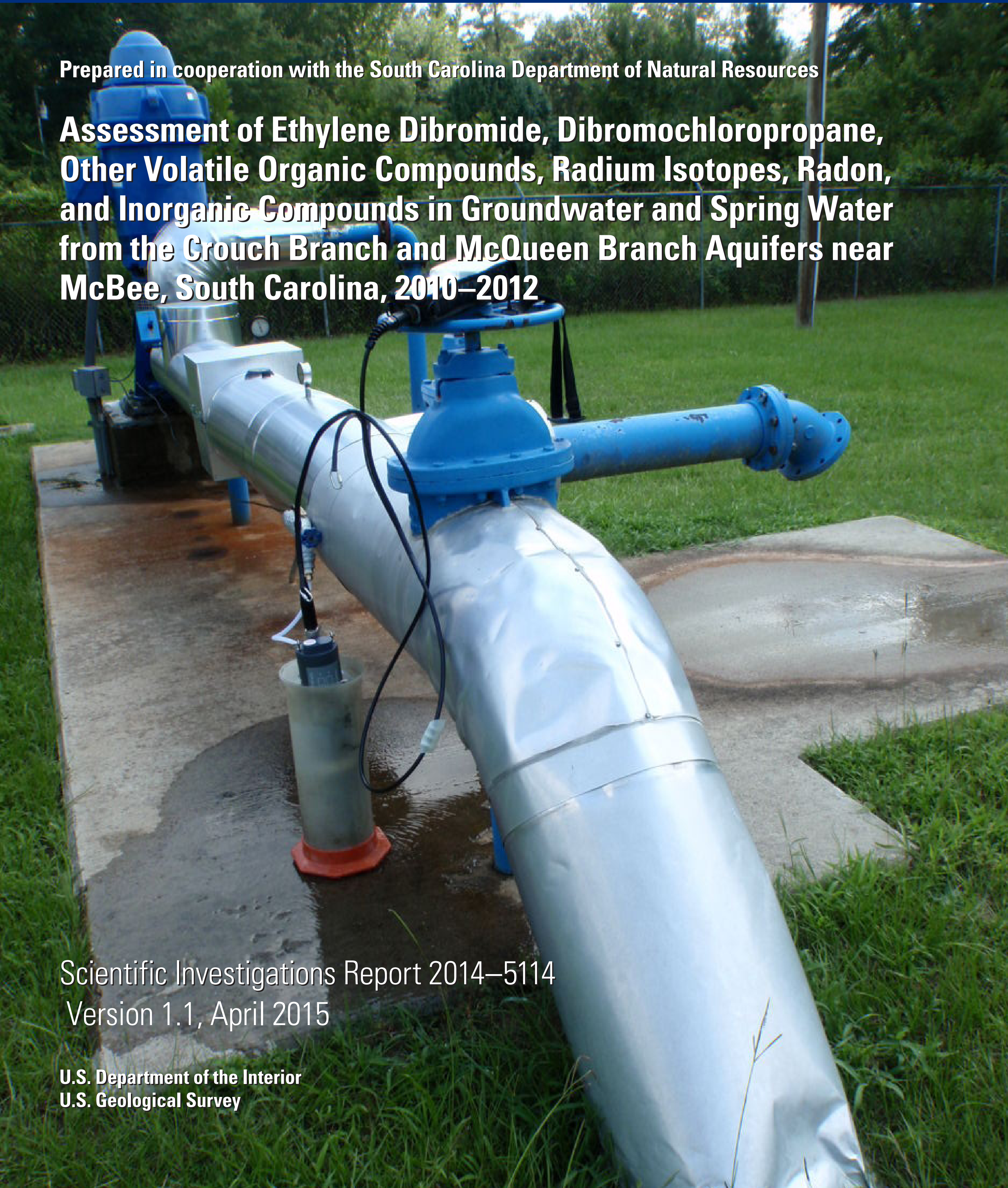
Prepared in cooperation with the South Carolina Department of Natural Resources

Assessment of Ethylene Dibromide, Dibromochloropropane, Other Volatile Organic Compounds, Radium Isotopes, Radon, and Inorganic Compounds in Groundwater and Spring Water from the Crouch Branch and McQueen Branch Aquifers near McBee, South Carolina, 2010–2012



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Cover. Alligator Rural Water and Sewer Company Public-Supply Well 5 and sonde used to measure the temperature, specific conductance, pH, dissolved-oxygen concentration, and turbidity of the groundwater prior to sample collection, July 29, 2010 (photograph by James E. Landmeyer, U.S. Geological Survey).

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By James E. Landmeyer and Bruce G. Campbell

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
gallon (gal)	3.785	liter (L)
	Flow rate	
foot per year (ft/yr)	0.3048	meter per year (m/yr)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29) or the North American Vertical Datum of 1988 (NAVD 88).

Altitude, as used in this report, refers to distance above the vertical datum.

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

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L), micrograms per liter (μg/L), picograms per kilogram (pg/kg; where 1 pg/kg is equivalent to 1.0×10^{-9} mg/L), moles per kilogram (mol/kg), or picocuries per liter (pCi/L).

Abbreviations

BTEX	benzene, toluene, ethylbenzene, and xylenes
C_{11}, C_{13}, and C_{15}	undecane, tridecane, and pentadecane (total)
CFC	chlorofluorocarbon
CFC-11	trichlorofluoromethane
CFC-12	dichlorodifluoromethane
CFC-113	1,1,2-trichloro-1,2,2-trifluoroethane
DBCP	dibromochloropropane, or 1,2-dibromo-3-chloropropane
1,1-DCA	1,1-dichloroethane
1,2-DCA	1,2-dichloroethane
1,1-DCE	1,1-dichloroethylene
DCM	dichloromethane
1,2-DCP	1,2-dichloropropane
1,3-DCP	1,3-dichloropropane
DHEC	South Carolina Department of Health and Environmental Control
E	estimated concentration
EDB	ethylene dibromide, or 1,2-dibromoethane
EPA	U.S. Environmental Protection Agency
GAC	granulated activated carbon
g/L	gram per liter
kg/ha	kilogram per hectare
<	less than
L	liter
L/ha	Liter per hectare
MCL	maximum contaminant level
µg	microgram
µg/g	microgram per gram
µg/L	microgram per liter
µmhos/cm	micromhos per centimeter
mg/L	milligram per liter
mL	milliliter
MRL	minimum reporting level
MTBE	methyl tert-butyl ether
n	unique county-well number
NPDWR	National Primary Drinking Water Regulations
NTU	nephelometric turbidity units
NWIS	National Water Information System
NWQL	National Water Quality Laboratory (U.S. Geological Survey)
NWR	National Wildlife Refuge
PAH	polycyclic aromatic hydrocarbons

PCE	perchloroethylene
pCi/L	picocurie per liter
pg/kg	picogram per kilogram
PVC	polyvinyl chloride
Ra	radium
^{226}Ra	radium-226
^{228}Ra	radium-228
Rn	radon
^{222}Rn	radon-222
S.C.	South Carolina
SCDNR	South Carolina Department of Natural Resources
1,1-TCA	1,1,1-trichloroethane
1,1,2-TCA	1,1,2-trichloroethane
TCE	trichloroethylene
Th	thorium
TPH	total petroleum hydrocarbons
U	uranium
USDA	United States Department of Agriculture
USGS	U.S. Geological Survey
VOC	volatile organic compound

Assessment of Ethylene Dibromide, Dibromochloropropane, Other Volatile Organic Compounds, Radium Isotopes, Radon, and Inorganic Compounds in Groundwater and Spring Water from the Crouch Branch and McQueen Branch Aquifers near McBee, South Carolina, 2010–2012

By James E. Landmeyer and Bruce G. Campbell

Abstract

Public-supply wells near the rural town of McBee, in southwestern Chesterfield County, South Carolina, have provided potable water to more than 35,000 residents throughout Chesterfield County since the early 1990s. Groundwater samples collected between 2002 and 2008 in the McBee area by South Carolina Department of Health and Environmental Control (DHEC) officials indicated that groundwater from two public-supply wells was characterized by the anthropogenic compounds ethylene dibromide (EDB) and dibromochloropropane (DBCP) at concentrations that exceeded their respective maximum contaminant levels (MCLs) established by the U.S. Environmental Protection Agency's (EPA) National Primary Drinking Water Regulations (NPDWR). Groundwater samples from all public-supply wells in the McBee area were characterized by the naturally occurring isotopes of radium-226 and radium-228 at concentrations that approached, and in one well exceeded, the MCL for the combined isotopes. The local water utility installed granulated activated carbon filtration units at the two EDB- and DBCP-contaminated wells and has, since 2011, shut down these two wells. Groundwater pumped by the remaining public-supply wells is currently (2014) centrally treated at a water-filtration plant.

To assess the occurrence, distribution, and potential sources of the anthropogenic and naturally occurring compounds detected in groundwater in the McBee area, samples of groundwater and spring water were collected from public-supply, domestic-supply, agricultural-supply, and monitoring wells and springs, respectively, between 2010 and 2012 by the U.S. Geological Survey. The water samples were analyzed for concentrations of EDB, DBCP, other volatile organic compounds (VOCs), radium-226 and radium-228, radon, and inorganic compounds. All wells sampled were screened in the shallow Crouch Branch aquifer, the deeper McQueen Branch aquifer, or, for most public-supply wells, both aquifers. In areas where no wells existed or wells could not be installed, passive samplers that adsorb EDB, DBCP, and various VOCs, were installed in the shallow subsurface. A representative groundwater flow pathway to each public-supply well and selected other wells was determined by using a calibrated three-dimensional groundwater-flow model of the Atlantic Coastal Plain in Chesterfield County and particle-tracking analysis. The aerial extent of the groundwater flow pathway to public-supply wells was mapped by using chlorofluorocarbon-concentration based, apparent-age dates of the groundwater.

The water-quality data collected between 2010 and 2012, in conjunction with groundwater flow pathways and historical aerial photographs of land uses near McBee, indicate an area where EDB-, DBCP-, 1,2-dichloropropane-, 1,3-dichloropropane-, and carbon disulfide-contaminated groundwater exists in the Crouch Branch aquifer in the Cedar Creek Basin and north of McBee and is most likely related to the past use of these compounds between the early 1900s and the 1980s as soil fumigants in predominately agricultural areas north of McBee. The highest EDB concentration detected (18.6 micrograms per liter) during the 3-year study was in a groundwater sample from an agricultural-supply well located north of McBee. Other VOCs, such as dichloromethane and 1,1,2-trichloroethane, also were detected in groundwater samples from this EDB-contaminated agricultural-supply well but are from unknown source(s). The fact that the agricultural area north of McBee is located in a recharge area for the Crouch Branch aquifer most likely facilitated the groundwater contamination in this area. DBCP-contaminated groundwater detected in three public-supply wells south of McBee in the deeper McQueen Branch aquifer appears to be related to past soil fumigation practices that used DBCP in agricultural areas located south of McBee. One of the three DBCP-contaminated public-supply wells also contained EDB, most likely present in groundwater due to the release of leaded gasolines that contained EDB as a fuel additive between the 1940s and 1970s. A gasoline-source of EDB, rather than a soil-fumigation source, is supported by the co-detection in groundwater from the well of 1,2-dichloroethane, a lead scavenger compound also added to leaded gasoline. Groundwater pumped from two public-supply wells located within and to the east of the McBee town limits and one domestic-supply well east of McBee was characterized by the detection of 1,1-dichloroethane, trichloroethylene, 1,1-dichloroethylene, and perchloroethylene. Groundwater flow pathways determined for these wells indicate that the potential source(s) of these compounds detected in one public-supply well and the domestic-supply well may be located within the McBee town limits, and that the potential source(s) of these compounds detected in the public-supply well to the east of McBee may be located in an area north of McBee formerly used for agriculture, but used for industry since at least the 1970s. Radium isotopes (defined in this study as the sum of radium-226 and radium-228 concentrations) and radon were detected in all wells sampled in the McBee area between 2010 and 2012. Wells characterized by radium isotope concentrations in groundwater that exceeded the MCL of 5.0 picocuries per liter were also characterized by specific conductance values greater than 30 microsiemens per centimeter and clustered north of McBee in a predominately agricultural area, and in agricultural and urban areas located within and east of McBee. The elevated specific conductance values measured in groundwater from these wells most likely are due to recharge by water mineralized by fertilizer application in agricultural areas, or due to the recharge by water mineralized by septic-tank drain-field effluent near urban areas. Radon was detected in groundwater from all wells sampled, and radon concentrations in groundwater from three monitoring wells exceeded the proposed MCL of 300 picocuries per liter. Concentrations of uranium in groundwater in the McBee area increased with increased groundwater-sample depth, most likely due to the proximity of the sample-collection location to basement rock that contains uranium-bearing minerals.

