	< .5	< .5	< .5	< .5	< .5	F14-135
192	< 2.0	12.2	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	2.3	F14-135
141	< 2.0	25.9	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	2.7	F14-210
154	< .5	7.8	< .5	< .5	< .5	< .5	< .5	< .5	0.7	F14-292
164	< 2.0	27.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	2.1	F14-292
137	< 2.0	11.3	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	2.9	G14-022
136	< .5	3.8	< .5	< .5	< .5	< .5	< .5	< .5	0.8	G14-165
51.2	< .5	1.7	< .5	< .5	< .5	< .5	< .5	< .5	< .5	G14-225
125	< .5	19.2	< .5	< .5	1.0	< .5	< .5	< .5	< .5	G14-225
121	< 2.0	13.7	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	3.0	G14-225
110	< .7	16.3	< .5	< .5	1.5	< .5	< .5	< .5	< .5	G14-285
146	< .5	6.6	< .5	< .5	< .5	< .5	< .5	< .5	1.9	G14-330
179	< 2.0	17.3	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	G14-330
54.4	< .5	4.0	< .5	0.7	0.9	< .5	< .5	< .5	< .5	G18-180

Appendix B3. *Concentrations of volatile organic compounds in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, August 4, 1998 through September 13, 1999--Continued*

			Chlorinated Ethanes					Chlorinated		
Site name	Replicate	Date sampled	1,1,2,2-Tetra-chloro-ethane (µg/L)	1,1,2-Tri-chloro-ethane (µg/L)	1,2-Di-chloro-ethane (µg/L)	1,1-Di-chloro-ethane (µg/L)	Chloro-ethane (µg/L)	Tetra-chloro-ethene (µg/L)	Tri-chloro-ethene (µg/L)	*cis* -1,2-Di-chloro-ethene (µg/L)
G18-180	NR	05/11/1999	122	3.2	< 2.0	< 2.0	< 2.0	< 2.0	19.8	17.3
G18-180	NR	09/02/1999	1.5	8.1	< 1.0	< 1.0	< 1.0	2.3	79.7	31.1
H07-030	NR	09/02/1999	69.4	4.7	< 1.0	< 1.0	< 1.0	2.0	21.4	43.6
H07-090	NR	09/02/1999	21.7	2.8	< 1.0	< 1.0	< 1.0	2.5	26.7	42.1
H07-150	NR	05/12/1999	75.6	< .5	< .5	< .5	< .5	< .5	42.6	101
H07-150	NR	09/02/1999	141	6.5	< 1.0	< 1.0	< 1.0	2.0	19.5	35.4
H07-210	NR	05/12/1999	< .5	3.8	< .5	< .5	< .5	< .5	18.5	20.4
H07-210	NR	09/02/1999	44.2	3.7	< 1.0	< 1.0	< 1.0	2.1	18.0	31.4
H07-330	NR	09/02/1999	35.1	< 4.0	< 4.0	< 4.0	< 4.0	< 4.0	12.2	31.0
H14-000	NR	08/04/1998	248	7.4	< .5	< .5	< .5	2.2	26.3	17.9
H14-000	NR	09/02/1999	85.1	< 4.0	< 4.0	< 4.0	< 4.0	< 4.0	31.6	35.8
H14-060	NR	10/19/1998	203	8.7	< .5	< .5	< .5	2.5	21.6 E	20.6
H14-060	NR	02/18/1999	144	3.5	< .5	< .5	< .5	1.9	11.1	26.7
H14-060	NR	09/02/1999	138	5.4	< 1.0	< 1.0	< 1.0	2.6	21.9	23.8
H14-120	NR	09/02/1999	28.5	4.7	< 1.0	< 1.0	< 1.0	1.7	17.3	40.3
H14-180	NR	09/02/1999	145	8.2	< 1.0	< 1.0	< 1.0	1.5	17.7	28.8
H14-240	NR	09/02/1999	114	7.6	< 4.0	< 4.0	< 4.0	< 4.0	18.1	32.0
H14-300	1	10/19/1998	98.7	5.9	0.5	< .5	< .5	2.1	21.7 E	37.3
H14-300	2	10/19/1998	103	5.9	< .5	< .5	< .5	2.4	21.7	42.0
H14-300	NR	02/18/1999	114	2.9	< .5	< .5	< .5	1.9	10.8	38.4
H14-300	NR	09/02/1999	52.8	4.5	< 1.0	< 1.0	< 1.0	2.0	17.3	38.2
I06-285	NR	09/07/1999	211	4.8	< 2.0	< 2.0	< 2.0	< 2.0	11.9	11.9
I07-112	NR	05/13/1999	162	6.0	< .5	< .5	< .5	1.4	48.9	4.1
I07-112	NR	09/03/1999	236	5.4	< 2.0	< 2.0	< 2.0	< 2.0	22.5	6.3
J06-000	NR	09/03/1999	616 E	6.1	< 2.0	< 2.0	< 2.0	3.2	12.1	5.7
J07-187	NR	09/03/1999	262	6.6	< 2.0	< 2.0	< 2.0	< 2.0	42.8	3.2
			Quality-Assurance Blanks							
WashBlank	NR	09/02/1999	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0
WashBlank	NR	05/05/1999	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5
WashBlank	NR	05/06/1999	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5
WashBlank	NR	05/07/1999	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5
WashBlank	NR	05/10/1999	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0
WashBlank	NR	05/10/1999	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0
WashBlank	NR	05/11/1999	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5
WashBlank	NR	05/12/1999	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5