Introduction

Ambient groundwater may contain chemical compounds that originate from both anthropogenic (human-generated) and naturally occurring sources. Frequently detected anthropogenic compounds in groundwater in the United States include 1,2-dibromoethane (commonly known as ethylene dibromide, or EDB) and 1,2-dibromo-3-chloropropane (commonly known as dibromochloropropane, or DBCP; Zogorski and others, 2006). Frequently detected naturally occurring compounds in groundwater include the radium isotopes radium-226 (^{226}Ra) and radium-228 (^{228}Ra), often collectively reported as the concentration of both isotopes (Szabo, dePaul, and others, 2012), and inorganic compounds such as uranium. Understanding the detection, distribution, sources, and fate of these manmade and natural compounds in ambient groundwater systems of the United States is essential to the protection of human health and the environment, because drinking water that contains these compounds may be associated with an increased risk of various types of cancer.

The detection of anthropogenic compounds in groundwater reflects the vulnerability of groundwater resources to past and current sources of contamination. For example, EDB and DBCP are both frequently detected in groundwater (Zogorski and others, 2006) even though the use of EDB as a soil fumigant and fuel additive and DBCP as a soil fumigant was banned in the early 1980s in the United States by the U.S. Environmental Protection Agency (EPA) because of the potentially carcinogenic properties of EDB and DBCP. Conversely, groundwater can become enriched in naturally occurring radium isotopes or uranium as groundwater flows through aquifer sediments characterized by uranium- and thorium-bearing minerals (Szabo, dePaul, and others, 2012).

In South Carolina, quarterly water-quality compliance sampling of potable water suppliers conducted by the South Carolina Department of Health and Environmental Control (DHEC) between 2002 and 2008 revealed that some of the public-supply wells located near the town of McBee, in rural southwestern Chesterfield County, South Carolina (S.C.) that tap the Crouch Branch and McQueen Branch aquifers, contained EDB and DBCP, as well as radium isotopes, at concentrations that exceeded their respective maximum contaminant levels (MCL) established by the EPA through the National Primary Drinking Water Regulations (NPDWR). The groundwater samples were collected as part of the Drinking Water Compliance Monitoring regulations R.61–58, promulgated pursuant to S.C. Code Sections 44–55–10 et seq, called the State Primary Drinking Water Regulations, with emphasis on MCLs in drinking water. Specifically, EDB and DBCP were detected in groundwater samples from Well 3 and Well 6 at concentrations that exceeded the MCLs of 0.05 and 0.20 microgram per liter (µg/L), respectively. Because the EDB and DBCP were detected in groundwater samples collected over one year of sampling, a granulated activated carbon (GAC) system was installed at each of the two wellheads to remove the compounds. Radium isotope concentrations in Well 8 exceeded the 5.0 picocuries per liter (pCi/L) MCL for radium isotopes, and that well subsequently was taken out of service. Since 2012, the two EDB- and DBCP-contaminated public-supply wells have been shut down, and groundwater pumped by all public-supply wells is treated at a centrally located water-filtration plant. Groundwater pumped by some privately owned, domestic-supply wells in the area also has been determined by DHEC sampling to contain EDB, DBCP, and radium isotopes but is not typically filtered.

To address the concerns of public, private, and governmental users of groundwater in the McBee area, the U.S. Geological Survey (USGS), in cooperation with the South Carolina Department of Natural Resources (SCDNR), collected and interpreted groundwater and spring-water quality data in the study area. Data collection was implemented to provide answers to the following general questions:

1. Is the source of the EDB detected in groundwater related to the past use of EDB as a soil fumigant, as a fuel additive, or both?
2. Does the detection of EDB and DBCP in groundwater 30 years after their use was banned indicate the presence of long-term source(s) in the subsurface in the McBee area or, conversely, that insufficient time has elapsed for these compounds to be removed from the subsurface by discharge to springs, lakes, or rivers?
3. Does the detection of higher concentrations of EDB and DBCP in groundwater in certain parts of the McBee area indicate differences in past or current land uses?
4. Do different land uses affect concentrations of radium isotopes in groundwater?
5. What is the source of elevated radium isotopes in some public-supply wells in the McBee area?

The water-quality data collected in the McBee area further the national-level understanding of the detection, distribution, and fate of EDB, DBCP, and radium isotopes in groundwater, which is a primary function of the USGS (National Research Council, 1996).

Purpose and Scope

The purpose of this report is to document the results of an assessment of the quality of groundwater and spring water from the Crouch Branch and McQueen Branch aquifers near McBee, S.C. Groundwater from these aquifers has been shown to contain EDB, DBCP, and radium isotope concentrations above their MCLs by prior sampling conducted by DHEC officials. The water-quality data collected as part of this study are intended to be used by municipal, county, and State water-resource managers responsible for the management of the Crouch Branch and McQueen Branch aquifers.

The scope of the investigation included the collection of groundwater samples between 2010 and 2012 from 10 public-supply wells, 3 domestic-supply wells, 4 agricultural-supply wells, and 8 monitoring wells, and samples from 4 springs in the McBee area. Between 2010 and 2012, some wells were sampled once, others multiple times. Basic physical properties and the chemical composition of the water samples are reported along with the concentration of EDB, DBCP, other volatile organic compounds (VOCs), and the radium isotopes ^{226}Ra and ^{228}Ra. The concentrations of radon (^{222}Rn) and inorganic compounds were measured in some wells during 2012. To address water-quality data gaps in areas where wells or springs either did not exist or could not be sampled, passive soil-gas samplers that can adsorb EDB, DBCP, and VOCs were installed in the subsurface. All public-supply wells were sampled in 2010 for concentrations of chlorofluorocarbons (CFCs) in groundwater to determine the apparent-age date of the groundwater sample. The apparent-age dates were used to determine the extent of groundwater flow pathways to wells determined by using a calibrated three-dimensional groundwater-flow model of the Atlantic Coastal Plain constructed for Chesterfield County, S.C. (Campbell and Landmeyer, 2014), based on the groundwater-flow model MODFLOW (Harbaugh and others, 2000). The groundwater flow pathways, or “particle-tracks,” determined were superimposed on historical aerial photographs of land uses in the McBee area that encompass the timeframe revealed by the apparent-age dates, and used in conjunction with the water-quality results to assess potential sources of these compounds detected in groundwater.

Previous Investigations

The groundwater resources of Chesterfield County, S.C., are described in a report by Newcome (2004). That report contains basic groundwater-quality results for Chesterfield County, including results for a few wells in the McBee area. A three-dimensional groundwater-flow model of groundwater resources in Chesterfield County was developed by the USGS and includes wells near McBee (Campbell and Landmeyer, 2014).

Description of the Study Area

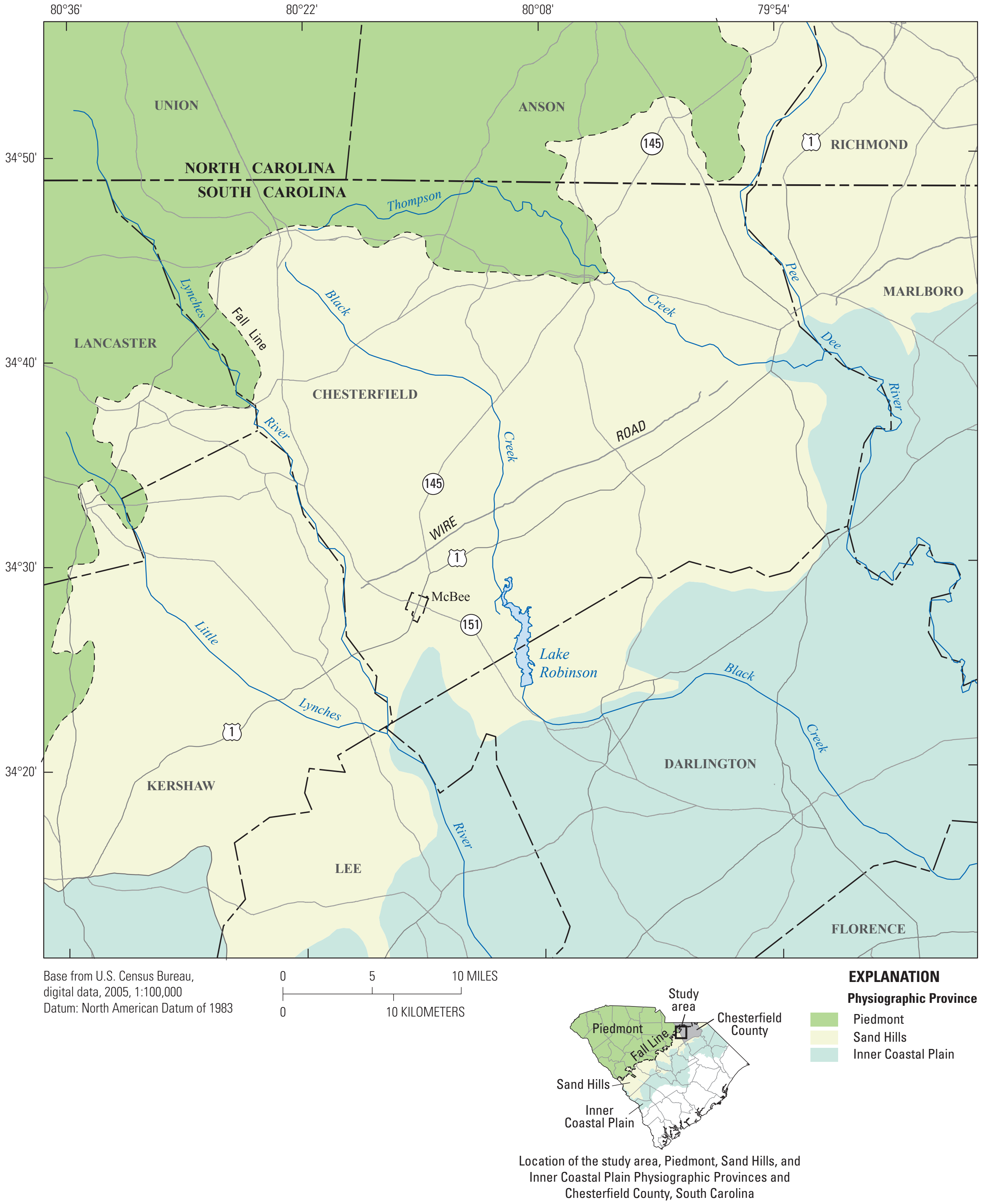
This section describes the population, land uses, hydrogeologic setting, springs, and groundwater quality in the McBee study area. The past detection of EDB, DBCP, and radium isotopes in groundwater samples collected by DHEC officials in the McBee area and their concentrations are briefly summarized.