Ethenes			Additional Volatile Organic Compounds							
trans -1,2-Di-chloro-ethene (µg/L)	1,1-Di-chloro-ethene (µg/L)	Vinyl chloride (µg/L)	Chloro-form (µg/L)	Chloro-methane (µg/L)	Bromo-methane (µg/L)	Di-bromo-chloro-methane (µg/L)	Di-chloro-difluoro-methane (µg/L)	Toluene (µg/L)	Tri-chloro-fluoro-methane (µg/L)	Site name
33.1	< 2.0	4.2	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	G18-180
68.9	< 1.0	2.8	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	1.6	G18-180
125	< 1.0	7.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	2.2	H07-030
141	< 1.0	7.4	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	1.9	H07-090
147	0.5	11.6	< .5	9.3	4.3	< .5	< .5	< .5	1.4	H07-150
87.0	< 1.0	4.3	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	1.6	H07-150
58.0	< .5	3.0	< .5	< .5	< .5	< .5	< .5	< .5	< .5	H07-210
105	< 1.0	4.9	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	1.6	H07-210
99.7	< 4.0	7.3	< 4.0	< 4.0	< 4.0	< 4.0	< 4.0	< 4.0	6.1	H07-330
25.2	< .5	0.5	1.0	< .5	< .5	< .5	< .5	< .5	0.7	H14-000
78.4	< 4.0	5.3	< 4.0	< 4.0	< 4.0	< 4.0	< 4.0	< 4.0	6.7	H14-000
62.1	< .5	1.1	< .5	< .5	< .5	< .5	< .5	< .5	< .5	H14-060
77.9	< .5	5.1	< .5	< .5	1.5	0.9	< .5	< .5	< .5	H14-060
92.0	< 1.0	3.1	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	1.5	H14-060
121	< 1.0	5.7	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	1.1	H14-120
40.9	< 1.0	1.7	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	1.5	H14-180
90.9	< 4.0	5.6	< 4.0	< 4.0	< 4.0	< 4.0	< 4.0	< 4.0	5.6	H14-240
89.8	< .5	2.3	< .5	< .5	< .5	0.9	< .5	< .5	< .5	H14-300
99.9	< .5	2.7	< .5	< .5	< .5	1.2	< .5	< .5	< .5	H14-300
72.7	< .5	5.4	< .5	< .5	1.2	< .5	< .5	< .5	< .5	H14-300
106	< 1.0	5.3	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	1.8	H14-300
19.7	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	I07-285
5.4	< .5	0.6	< .5	< .5	< .5	< .5	< .5	< .5	< .5	I07-112
2.9	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	I07-112
6.1	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	2.1	J06-000
< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	J07-187
< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	1.3	WashBlank
< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	WashBlank
< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	WashBlank
< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	WashBlank
< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	WashBlank
< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	WashBlank
< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	WashBlank
< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	< .5	WashBlank

Appendix B4. *Concentrations of methane in ground-water samples collected from the tracer array at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, August 1998 and September 1999*

[μg/L, micrograms per liter; <, less than]

August 1998		**September 1999**	
Site name	**Methane (μg/L)**	**Site name**	**Methane (μg/L)**
A13-300	2,450	A00-300	2,880
A14-127	4,530	A14-015	2,000
B14-037	1,830	A14-127	1,740
C14-322	750	B07-202	3,040
D07-022	191	B07-292	2,880
D07-277	198	C14-270	2,560
E14-157	<77.6	C14-322	2,780
E14-315	121	D14-352	3,780
F14-045	<78.3	D24-045	2,440
F14-292	<75.0	E07-120	342
G14-165	<79.1	E07-180	356
H14-000	<78.3	E14-277	518
H14-180	<60.8	F07-315	213
		F14-135	135
		G07-060	100
		G07-195	109
		H00-000	<49.7
		H07-270	<78.0
		H14-060	<76.8
		H14-180	<77.3
		H14-240	<78.6
		I06-285	<72.3
		J06-000	<77.0
		J07-187	<77.5
		Wash Blank	<76.1
		Wash Blank	<79.4
		Wash Blank	<76.7