Population

The town of McBee is located in southwestern Chesterfield County, S.C. (fig. 1). McBee was incorporated in 1901, and the general history of McBee and Chesterfield County is reported in Latimer and others (1915). The population of McBee was 867 in 2010 (U.S. Census Bureau, 2013). Most of the population is located in rural areas (Newcome, 2004).

Land Use

Since the 1800s, the predominant land uses in the McBee area of Chesterfield County have been related to the agricultural and silviculture industries. To facilitate agricultural land use, timber was extensively cleared in the 1900s, including removal of native longleaf pines (Finch and others, 2012). As early as the 1910s several small peach orchards around McBee were noted by Latimer and others (1915) as being “well-cared for,” and peach production continues in the McBee area to the



Location of the study area, Piedmont, Sand Hills, and Inner Coastal Plain Physiographic Provinces and Chesterfield County, South Carolina

Figure 1. Location of generalized boundaries of physiographic provinces and study area near McBee, Chesterfield County, South Carolina.

present (2014). Other crops such as strawberries, soybeans, sorghum, rye, and Sericea lespedeza (a perennial legume) also are produced.

Clearcutting and the use of 20th century agricultural practices resulted in many acres of highly eroded land across South Carolina, including the McBee area. Large tracts of this economically poor land were purchased by the Federal Government between 1935 and 1939 as part of the Resettlement Act (Finch and others, 2012). In 1939, some of the land was designated as the Carolina Sandhills National Wildlife Refuge (NWR; fig. 2). The remainder of the land was used for timber production and managed by the S.C. Forestry Commission for the U.S. Department of the Interior until 1991, when part of the land was transferred to the State of South Carolina and was designated as the Sand Hills State Forest (fig. 2).

Land use within or near the town limits of McBee primarily is non-agricultural. Such land uses include housing; various privately owned, light- to heavy-industrial and manufacturing processes; a transportation maintenance facility; railroad and railway easements; and various old and new gasoline stations. In some cases, the land had been used for agricultural purposes prior to these current land uses.

Hydrogeology and Water Quality

Approximately 80 percent of Chesterfield County, including the McBee study area, lies within the Inner Coastal Plain of the Atlantic Coastal Plain physiographic province (fig. 1). A detailed hydrogeologic framework of the Atlantic Coastal Plain in South Carolina that includes Chesterfield County is presented in Gellici and Lautier (2010), summarized in Campbell and Landmeyer (2014), and the generalized discussion here is mostly derived from these reports.

The McBee study area is located in the Sand Hills physiographic province, an area of generally high topography defined to the north by the Fall Line and to the south by the lower altitudes of the Inner Coastal Plain (fig. 1), and is incised by spring-fed streams (fig. 2). The hydrogeologic framework in the McBee area consists of two aquifers separated by a clay confining unit (fig. 3). The shallower Crouch Branch aquifer (called the upper unit in this report), consists of sands of the Upper Cretaceous series. To the south of McBee, the upper unit is underlain by the McQueen Branch confining unit, a clay of variable thickness and distribution, and then the McQueen Branch aquifer (called the lower unit in this report). The lower unit also consists of sands of the Upper Cretaceous series and unconformably overlies metamorphic rocks of pre-Paleozoic age (fig. 3).

Groundwater is present under water-table conditions in the upper unit. Depth to groundwater can be as great as 160 feet (ft) below land surface. Groundwater in the lower unit is present under confined conditions where overlying clay is present. Results of aquifer tests performed on public-supply wells near the McBee area indicate an average hydraulic conductivity of about 50 feet per day (ft/d; Newcome, 2004); these wells are screened across both upper and lower units. The generally high-yielding public-supply wells can produce groundwater at rates that exceed 1,000 gallons per minute (gal/min; fig. 4).

Springs

Many springs are located in the McBee area, some of which have been documented by Mitchell (2004). Some springs in the study area are located northwest of McBee in the Cedar Creek Basin that drains to the Lynches River (fig. 5). Most springs are found where the altitude of the water table in the upper unit intersects the land surface at lower altitudes, resulting in the focused discharge of groundwater (fig. 6). Due to annual rainfall that approaches 45 inches and the permeable nature of the sand in the McBee area, the volume of groundwater discharged at some springs is sufficient to produce perennial streams.

In general, the chemical properties of the springs sampled across South Carolina are similar to that of ambient groundwater (Mitchell, 2004). Samples of water from some springs in the Cedar Creek Basin were reported to contain EDB at concentrations above the detection level when collected in 2008 (Glenn Odum, Alligator Rural Water and Sewer Company, oral commun., March 11, 2010).

Groundwater

The chemical quality of groundwater in the McBee area is generally good (Park, 1979; Newcome, 2004). Groundwater samples collected between 1991 and 2007 in the McBee area as part of the State-administered public-supply well certification process, reveal a chemical composition of groundwater that is characterized by the following average values, all of which are considered low for ambient groundwater produced from the Atlantic Coastal Plain (table 1): turbidity, 2.39 nephelometric turbidity units (NTUs); specific conductance, 21.04 micromhos per centimeter (μmhos/cm); total dissolved solids, 44.56 milligrams per liter (mg/L); chloride, less than (<) 5 mg/L; sodium, 1.71 mg/L; aluminum, 0.36 mg/L; barium, 0.01 mg/L; iron, 0.25 mg/L; nitrate, 0.89 mg/L; and calcium, 0.99 mg/L. The chemical composition of groundwater in the McBee area is similar to that of rainwater (Newcome, 2004) and is also similar to the groundwater quality reported from aquifers in the Inner Coastal Plain in adjacent counties (Feder and Lee, 1981; Curley, 1990).

Concentrations of EDB and DBCP that exceeded their respective MCLs were detected in some public- and domestic-supply wells in the McBee area in samples collected by DHEC officials during routine quarterly water-quality sampling conducted between 2002 and 2008. Specifically, EDB was detected in groundwater from public-supply Well 3 and Well 6 at concentrations that ranged from less than 0.030 to 0.063 μg/L, and concentrations of DBCP that ranged from less than 0.030 to 0.690 μg/L (*http://www.wistv.com/story/19725643/look-at-the-dhec-mcbee-private-well-map-pdf*, accessed April 4, 2013). The concentrations of EDB detected in groundwater from domestic-supply wells in the McBee area ranged from less than 0.020 to 9.10 μg/L, and concentrations of DBCP ranged from less than 0.030 to 2.20 μg/L

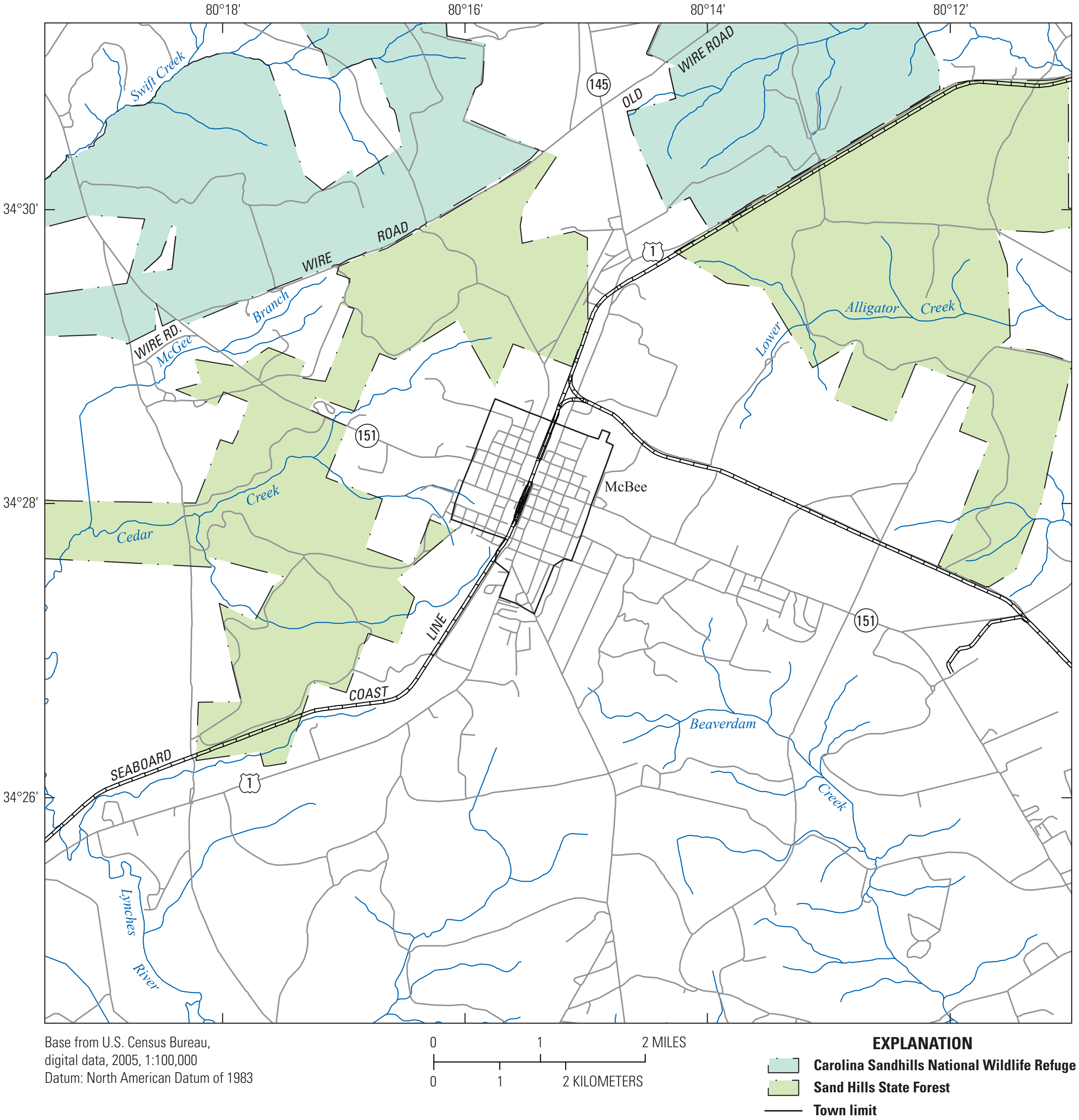
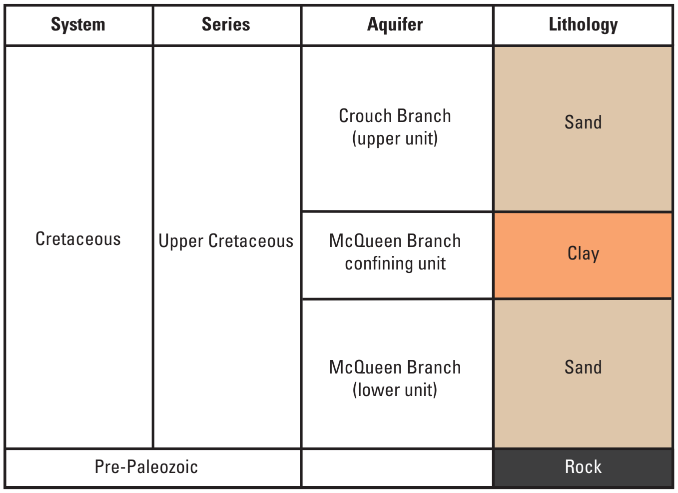


Figure 2. Location of the boundaries of the Carolina Sandhills National Wildlife Refuge and Sand Hills State Forest in the McBee study area, Chesterfield County, South Carolina, 2014.



System	Series	Aquifer	Lithology
Cretaceous	Upper Cretaceous	Crouch Branch (upper unit)	Sand
		McQueen Branch confining unit	Clay
		McQueen Branch (lower unit)	Sand
Pre-Paleozoic			Rock

Figure 3. Generalized hydrogeology underlying the McBee, South Carolina, study area showing the Crouch Branch aquifer (upper unit) and McQueen Branch aquifer (lower unit) separated by the McQueen Branch confining unit.

Figure 4. Public-supply Well 8 being pumped at nearly 1,000 gallons per minute prior to being sampled on August 4, 2010, for this study (photograph by Bruce G. Campbell, U.S. Geological Survey).

(*http://www.wistv.com/story/19725643/look-at-the-dhec-mcbee-private-well-map-pdf*, accessed April 4, 2013). DHEC officials determined the horizontal and vertical extent of the contamination in the McBee area, described potential sources of the EDB and DBCP, and held informational public meetings. Groundwater samples collected by DHEC also revealed concentrations of radium isotopes at levels that exceeded the MCL in some public-supply (and domestic-supply) wells near McBee. The detection of radium isotopes in groundwater from the Crouch Branch and McQueen Branch aquifers in the McBee area is not unexpected; radium isotopes in groundwater have exceeded the MCL in many wells in other counties in South Carolina that are also located in the Inner Coastal Plain (fig. 7).

General Information on EDB, DBCP, Radium Isotopes, and Radon in Groundwater

This section provides general information on the history, chemical properties, and principle uses of the manmade compounds detected in groundwater and spring water in the McBee area, and introduces basic concepts about the sources, transport, and fate of naturally occurring radium isotopes and radon in groundwater. A brief history of the practice of soil fumigation, including the use of EDB and DBCP as soil fumigants in the Southeastern United States, is also included.

Ethylene Dibromide (EDB)

Ethylene dibromide is a manmade halogenated organic compound first produced in 1923 (Scheibe and Lettenmaier, 1989). In the United States, EDB has had two principle uses: (1) as an additive to leaded automotive fuels and (2) as a soil fumigant.

After 1923, EDB was added at high concentrations to gasoline that contained tetraethyl lead to remove lead oxide and sulfate deposits in internal combustion engines. The EDB effectively “scavenged” the lead by converting solid lead that deposited on engine valves to volatile lead halides, which were discharged with the exhaust gases (Boyd, 1950). The amount of EDB in leaded gasoline peaked at concentrations of 0.27 to 0.32 gram per liter (g/L; or 270 to 320 mg/L; Wilson and others, 2008) from 1969 to 1972. In 1974, the EPA mandated reductions in leaded gasoline and, since 1996, tetraethyl lead has been banned from use in automotive fuels in the United States. Leaded gasoline, including gasoline with EDB, is still used in aviation fuel, although at greatly decreased concentrations (Jacobs, 1980; Falta and Bulsara, 2004).

Ethylene dibromide also was used after the 1940s as an effective soil fumigant to control root nematodes following its registration by the U.S. Department of Agriculture (USDA; Katz, 1993). Large amounts of EDB, up to 70 million pounds per year by the early 1980s, were used as a pre-plant soil fumigant (Scheibe and Lettenmaier, 1989). Soil fumigants with EDB were used widely across the United States for root crops such as potatoes as well as strawberries and raspberries in Washington and citrus crops in Florida (Scheibe and Lettenmaier, 1989). Soil fumigation by EDB to control nematodes was found to be especially important for peach (*Prunis persica* (L.) Batsch) orchards, both prior to and routinely after planting (Carter and others, 1984). Soil fumigation of peach orchards was done to avoid “peach tree short life,” the sudden springtime death of young trees from 3 to 7 years of age when nighttime temperatures drop drastically from daytime highs (Doubrava and others, 2006). Ethylene dibromide was also used to prevent diseases fatal to peach trees caused by the root and ring nematodes *Criconemella xenoplax* and *Macroposthonia xenoplax* and root-knot nematodes, such as *Meloidogyne* sp. that infect the roots of peach trees (Carter and Riley, 1984).

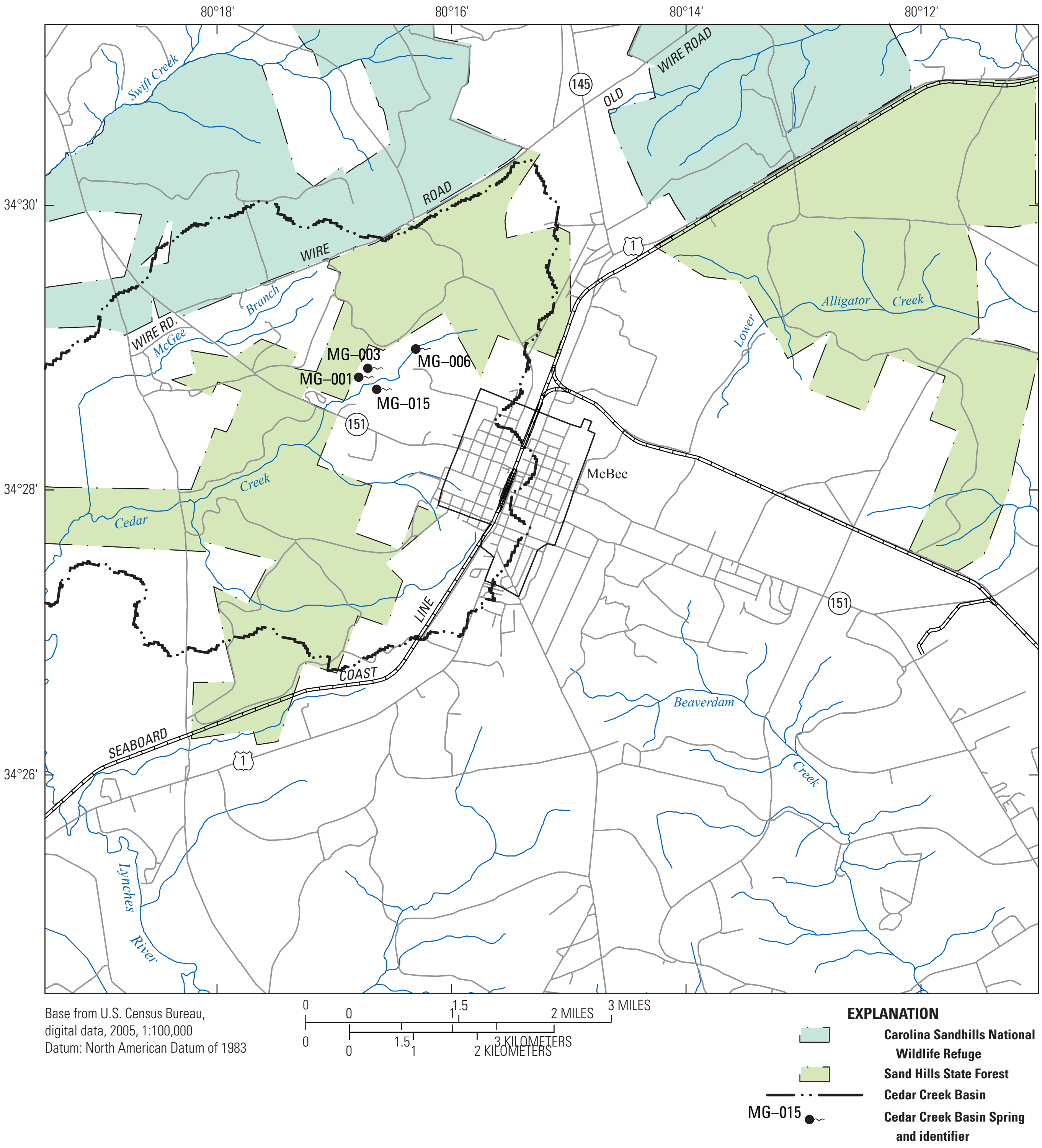


Figure 5. Location of the boundaries that define the Cedar Creek Basin near the study area of McBee, South Carolina. The locations of the four springs sampled for this study are shown.

Figure 6. The headwaters of a spring located in the Cedar Creek Basin (MG–003, figure 5), prior to being sampled on December 7, 2010, for this study, McBee, South Carolina (photograph by James E. Landmeyer, U.S. Geological Survey).

The use of EDB as a soil fumigant was banned by the EPA in 1983 over concerns of the increased risk of cancer.

Dibromochloropropane (DBCP)

Dibromochloropropane was introduced in 1955 as a pre- and post-plant fumigant to control the root and ring nematodes *Criconemella xenoplax* and *Macroposthonia xenoplax* and root-knot nematodes, such as *Meloidogyne* sp. (Oki and Giambelluca, 1987). Dibromochloropropane was used primarily as a post-plant soil fumigant until its suspension and cancellation by the EPA in 1979 after being detected in groundwater; DBCP has the notoriety of being the first pesticide to become a groundwater contaminant (Wang and others, 2008).

Soil Fumigation Practices

In general, there are two methods by which soil fumigants, such as EDB or DBCP, can be applied to soil to control root nematodes—the push-and-treat method and the buffer-zone method. Knowledge of the application methods used in a particular area can be useful in distinguishing between point and non-point sources of these compounds once detected in groundwater. The push-and-treat method is based on bulldozing heavily infested plants toward a central area and then burning the plants. The burned area is then fumigated with EDB, DBCP, or alternative fumigants, such as 1,2-dichloropropane (1,2–DCP; Lembright, 1990), by using chisel soil-injection equipment (tractor-mounted shank injection) at depths of 11.8 inches (in.) in troughs about 18 in. apart. The fumigants typically are applied as a solution from 10 to 85 percent fumigant by volume, dissolved in naptha (Newhall, 1955). The fumigated soil is then tamped to limit fumigant loss to the air (Albrecht and Chenchin, 1985). The buffer-zone method involves continually treating an approximately 16 to 33 foot (ft) area in order to minimize the spread of nematodes from one orchard to an adjacent orchard. These methods were used mostly in the Southeastern United States and differ from methods used in California, where soil fumigants are applied through irrigation water (Carter and others, 1984; Lembright, 1990).

The amount of EDB or DBCP used differs depending on the application method. The rate of EDB application in buffer zones in Florida (Katz, 1993) is nearly twice that of the push-and-treat method–an initial application of 470 liters per hectare (L/ha) and maintenance applications of 240 L/ha every 6 months. The rate of EDB application ranges from 27 to 242 kilograms per hectare (kg/ha), or about 24 to 216 pounds (lbs) per acre (Pignatello, 1986); this rate of application would result in a soil concentration of EDB between 12 and 108 parts per million. Newhall (1955) stated that when EDB was applied in its most concentrated form (85 percent by volume) only 4 to 6 gallons (gal) are applied per acre. The fumigant DBCP was applied prior to planting peach orchards and at 2-year “post-plant” intervals primarily in the fall (Carter and Riley, 1984; Lembright, 1990), in which the recommended treatment rate is 46.8 L/ha. In some cases, applications were made using flood, furrow, and sprinkler irrigation (Lembright, 1990). At the time of this report (2014), it is not clear which of the two application methods had been used in agricultural areas near McBee. The detection of higher concentrations of EDB in groundwater relative to DBCP, however, indicates that EDB was most likely applied in greater volume than DBCP.