Appendix B5. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in quality-assurance blanks collected during the tracer test at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 15, 1998 through October 7, 1999*

[SF_6, sulfur hexafluoride; µg/L, micrograms per liter; mg/L, milligrams per liter; ng/L, nanograms per liter; mL, milliliters; --, not analyzed; <, less than]

Sample type	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluorescein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colorimetric method (mg/L)	Sulfur hexafluoride (ng/L)
Ambient Blank	07/15/1998	-2	-51	< 5.0	--	--	--
Ambient Blank	07/17/1998	0	-49	< 5.0	--	--	--
Wash Blank	08/19/1998	33	-16	< 5.0	< 1.0	--	--
Wash Blank	08/19/1998	33	-16	< 5.0	--	--	--
Ambient Blank	08/20/1998	34	-15	< 5.0	--	--	--
Wash Blank	08/20/1998	34	-15	< 5.0	--	--	--
Wash Blank	09/17/1998	62	13	< 5.0	< 1.0	--	< 0.01
Wash Blank	09/17/1998	62	13	< 5.0	< 1.0	0.01	< 0.01
Ambient Blank	09/18/1998	63	14	< 5.0	< 1.0	--	--
Wash Blank	09/18/1998	63	14	< 5.0	< 1.0	--	--
Wash Blank	09/23/1998	68	19	--	< 1.0	--	--
Wash Blank	09/30/1998	75	26	< 5.0	< 1.0	--	--
Wash Blank	09/30/1998	75	26	< 5.0	< 1.0	0.10	--
Wash Blank	10/01/1998	76	27	< 5.0	< 1.0	--	--
Wash Blank	10/09/1998	84	35	--	< 1.0	--	--
Wash Blank	10/09/1998	84	35	--	< 1.0	--	--
Wash Blank	10/19/1998	94	45	< 5.0	< 1.0	--	--
Wash Blank	10/19/1998	94	45	< 5.0	< 1.0	0.02	--
Ambient Blank	10/20/1998	95	46	--	< 1.0	--	--
Wash Blank	10/20/1998	95	46	< 5.0	< 1.0	--	--
Wash Blank	10/20/1998	95	46	< 5.0	--	--	--
Wash Blank	10/21/1998	96	47	< 5.0	< 1.0	--	--
Ambient Blank	11/04/1998	110	61	< 5.0	--	--	--
Wash Blank	11/05/1998	111	62	< 5.0	< 1.0	--	--
Ambient Blank	11/09/1998	115	66	< 5.0	< 1.0	--	--
Wash Blank	11/09/1998	115	66	--	< 1.0	--	--
Wash Blank	11/19/1998	125	76	--	< 1.0	--	--
Air Blank	11/18/1998	130	81	--	--	--	1.52
Air Blank	11/19/1998	129	80	--	--	--	<1.20
Ambient Blank	12/02/1998	138	89	< 5.0	--	--	--

Appendix B5. *Concentrations of fluorescein, bromide, and sulfur hexafluoride in quality-assurance blanks collected during the tracer test at West Branch Canal Creek, Aberdeen Proving Ground, Maryland, July 15, 1998 through October 7, 1999--Continued*