Ethylene Dibromide and Dibromochloropropane Fate and Transport

When used as soil fumigants, EDB and DBCP were injected as liquids that produced vapors. The vapors acted as the fumigating vector, with the remaining liquid dissolving into soil moisture (Lembright, 1990). Ironically, during the time of extensive use of EDB as a soil fumigant, EDB was believed to pose no threat to groundwater resources because of its relatively high volatility. A release of EDB near a water-supply well in Hawaii, however, drew attention to the possibility of the detection of EDB and other pesticides in groundwater (Oki and Giambelluca, 1987). This event and the discovery of DBCP contamination in groundwater in other states revealed that EDB and DBCP have high solubilities in water (table 2).

Table 1. Chemical composition of groundwater from public-supply wells, 1991–2007, McBee, South Carolina.

[ID, identification; CTF-, Chesterfield County; n, unique county-well number; (R), replacement well; —, no data available; NTU, nephelometric turbidity units; µmho/cm, micromhos per centimeter; mg/L, milligrams per liter; <, less than]

Public-supply well ID	Public-supply well county number, CTF-n	Date sample collected	Laboratory type that performed analyses	Turbidity (NTU)	Specific conductance (µmho/cm)	Chloride (mg/L)	Nitrate (mg/L)	Calcium (mg/L)	Iron (mg/L)	Sodium (mg/L)	Aluminum (mg/L)	Barium (mg/L)	Total dissolved solids (mg/L)
Well 3	CTF–83	July 21, 1995	Commercial laboratory	<1	—	—	<0.02	<1	<0.1	1.8	0.19	<0.025	—
Well 4	CTF–88	May 3, 2001	Commercial laboratory	1	27	<5	0.86	0.53	0.03	1.79	<0.05	0.01	30
Well 5	CTF–89	July 17, 2001	Commercial laboratory	0.3	—	—	0.61	—	—	—	—	—	28
Well 6	CTF–106	August 19, 2002	Commercial laboratory	—	—	<5	0.41	0.42	<0.05	1.8	0.11	<0.01	20
Well 6	CTF–106	September 5, 2002	Commercial laboratory	—	20	—	—	0.18	—	—	—	—	24
Well 7	CTF–107	September 12, 2002	Commercial laboratory	1.15	20	<5	1	1.22	<0.05	2.71	<0.05	<0.01	74
Well 8	CTF–108	January 7, 2003	Commercial laboratory	0.44	26.5	<5	1.7	1.18	0.30	1.5	0.59	0.01	24
Well 9	CTF–198	October 17, 2007	Commercial laboratory	0.94	17.6	<3	0.7	3.2	<0.02	—	<0.023	<0.001	137
Well 10	CTF–219	November 14, 2006	Commercial laboratory	0.13	18	<3	1	<0.041	<0.02	—	<0.023	<0.001	49
Well 11	CTF–313	April 1, 2011	Commercial laboratory	15	11	<2	0.4	0.3	0.07	1.7	0.06	0.00	15
McBee well	CTF–55	September 24, 1991	Commercial laboratory	0.19	—	<5	<0.1	0.3	<0.05	0.7	—	<0.1	—
McBee well(R)	CTF–179	October 14, 2004	Commercial laboratory	—	28.2	<5	1.3	1.55	0.60	—	0.84	<0.01	—
Average				2.39	21.04	<5	0.89	0.99	0.25	1.71	0.36	0.01	44.56

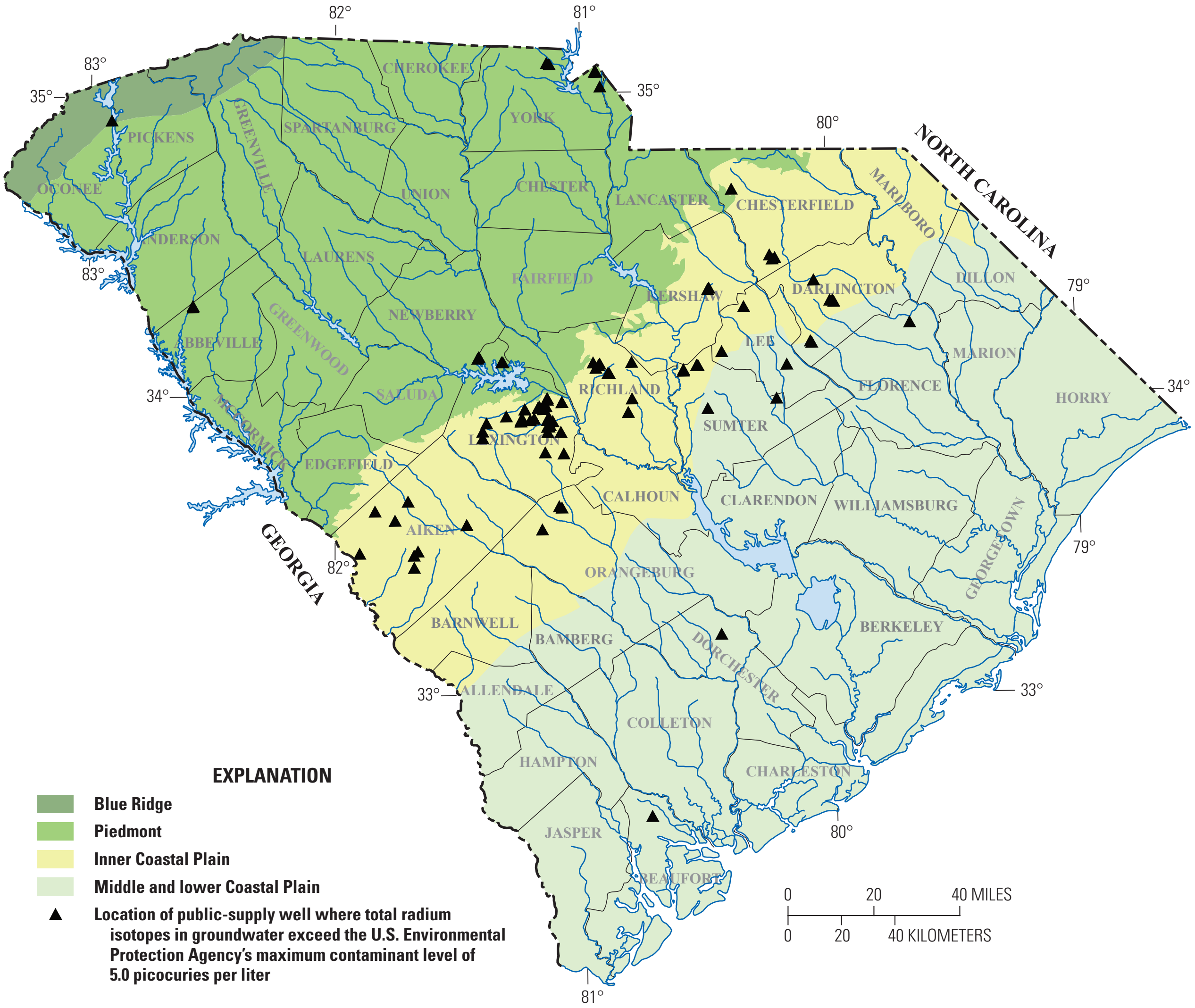


Figure 7. Locations of public-supply wells in South Carolina that had radium isotope concentrations greater than the U.S. Environmental Protection Agency maximum contaminant level of 5.0 picocuries per liter.

Table 2. Physical and chemical properties of ethylene dibromide and dibromochloropropane.

[g/mol, grams per mol; mg/L, milligrams per liter; kPa, kilopascal; K_{ow}, octanol-water partition coefficient; log, logarithim]

Property	Ethylene dibromide	Dibromochloro -propane
Molecular weight (g/mol)	187.86	236.33
Water solubility (mg/L)	4,321	1,230
Vapor pressure (kPa)	1.47	0.1
K_{ow}	58	269
Log K_{ow}	1.76	2.43
Henry's constant	0.029	0.0056
Specific gravity	2.17	2.08

Plants that grow in the fumigated soil contribute to some removal of the mass of EDB and DBCP injected into the soil zone. One of the physical properties of all organic compounds, the logarithm of the octanol-water partition coefficient (log K_{ow}), is related to the ability for a particular compound to enter into a plant root; a greater probability exists for plant-entry if the log K_{ow} is between 1 and 3 (Briggs and others, 1982). Because EDB and DBCP have log K_{ow}s of 1.76 and 2.43, respectively (table 2), the uptake of EDB and DBCP is expected and has been observed to occur for some plants (Frink and Bugbee, 1989; Davis and Erickson, 2002). Carter and Riley (1984) detected DBCP residue in peaches harvested from trees that grew in fumigated and non-fumigated soil. On the other hand, EDB in water applied to the surface of some fruits has been shown to migrate into the fruit (Xia and Rice, 2001). In areas where DBCP was used at greater amounts than the recommended rates, the DBCP residue on peaches increased (Carter and Riley, 1984).

Recharge by precipitation or induced recharge by irrigation can transport dissolved EDB and DBCP through the unsaturated zone to the water table. Deeper entry into the groundwater system is facilitated by both EDB and DBCP being weakly sorbed onto minerals that comprise aquifer sediments. In Oahu, Hawaii, where DBCP and EDB had been detected in wells near pineapple fields (Oki and Giambelluca, 1987), it was estimated that it took between 14 to 32 years for EDB and DBCP to travel from the soil zone to the water table through an unsaturated zone that was greater than 600 ft thick (Rungvetvuthivitaya and others, 2007). At that location, characterized by porous basalt aquifers, the rate of transport would be about 26 feet per year. Moreover, Rungvetvuthivitaya and others (2007) cautioned that the groundwater could be continually contaminated by residual DBCP and EDB in the soil and unsaturated zone.

Once EDB or DBCP has entered the groundwater system, each compound can be transported in the subsurface great vertical and lateral distances. This behavior and fate results from the physical and chemical properties of EDB and DBCP; both EDB and DBCP have fairly high solubilities in water (4,321 and 1,230 mg/L, respectively; Montgomery (1997)) and have specific gravities greater than water (2.17 and 2.08, respectively) and therefore, can move vertically downward rapidly through the water table (table 2).

Extensive lateral transport in groundwater is facilitated by the lack of or slow to minimal biodegradation potential of EDB and DBCP. Aerobic biodegration of EDB has been reported for EDB-contaminated groundwater, although occurring at slow rates relative to rates of groundwater flow (Pignatello, 1986). Some biodegradation of EDB has been reported to occur under anaerobic conditions by dihaloelimination to ethene (Henderson and others, 2008; Wilson and others, 2008). Laboratory experiments indicate a half-life of EDB in groundwater of less than 1 year to more than 8 years, but EDB has been detected in groundwater more than 25 years after its last known application (Steinberg and others, 1987). In contrast, DBCP is not amenable to biodegradation under oxic conditions (Bloom and Alexander, 1990), and the half-life of DBCP ranges from 6.1 years (Deeley and others, 1991) to greater than 140 years (Burlinson and others, 1982). The slow biodegradation rates explain why EDB and DBCP have been detected in groundwater more than 25 years after their use was banned in the 1980s (Burow and others, 2007).

The widespread use, chemical properties, and slow biodegradation rates of EDB and DBCP make these compounds common groundwater contaminants in areas where leaded automotive fuels or agricultural land uses occur or have occurred (Falta, 2004; Falta and others, 2005). One of the earliest studies of EDB contamination of groundwater was reported for the Upper Floridan aquifer in southwestern Georgia (McConnell and others, 1984). Results of that study, conducted right after the 1982 ban on the use of EDB, and a series of follow up studies (McConnell, 1987, 1988) were not able to determine if the EDB that was detected in groundwater at concentrations up 11.8 µg/L was due to the nonpoint source use of EDB as a fumigant or was due to a point-source spill of the fumigant. Spills of leaded gasoline that contained EDB have been observed to exceed 1 mile in length (Savoie, 1999). Plumes of EDB related to fumigation rather than fuel (because DBCP also was detected) have been detected in public-supply wells in Fresno, California (Kloos, 1996).

Radium Isotopes and Radon

Radium is a naturally occurring, divalent alkaline-earth element (metal) and is naturally radioactive. Radioactivity is defined here as the spontaneous disintegration, or decay, of an atom's nucleus followed by the emission of one or more particles from the nucleus. When the nucleus of an atom disintegrates, it does not disappear, but is changed into another form called an isotope. An isotope of a particular element has a different mass than its non-isotopic form, where the mass difference comes from the variation in the number of neutrons in the nucleus of the atoms of that element.

The energy of the decays, or emissions, are different for each type of particle that undergoes decay. The emissions can be in the form of alpha particles, which consist of two protons and two neutrons (helium ions) and, although strongly ionizing, have very low penetration. Beta particles are electrons that are ejected from the nucleus at speeds near that of light particles and, therefore, can achieve great depths of penetration. A gamma ray is an electromagnetic wave of high energy, called a photon, that also has great penetration.

The decay (or conversion of one element into another) occurs at a rate that is unique to each isotope and is quantified by the half-life. The half-life denotes the time required for one-half the initial amount of radioactive element to decay. Much background information is available in multiple reports on radium isotopes in groundwater (Szabo and others, 1997; Szabo and dePaul, 1998; Szabo, dePaul, and others, 2012; Szabo, Fischer, and Hancock, 2012) and is not reproduced here; however, some basic information on radium isotopes pertinent to groundwater is summarized below.

Radium (Ra) isotopes are produced naturally by the radioactive decay of uranium- (U) and thorium- (Th) bearing minerals that are present in most, if not all, rocks. Uranium and thorium are found in resistate minerals that include monazite and labile minerals that include biotite and chlorite. For example, the average concentration of uranium in many rocks is from 1 to 3 micrograms per gram (µg/g; Otton and others, 1993). Specifically, uranium (as ^{238}U, which makes up more than 99 percent of the uranium found in nature) will decay, through numerous intermediate emissions, to the radium isotope ^{226}Ra, and then to the inert gas radon (^{222}Rn). The half-life of ^{238}U is 4.47×10^9 years, of ^{226}Ra is 1,620 years, and of ^{222}Rn is 3.8 days. Thorium (as ^{232}Th) will decay to the radium isotope ^{228}Ra. The half-life of ^{232}Th is 1.41×10^{10} years and of ^{228}Ra is 5.7 years.

Because the half-life of ^{226}Ra is longer than that of ^{228}Ra, it tends to be more abundant in samples of rock or water than ^{228}Ra (Kraemer, 1991). This difference in the half-lives of these isotopes gives rise to the concept of radioactive equilibrium and is important in terms of how to evaluate radioactive substances in groundwater systems. When equilibrium is reached for a particular decay series ($^{238}U \rightarrow {}^{226}Ra \rightarrow {}^{222}Rn$) the isotope with the longer-lived half-life will be present in the greatest quantity and, conversely, the isotope with the shorter-lived half-life will be present in the smallest quantity. Hence, where conditions are at equilibrium, groundwater should contain more ^{226}Ra than ^{228}Ra. Because radium in water is decaying at a faster rate than its formation by uranium and thorium decay, groundwater must be continually replenished by new radium (Kraemer, 1991). This process is enhanced in oxic conditions. If the parent of a decay product with a short half-life, like ^{228}Ra, is not also present, then little ^{228}Ra should be detected due to this “unsupported” transport; hence, ^{228}Ra cannot migrate far from its source (Focazio and others, 2001).

Where water moves through rock or sediments that contain uranium- and thorium-bearing minerals, water comes into contact with their decay-series products, and these products will dissolve into groundwater based on the unique aqueous geochemistry of each species. For example, soluble uranium has several oxidation states, and its mobility is greatly affected by the prevailing oxidation potential. Uranium and radium oxides (of which radium has a single, divalent oxidation state), such as complexes of uranium with phosphate or radium with sulfate, can be transported some distance from their original mineral sources; when oxygen is depleted, these oxides will reprecipitate, a process that produces “roll-front deposits” often of economic importance. Conversely, thorium and radium have one oxidation state. In dilute groundwater, it is possible for radium to be present as uncomplexed Ra^{2+} ions. Concentrations of uranium in groundwater typically are higher in oxidizing water near recharge areas. Whereas thorium is sparingly soluble and, therefore, has little transport potential even in oxic conditions, radium is much less so. On the other hand, radium transport in groundwater is limited by absorption onto iron-hydroxides in aquifers with dilute groundwater and having a pH greater than 7 (Korner and Rose, 1977). Hence, radium transport in groundwater will be much less than groundwater-flow rates under these circumstances.

Radon is a naturally occurring radioactive element that is a gas at normal atmospheric temperatures and pressures. Radon is produced by the decay of radium-226, is mobile, and dissolves readily in water. Radon decays by several successive steps to nonradioactive lead-206 (^{206}Pb). The average radon concentration in public water-supply systems in the United States in 250 pCi/L (National Research Council, 1999). The proposed MCL for radon is 300 pCi/L for those public-water suppliers that do not have radon mitigation programs and 4,000 pCi/L for those suppliers that do. The presence of radon in groundwater indicates a close proximity to sources of ^{226}Ra. Some studies have shown a positive relation between radon concentrations in groundwater and proximity to fault or shear zones, particularly in the Appalachian region of the eastern United States (Gunderson, 1991).

High concentrations of radium isotopes and radon in groundwater can be related to:

1. Radium-isotope sources: Distribution of unweathered source rocks, principally granitic and metamorphic rocks, that contain elevated uranium and thorium concentrations, and dissolve and become mobile relative to their aqueous solubility.

2. Radium-isotope concentration processes: Processes that concentrate radium isotopes in the subsurface, such as the *physical* concentrations of elevated uranium and thorium in weathered source rocks that have been transported near or far from source areas; this includes uranium and thorium mineral sources from other areas that have been mined, transported, and redeposited, and *chemical* processes of concentration that occur in the subsurface of a given geological area, such as changes in groundwater chemistry (oxidation-reduction potential, mineral saturation, desorption, ion-exchange, conductivity (Kraemer and Reid, 1984; Herczeg and others, 1988)), possibly related to changes in land uses, such as agriculture, that increase salinity (Szabo and dePaul, 1998), or alpha-recoil of ^{226}Ra into solution.

On the basis of the properties of uranium and thorium, it is not surprising that radium concentrations in groundwater are elevated in Atlantic Coastal Plain aquifers, particularly in the Inner Coastal Plain near the Fall Line of North and South Carolina (fig. 7) where the sediments are weathered from granitic/metamorphic rocks and groundwater is oxic. In the McBee area, the McQueen Branch aquifer is characterized by unconsolidated, poorly sorted fine- to coarse-grained sand and clayey sand with local gravel that overlies a weakly metamorphosed clay (Gellici and Lautier, 2010). The sand fraction consists of quartz with sparse carbonaceous material, mica, feldspar, and monazite, a potential source of uranium and thorium.

Study Design for Data Collection

Wells tapping the Crouch Branch (upper unit) and McQueen Branch (lower unit) aquifers that were sampled during the study included 10 public-supply, 3 domestic-supply, 4 agricultural-supply wells, and 10 previously installed monitoring wells (fig. 8). To address gaps in groundwater data, one existing monitoring well had to be replaced, and one new monitoring well was installed (Campbell and Landmeyer, 2014). Several springs in the Cedar Creek Basin to the west of the McBee area also were sampled. In areas where wells or springs did not exist, multiple soil-gas samplers that can adsorb VOCs were installed in the shallow subsurface. The location of each well, spring, and soil-gas sampler was determined by the USGS using a global positioning system reporting latitude and longitude using the North American Datum of 1983 (NAD 83). The altitude of each well or spring was taken from existing well records and (or) light detection and ranging coverage. This section provides information on the wells, springs, and soil-gas samplers from which data were collected between 2010 and 2012.

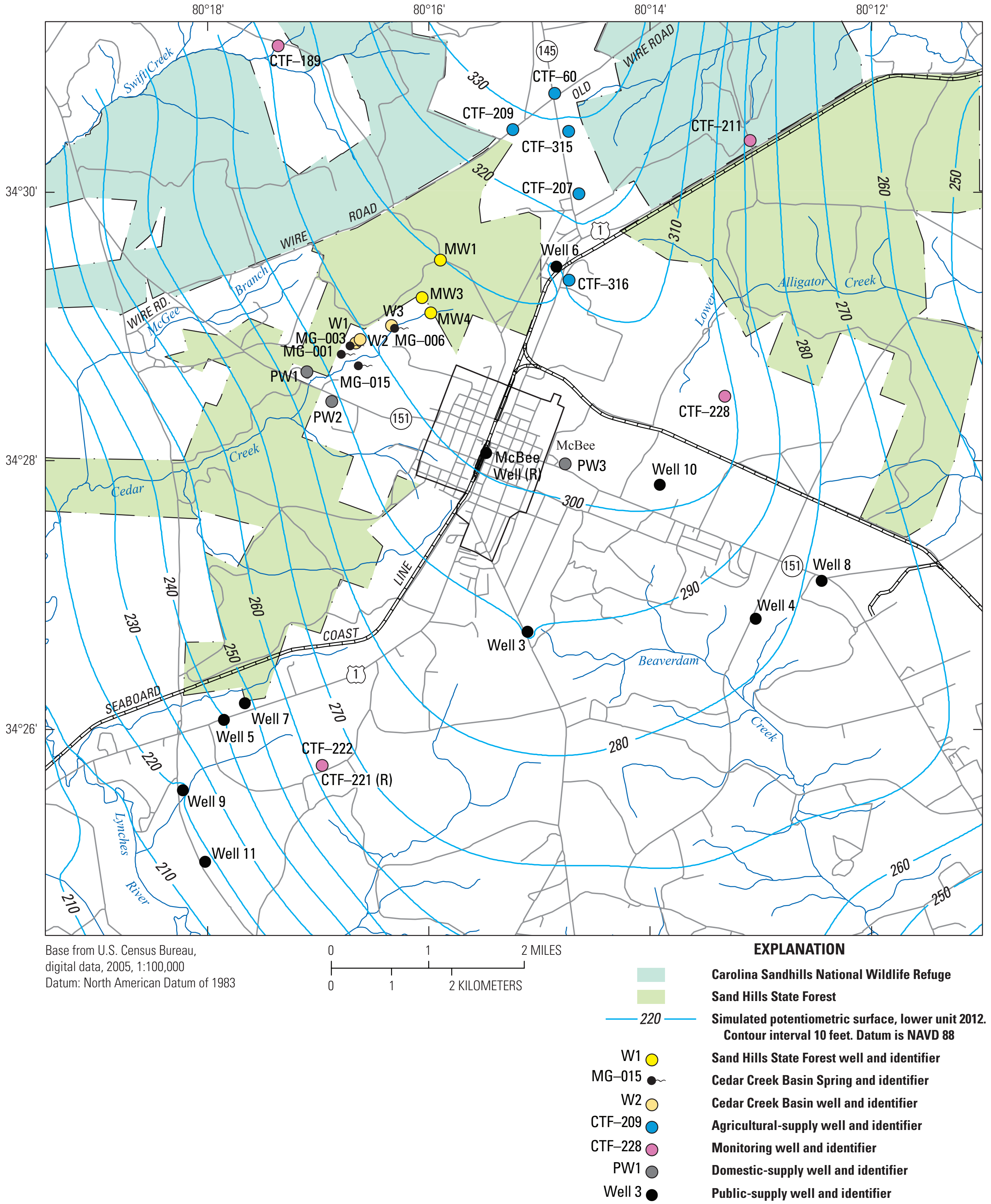


Figure 8. Location of public-supply, domestic-supply, agricultural-supply, and monitoring wells and springs sampled between 2010–2012 for this study, McBee, South Carolina. The potentiometric surface for the lower unit for 2012 was simulated using the model described in Campbell and Landmeyer (2014).