Sample type	Date sampled	Days after fluorescein injection, 07/17/1998	Days after bromide and SF_6 injection, 09/04/1998	Fluorescein (µg/L)	Bromide, ion-selective electrode (mg/L)	Bromide, colorimetric method (mg/L)	Sulfur hexafluoride (ng/L)
Wash Blank	12/02/1998	138	89	< 5.0	< 1.0	--	--
Wash Blank	12/02/1998	138	89	< 5.0	< 1.0	--	--
Wash Blank	12/02/1998	138	89	< 5.0	< 1.0	--	--
Wash Blank	12/02/1998	138	89	< 5.0	< 1.0	--	--
Ambient Blank	12/07/1998	143	94	< 5.0	< 1.0	--	--
Ambient Blank	12/07/1998	143	94	< 5.0	< 1.0	--	--
Ambient Blank	12/07/1998	143	94	< 5.0	< 1.0	--	--
Wash Blank	12/16/1998	152	103	< 5.0	< 1.0	--	--
Wash Blank	12/16/1998	152	103	< 5.0	< 1.0	--	--
Wash Blank	12/16/1998	152	103	< 5.0	< 1.0	--	--
Wash Blank	12/16/1998	152	103	< 5.0	< 1.0	--	--
Wash Blank	12/17/1998	153	104	< 5.0	< 1.0	--	--
Wash Blank	12/17/1998	153	104	< 5.0	< 1.0	--	--
Wash Blank	01/07/1999	174	125	--	< 1.0	--	--
Wash Blank	02/25/1999	223	174	--	< 1.0	--	< 0.08
Wash Blank	02/25/1999	223	174	--	< 1.0	--	--
Wash Blank	05/11/1999	298	249	--	--	0.05	--
Wash Blank	05/13/1999	300	251	--	--	0.05	--
Wash Blank	05/13/1999	300	251	--	--	0.10	--
Wash Blank	05/13/1999	300	251	--	--	0.33	--
Wash Blank	05/17/1999	304	255	< 5.0	--	--	--
Wash Blank	05/17/1999	304	255	< 5.0	--	--	--
Wash Blank	05/17/1999	304	255	< 5.0	--	--	--
Wash Blank	06/22/1999	304	255	< 5.0	< 1.0	--	--
Wash Blank	06/22/1999	304	255	< 5.0	< 1.0	--	--
Wash Blank	09/08/1999	418	369	--	--	--	0.74
Wash Blank	09/10/1999	420	371	--	--	--	0.92
Wash Blank	09/13/1999	423	374	< 5.0	--	--	< .55
Wash Blank	09/13/1999	423	374	< 5.0	< 1.0	--	< .96
Wash Blank	09/14/1999	424	375	--	--	--	0.72

Appendix C. *Sample calculation of sulfur hexafluoride concentrations in ground-water samples*

1. Determine the partial pressure of the SF_6 standard used at the Reston Chlorofluorocarbon Laboratory, P_{SF6RCL}:

$$P_{SF6RCL} = P_{SF6STD} \times (P_{RCL} / P_{STD}), \qquad (1)$$

where:

P_{RCL} = atmospheric pressure at the Reston Chlorofluorocarbon Laboratory, 0.987 atm

P_{STD} = atmospheric pressure at standard conditions (0°C dry air at sea level), 1 atm

P_{SF6STD} = the partial pressure of 0.104 ppt (parts per trillion, vol/vol) SF_6 calibration gas at standard conditions, 1.04×10^{-10} atm

$$P_{SF6RCL} = 1.03\times10^{-10}\text{ atm} \qquad (1)$$

2. Determine the number of moles of SF_6 calibration gas injected during calibration, n:

Solve the ideal gas law, PV=nRT, for n:

$$n = PV/RT, \qquad (2)$$

where:

P = P_{SF6RCL} from equation 1, 1.026×10^{-10} atm

V = volume of the sample loop, 3.015×10^{-4} L

R = ideal gas constant, 8.206×10^{-2} Latm/molK

T = room temperature, 298.15 K

$$n = 1.265\times10^{-15}\text{ mol} \qquad (2)$$

3. Determine the concentration of SF_6 in the diluted headspace of the environmental sample (SF6-TS1A analyzed on January 5, 2001), C_{DHSP}:

$$C_{DHSP} = A \times RFC_{3.015}, \qquad (3)$$

where:

A = instrument response measured as the area of the SF_6 peak for the environmental sample, 42,610

$RFC_{3.015}$ = instrument response factor for the 0.3015-mL sample loop calculated as the concentration of the calibration standard divided by the area of the SF_6 peak, averaged for several calibration runs, 4.768×10^{-3}

$$C_{DHSP} = 203.15\text{ ppt} \qquad (3)$$

4. Determine the concentration of undiluted SF_6 in the headspace of the 25-mL serum vial, C_{HSP}:

$$C_{HSP} = C_{DHSP} \times (V_{dv} / V_a) \qquad (4)$$

where:

C_{DHSP} = C_{DHSP} from equation 3, 203.15 ppt

V_{dv} = volume of the dilution vessel, 292.8 mL

V_a = volume of the aliquot of headspace withdrawn from the serum vial, 1.00 mL

$$C_{HSP} = 59{,}481 \text{ ppt} \qquad (4)$$

5. Determine the number of moles of SF_6 in the diluted of headspace of the environmental sample, n_{DHSP}:

$$n_{DHSP} = A \times RFN_{3.015} \qquad (5)$$

where:

A = the instrument response (area) used in equation 3; 42,610

$RFN_{3.015}$ = the instrument response factor for the 0.3015-mL sample loop calculated as the number of moles of the calibration standard (from equation 2) divided by the area of the SF_6 peak , averaged for several calibration runs, 5.798×10^{-20}

$$n_{DHSP} = 2.470\times10^{-15} \text{ mol} \qquad (5)$$

6. Determine the number of moles of SF_6 in the 1.00-mL aliquot of undiluted headspace of the environmental sample, n_{AHSP}:

$$n_{AHSP} = n_{DHSP} \times (V_{dv} / V_a) \qquad (6)$$

where:

n_{DHSP} = n_{DHSP} from equation 4, 2.470×10^{-15} mol

V_{dv} = the volume of the dilution vessel, 292.8 mL

V_a = the volume of the aliquot of headspace withdrawn from the serum vial, 1.00 mL

$$n_{AHSP} = 7.258\times10^{-13} \text{ mol} \qquad (6)$$

Appendix C. *Sample calculation of sulfur hexafluoride concentrations in ground-water samples—Continued*

7. Determine the total number of moles of SF_6 in the entire volume of headspace in the 25-mL serum vial of environmental sample, n_{HSP}:

$$n_{HSP} = n_{AHSP} \times V_{HSP} \qquad (7)$$

where:

$n_{HSP} = n_{AHSP}$ from equation 5, 7.258×10^{-13} mol

V_{HSP} = the volume of headspace in the 25-mL serum vial, 22.485 mL

$$n_{HSP} = 1.632\times10^{-11}\ \text{mol} \qquad (7)$$

8. Determine the Henry’s law constant at 25.0°C (298.15 K), K_H:

$$K_H = 2.4396\times10^{-4}\ \text{mol/Latm}\ \ \text{(Wilhelm and others, 1977)} \qquad (8)$$

9. Calculate the concentration of SF_6 in the aqueous phase in the 25-mL serum vial, C_{AQ}:

Solve Henry’s Law, $K_H = C_{AQ} / C_{HSP}$, for C_{AQ}:

$$C_{AQ} = K_H \times C_{HSP} \qquad (9)$$

where:

$K_H = K_H$ from equation 8, 2.4396×10^{-4} mol/Latm

$C_{HSP} = C_{HSP}$ from equation 4, 5.948×10^{4} ppt or 5.948×10^{-8} atm

$$C_{AQ} = 1.451\times10^{-11}\ \text{mol/L} \qquad (9)$$

10. Determine the number of moles of SF_6 in the aqueous phase in the 25-mL serum vial, n_{AQ}:

$$n_{AQ} = C_{AQ} \times V_{AQ} \qquad (10)$$

where:

$C_{AQ} = C_{AQ}$ from equation 9, 1.451×10^{-11} mol/L

V_{AQ} = volume of aqueous phase in 25-mL serum vial, 2.634 mL or 2.634×10^{3} L

$$n_{AQ} = 3.822\times10^{-14}\ \text{mol} \qquad (10)$$

Appendix C. *Sample calculation of sulfur hexafluoride concentrations in ground-water samples—Continued*

11. Determine the total number of moles of SF_6 in both phases in the 25-mL serum vial, n_T:

$$n_T = n_{HSP} + n_{AQ} \qquad (11)$$

where:

n_{HSP} = n_{HSP} from equation 7, 1.632×10^{-11} mol

n_{AQ} = n_{AQ} from equation 10, 3.822×10^{-14} mol

$$n_T = 1.636\times10^{-11} \text{ mol} \qquad (11)$$

12. Determine the original concentration of SF_6 in the ground-water sample at the time of sample collection, prior to partitioning, C:

$$C_M = n_T / V_{AQ} \qquad (12)$$

where:

n_T = n_T from equation 11, 1.636×10^{-11} mol

V_{AQ} = volume of ground-water sample, also used in equation 10, 2.634×10^{3} L

$$C_M = 6.210\times10^{-9} \text{ mol/L} \qquad (12)$$

13. Convert the concentration of SF_6 in the ground-water sample to units of ng/L:

$$C = C_M \times Mm \times (1{,}000{,}000{,}000 \text{ ng} / 1 \text{ g}) \qquad (13)$$

where:

C_M = C_M from equation 12, 6.210×10^{-9} mol/L

M_M = the molar mass of SF_6, 146.1 g/mol

$$C = 907 \text{ ng/L} \qquad (13)$$

(Result is rounded based upon the least precise measurement used throughout the equations.)