Public-Supply Wells

The distribution of the public-supply wells in and around McBee provided good coverage across the study area and represented the major land uses in the area (fig. 8). Groundwater-quality results from all public-supply wells are comparable because most wells have similar construction, including similar depth, multiple screened intervals, and are pumped by turbine pumps at rates near 1,000 gal/min (fig. 4). Total depth for each public-supply well sampled is provided (table 3). Each public-supply well was sampled at least once between 2010 and 2012, regardless of whether EDB, DBCP, or radium isotopes had been detected previously. Some wells were sampled up to three times between 2010 and 2012 to examine water-quality trends over time. Public-supply Well 11 was installed in 2012 and was sampled once. Public-supply Well 1 and Well 2 located to the east of the study area (not shown on fig. 8) were sampled in 2010 but are not discussed in this report because the wells produce little of the total volume of groundwater produced by the well field, and may be abandoned (Campbell and Landmeyer, 2014).

Domestic-Supply Wells

Three domestic-supply wells (fig. 8) were sampled in 2012 to address data gaps that arose from sampling the public-supply wells. Each domestic-supply well owner gave permission to sample their well and was on site to observe sample collection. One well (PW3) is located between McBee and Well 10 and the other two wells (PW1 and PW2) are located to the west of McBee along Highway 151 West and downgradient from the Cedar Creek Basin springs. Comparatively little well-construction data, other than total well depth, are available for these domestic-supply wells (table 3). The shallow depth of these wells indicates that they are most likely screened in the Crouch Branch aquifer (upper unit).

Agricultural-Supply Wells

Four agricultural-supply wells used by the agricultural industry in McBee were each sampled once in 2011 (fig. 8). One agricultural-supply well (CTF–60; fig. 9) had been used since the 1980s for irrigation and other purposes. Two agricultural-supply wells sampled (CTF–315 and CTF–316) had been installed more recently than CTF–60 and were used to either fill a water tank in a field or to process fruit in a packing shed, respectively. The fourth agricultural-supply well sampled (CTF–209) was used to supply drinking water for temporary workers. An additional agricultural-supply well (CTF–207) was pumped but not sampled due to well-construction problems and outgassing in the sampled water. These agricultural-supply wells are most likely screened across the Crouch Branch (upper unit) aquifer (table 3).

Figure 9. Agricultural-supply well CTF–60, located at the northeastern side of the intersection of Wire Road and S.C. Highway 145 North to the north of McBee, South Carolina (photograph by James E. Landmeyer, U.S. Geological Survey).

Monitoring Wells

Ten pre-existing monitoring wells (fig. 8) were sampled between 2010 and 2012. Monitoring wells CTF–221(D, deep) and CTF–222(S, shallow) had been installed as nested wells specifically for the Chesterfield County study described in Campbell and Landmeyer (2014), and were each sampled once in 2010. Monitoring well CTF–221(D) is screened in the McQueen Branch aquifer (lower unit) and, therefore, is similar in construction to public-supply wells in the area (table 3). In contrast, monitoring well CTF–222(S) is screened in the Crouch Branch aquifer (upper unit) and is similar in construction to domestic-supply wells in the study area. Groundwater levels are measured at both of these monitoring wells in near-real time, and data are available at the USGS National Water Information System (NWIS) Web site at *http://waterdata.usgs.gov/sc/nwis/current/?type=gw&group_key=county_cd* (accessed March 5, 2014). Groundwater samples could not be collected from CTF–221(D) in 2010 because the well casing had collapsed above the water table. This well was abandoned in 2011. A replacement (denoted with the suffix “(R)”) monitoring well of similar construction was drilled near CTF–221(D), and the new well retained the old name (as CTF–221(R)) and USGS site identification (ID) number (Campbell and Landmeyer, 2014).

To further examine the difference in groundwater quality between the Crouch Branch and McQueen Branch aquifers in the McBee area, an additional monitoring well (CTF–228) was installed in 2010 to the northeast of Well 10 (fig. 8). Monitoring well CTF–228 was drilled using mud-rotary methods (fig. 10) and was constructed with 6-in.-diameter, flush-jointed polyvinyl chloride (PVC) casing and well screen, to a depth of 335 ft below land surface where slightly metamorphosed blue slates were encountered (Campbell and Landmeyer, 2014).

Table 3. Identification, year installed, altitude of land surface, and total depth of wells sampled near McBee, South Carolina, 2010–2012. Identification of springs sampled are also listed.

[ID, identification; n, unique county-well number; USGS, U.S. Geological Survey; NGVD 29, National Geodetic Vertical Datum of 1929; (R), replacement well; PW, privately owned, domestic-supply well; CTF-, Chesterfield County well prefix; S, shallow-screened interval; D, deep-screened interval; —, no data available; MG-, springs; W-, well; MW, monitoring well; locations of wells and springs are shown in figure 8. CTF–222 location represents CTF–221 and CTF–221(R); *, altitude as provided on water well record form, often estimated from topographic map; +, depth as provided on water-well record form]

Well ID	County number, CTF-n	USGS site ID number	Year installed	Altitude of land surface, feet NGVD 29*	Total depth of completed well, feet below land-surface altitude+	Aquifer
Public-supply wells						
Well 3	CTF–83	342642080150709	1995	420	360	Crouch Branch and McQueen Branch
Well 4	CTF–88	342652080130109	2001	395	333	Crouch Branch and McQueen Branch
Well 5	CTF–89	342559080180509	2001	280	240	Crouch Branch and McQueen Branch
Well 6	CTF–106	342929080145009	2002	480	303	Crouch Branch and McQueen Branch
Well 7	CTF–107	342711080174909	2002	360	267	Crouch Branch and McQueen Branch
Well 8	CTF–108	342707080122909	2003	430	346	Crouch Branch and McQueen Branch
Well 9	CTF–198	342532080181309	2007	289	245	Crouch Branch and McQueen Branch
Well 10	CTF–219	342749080135509	2006	415	352	Crouch Branch and McQueen Branch
McBee well(R)	CTF–179	342803080152909	2004	465	345	Crouch Branch and McQueen Branch
Well 11	CTF–313	342500080180200	2011	289	271	Crouch Branch and McQueen Branch
Domestic-supply wells						
PW1	CTF–317	342839080170601	—	—	190	Crouch Branch
PW2	CTF–318	342826080165201	—	—	190	Crouch Branch
PW3	CTF–319	342758080144601	—	—	200	Crouch Branch
Agricultural-supply wells						
CTF–60	CTF–60	343044080145200	1981	530	435	Crouch Branch
CTF–315	CTF–315	343027080144400	2002	521	—	Crouch Branch
CTF–316	CTF–316	342920080144300	2008	470	—	Crouch Branch
CTF–207	CTF–207	342954080143900	2004	503	180	Crouch Branch
CTF–209	CTF–209	343027080151400	2000	343	223	Crouch Branch
Monitoring wells						
CTF–222(S)	CTF–222(S)	342543080165800	2008	395	175	Crouch Branch
CTF–221(D)	CTF–221(D)	342543080165801	2008	395	260	McQueen Branch
CTF–221(R)	CTF–221R	342543080165801	2011	395	260	McQueen Branch
CTF–189	CTF–189	343105080172100	—	304	90	Crouch Branch
CTF–211	CTF–211	343023080130600	—	410	—	Crouch Branch
CTF–228	CTF–228	342828080131900	2010	456	335	Crouch Branch and McQueen Branch
Cedar Creek Basin wells						
W1	CTF–230	342852080163900	2008	315	42	Crouch Branch
W2	CTF–229	342853080163900	2008	315	52	Crouch Branch
W3	CTF–231	342854080163700	2008	330	52	Crouch Branch
Sand Hills State Forest wells						
MW1	CTF–224	342929080155300	2008	485	220	Crouch Branch
MW3	CTF–226	342912080160300	2008	380	110	Crouch Branch
MW4	CTF–227	342905080155900	2008	357	57	Crouch Branch
Cedar Creek Basin Springs						
MG–015	—	342842080163800	—	290	—	Crouch Branch
MG–001	—	342847080164700	—	290	—	Crouch Branch
MG–006	—	342859080161800	—	305	—	Crouch Branch
MG–003	—	342851080164200	—	285	—	Crouch Branch

Figure 10. Installation of monitoring well CTF–228 using the mud-rotary drilling method, east of McBee and north of S.C. Highway 151 East, September 9, 2010. Water coming from the top of the borehole is return flow from advancing the drill bit and does not represent artesian conditions. The trees in the background are young longleaf pines and are characterized by a root system that can tap deep groundwater (photograph by James E. Landmeyer, U.S. Geological Survey).

The water table was at 160 ft below land surface during drilling. The upper unit was screened from 200 to 220 ft below land surface (referred to as CTF–228(S)), and the lower unit was screened from 310 to 330 ft below land surface (referred to as CTF–228(D)). Groundwater samples were collected adjacent to the midpoint of each screened interval multiple times between 2010 and 2012.

Two additional monitoring wells, CTF–189 and CTF–211 (fig. 8), used to monitor changes in groundwater levels as part of the study reported in Campbell and Landmeyer (2014) also were sampled for groundwater quality. Groundwater samples were collected once from shallow well CTF–189, located in the Swift Creek Basin to the northwest of the Cedar Creek Basin and McBee. Samples also were collected multiple times between 2010 and 2012 from well CTF–211 located northeast of McBee along U.S. Highway 1 near the Carolina Sandhills NWR.

Six monitoring wells installed in the Cedar Creek Basin in 2008 by a private party were sampled once in 2011 as part of this study (fig. 8; table 3). Three wells (W1, W2, and W3) were located in the Cedar Creek Basin, and three wells (MW1, MW3, and MW4) were located in the Sand Hills State Forest.

Springs

Water samples were collected once during December 2010 at four springs (table 3) located in the Cedar Creek Basin to the west of McBee, north of S.C. Highway 151 West (fig. 8). These springs represent the discharge of groundwater in the upper unit recharged locally and at higher altitudes near Wire Road and S.C. Highway 145 North.

Soil Gas

Soil-gas samples were collected in areas where public-supply, domestic-supply, agricultural-supply, and monitoring wells either did not exist or could not be sampled. In this report, the term “soil gas” is defined as the mixture of air, gases, and volatile compounds present in the pore spaces between sediment grains in the unsaturated zone above the water table. Because the soil gas could contain the volatile component of anthropogenic VOCs, such as the EDB and DBCP detected in groundwater by DHEC, passive soil-gas samplers were deployed in the shallow subsurface to act as “proxy” samplers for subsurface contamination by VOCs. Specific information on the passive soil-gas samplers is provided in the following section.

Methods of Data Collection and Analysis

This section describes the methods used to collect groundwater, spring water, and soil-gas samples in the McBee area between 2010 and 2012. Technical guidelines applicable to the collection of all water samples for this study can be found in the USGS National Field Manual (U.S. Geological Survey, variously dated). Prior to sampling each well or spring, location data were used to create a USGS site identification (ID) number and entered in the USGS NWIS.

Groundwater Samples

Groundwater samples were collected by using approaches designed specifically for the type of well being sampled and (or) the depth to groundwater encountered at a particular well. For all public-supply wells, groundwater samples were collected from a tap at the wellhead and represent “raw” water prior to treatment by lime, chlorine, or carbon filtration at either of the two wells that had a GAC unit. A sample was immediately collected at a public-supply well if the well had been running for a few hours prior to arrival at the wellhead; conversely, public-supply wells not found to have been previously run were turned on and allowed to run for at least 1 hour before sample collection. Samples from agricultural-supply wells were collected as raw samples from the wellhead as described for public-supply wells. Samples from monitoring wells were collected by using one of the following methods: a peristaltic pump was used to collect groundwater from wells that had a depth to groundwater less than 30 ft below land surface altitude, a development (Waterra) pump, a positive-displacement-type bladder pump, or a submersible (Grundfos) pump was used for depths to groundwater greater than 30 ft. For all methods, the groundwater samples were collected adjacent from the midpoint of the screened interval, if known. When applicable, measurement of the static groundwater level was made with a calibrated electric tape to one-hundredth of a foot prior to sample collection; multiple "replicate" measurements were made during each visit to ensure the accuracy of the water level measured. Groundwater levels in public-supply wells, however, could not be measured. All groundwater samples were collected using low-flow techniques following USGS sampling protocols reported in the USGS National Field Manual (U.S. Geological Survey, variously dated). To reduce the possibility of cross contamination, fresh tubing was used for each well sampled by the peristaltic pump and Waterra pump, and the bladder pump was decontaminated between wells by scrubbing with soapy water (non-phosphate soap and distilled water) and rinsing with tap water, after which the equipment was allowed to air dry.

Spring-Water Samples

All springs were sampled using a consistent method that included immersion of sample bottles below the water level at each spring and allowing the bottle to overflow for at least 1 minute. Samples were collected and processed in accordance with standard USGS methods described in the USGS National Field Manual (U.S. Geological Survey, variously dated). To minimize sample disturbance, all sample bottles were filled directly in the spring. Processing of the spring-water samples was similar to processing of groundwater samples.

Field and Laboratory Analyses of Groundwater and Spring-Water Samples

Water samples were analyzed for many different constituents. Some of these constituents were analyzed in the field, while other constituents were analyzed in various laboratories. Analytical laboratories, a brief description of the constituents analyzed, and laboratory minimum reporting levels are included in this section.

Field Analyses of Groundwater and Spring Water

For each well sampled, groundwater was pumped through a flow-through chamber (a large, nylon, graduated cylinder) until at least three well-casing volumes had been removed and (or) measurements of physical properties of groundwater, such as dissolved oxygen, pH, specific conductance, temperature, and turbidity measured using a YSI 6600 sonde (YSI, Inc.) had stabilized during pumping. The sonde was calibrated daily prior to sampling by using appropriate standard methods for dissolved oxygen, specific conductance, and pH as reported in the USGS National Field Manual (U.S. Geological Survey, variously dated). Groundwater and spring-water samples did not require filtration because of the low turbidity (<5 NTU) of the sampled water; however, one monitoring well (CTF–211) had excessive iron precipitation during sample collection and high turbidity.

Laboratory Analyses of Groundwater and Spring Water

Groundwater and spring-water samples were collected for laboratory analysis of anthropogenic and naturally occurring radioactive and inorganic compounds. Water samples for analysis of the anthropogenic compounds EDB, DBCP, as well as other VOCs, were analyzed at the USGS National Water Quality Laboratory (NWQL) in Denver, Colorado, using methods developed by the USGS National Water Quality Assessment Program for the low-level detection of VOCs (Connor and others, 1998). Throughout the report, an "estimated" (E) concentration of a particular compound reflects a concentration less than the laboratory reporting level but equal to or greater than the laboratory method detection level.

Water samples for the determination of EDB, DBCP, and other VOC concentrations were collected in 40 milliliter (mL) amber vials in triplicate. Concentrations of EDB and DBCP were analyzed by using two methods. The first method provided EDB and DBCP concentrations at minimum reporting levels (MRL) of 0.028 and 0.40 µg/L, respectively. The second method provided lower MRL concentrations of 0.018 and 0.03 µg/L, respectively. The vials to be analyzed by the first method were preserved to a pH of 2 with a 1:1 solution of hydrochloric acid and chilled; the vials to be analyzed by the second method were only chilled for preservation. For each water sample collected, the EDB and DBCP result used in the discussion represents either the lowest or highest concentration detected. All samples were stored on ice and shipped to the USGS NWQL for analysis. The MRLs of the other VOCs varied with each compound analyzed and are reported with the results.

Water samples collected for radium isotope analysis were preserved with nitric acid (Ultrex grade 7.7 Normal (N)) to a pH of 2, stored on ice, and analyzed by Eberline Laboratories, Irvine, California, the USGS NWQL subcontractor for radiochemical analyses. The MRLs for radium-226 and radium-228 were 0.1 and 1.0 pCi/L, respectively. Because radium has little tendency to form aqueous complexes between pHs of 3 to 10, it may be safely assumed that the water samples contained uncomplexed, ionic radium as Ra^+ (Pardue and Guo, 1998).

Groundwater samples for radon analysis were collected in a 10-mL syringe, which was then slowly injected into 10 mL of a previously prepared liquid scintillation cocktail. Water samples were shipped the day of sample collection for overnight delivery, if possible. Radon was analyzed in groundwater samples for most public-supply wells during August 2011, some agricultural-supply wells during

August 2011, and public-supply Well 11 installed in 2012. Samples were analyzed at the USGS NWQL by using liquid scintillation detection, and the MRL was 20 pCi/L.

Groundwater samples for inorganic analyses were collected during 2012 only. The water samples were preserved with nitric acid (Ultrex grade 7.7 N) to a pH of 2, stored on ice, and shipped to the USGS NWQL. Because of low water-sample turbidity, the samples were not filtered, and results are considered as the "total" concentration of each particular inorganic analyzed. The MRL for individual inorganic compounds varied and are reported with the results.

Soil-Gas Samples

Soil-gas samples were collected by using passive-vapor samplers (soil-gas sampler). The soil-gas sampler consists of proprietary adsorbent medium placed inside a shoestring-shaped tube made of GORE-TEX®, which is stored in a sealed, individually numbered, 20-mL glass vial before and after sample collection (fig. 11). The proprietary medium can adsorb a wide variety of VOCs and semivolatile organic compounds (SVOCs), including trichloroethylene (TCE) and perchloroethylene (PCE; also known as tetrachloroethene); gasoline-range compounds, such as benzene, toluene, ethylbenzene, and xylenes (collectively referred to as BTEX); the gasoline additive methyl *tert*-butyl ether (MTBE); diesel-range compounds, such as undecane, tridecane, and pentadecane (collectively referred to as C_{11}, C_{13}, and C_{15}); and polycyclic aromatic hydrocarbons (PAHs), such as naphthalene. Although soil-gas results can indicate the presence of particular VOCs, the results do not reveal if the detection was derived from free product, residual-phase compounds adsorbed on soil particles, vapors in the unsaturated zone, or the dissolved compound in shallow and deep groundwater (unless the soil-gas sampler is deployed in direct contact with water; U.S. Environmental Protection Agency, 1998; Amplified Geochemical Imaging, LLC (AGI; formerly W.L. Gore & Associates, Inc., 2004)).

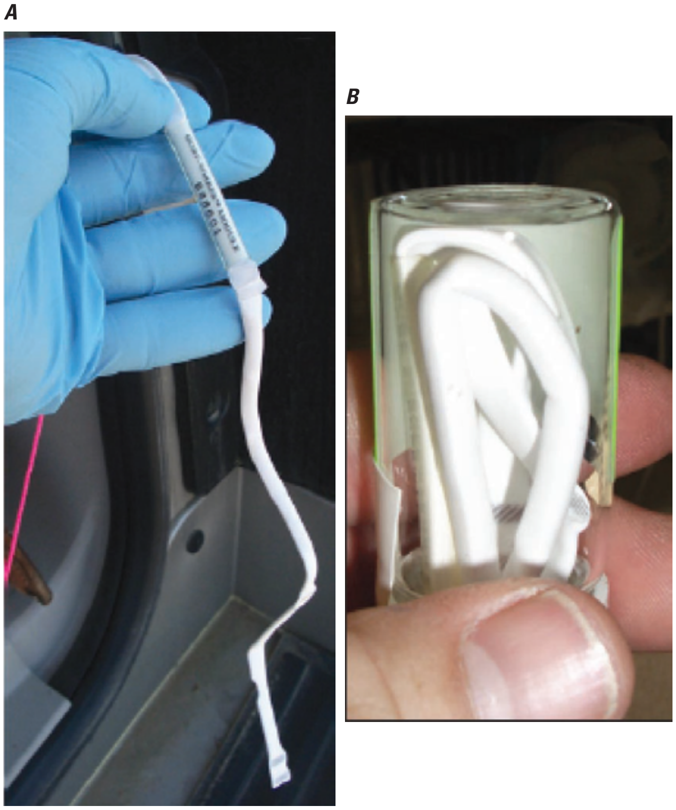


Figure 11. Soil-gas sampler (*A*) prior to installation in the subsurface near McBee, South Carolina, and (*B*) after retrieval and placement in its original numbered vial (photograph by James E. Landmeyer, U.S. Geological Survey).

Soil-gas samplers were installed in the shallow subsurface by creating a borehole by using a stainless steel bit attached to a cordless drill. The bit was used to drill a vertical borehole in the soil with a 0.5-in. -diameter and a 15-in. -depth. A string was attached to a cork plug at one end and the soil-gas sampler was attached at the other end. The string was used to lower and suspend the sampler in the borehole. The cork plug was used to seal the borehole at land surface to prevent surface water and ambient land-surface material from entering the borehole. The depth of 15 in. is similar to the depth recommended by the EPA for soil-gas investigations (U.S. Environmental Protection Agency, 1998).

Each soil-gas sampler recovered in the field was placed in its original, numbered, 20-mL air-tight vial provided by the laboratory and sent to a commercial laboratory (AGI, Elkton, Maryland) for analysis. Some of the samplers were kept in the air-tight vials during the deployment and recovery of environmental samplers and were shipped back to the laboratory as trip blanks with the environmental samplers. All samplers were processed and analyzed at the laboratory by using a modification of EPA method 8260/8270 (U.S. Environmental Protection Agency, 2006). Prior to analysis, each sampler was processed in an automated thermal desorption unit to produce a VOC/SVOC gas sample. The gas sample was analyzed by a gas chromatograph equipped with mass-selective detectors. The laboratory analyzed method blanks for quality assurance and was in compliance with Good Laboratory Practices and ISO Guide 25 (International Organization for Standardization, 1990).

Results are reported as mass of a particular VOC in micrograms. Results for total petroleum hydrocarbons (TPH) represent a laboratory-derived estimate based on the area under the chromatogram for all aliphatic hydrocarbons, including all gasoline-range (C_4 to C_{10}) and diesel-range (C_{10} to C_{20}) compounds. In addition, results of individual VOCs were summed to calculate values for the combined mass in soil gas for BTEX, C_{11}, C_{13}, and C_{15}, 1,2,4- and 1,3,5-trimethylbenzene as trimethylbenzene, trans- and cis-1,2-dichloroethene as 1,2-dichloroethene, and naphthalene and 2-methyl naphthalene as naphthalene.

The soil-gas samplers were installed at land surface in areas of previously detected groundwater contamination, or groundwater contamination detected during this study, during four separate events between 2010 and 2012 (fig. 12).

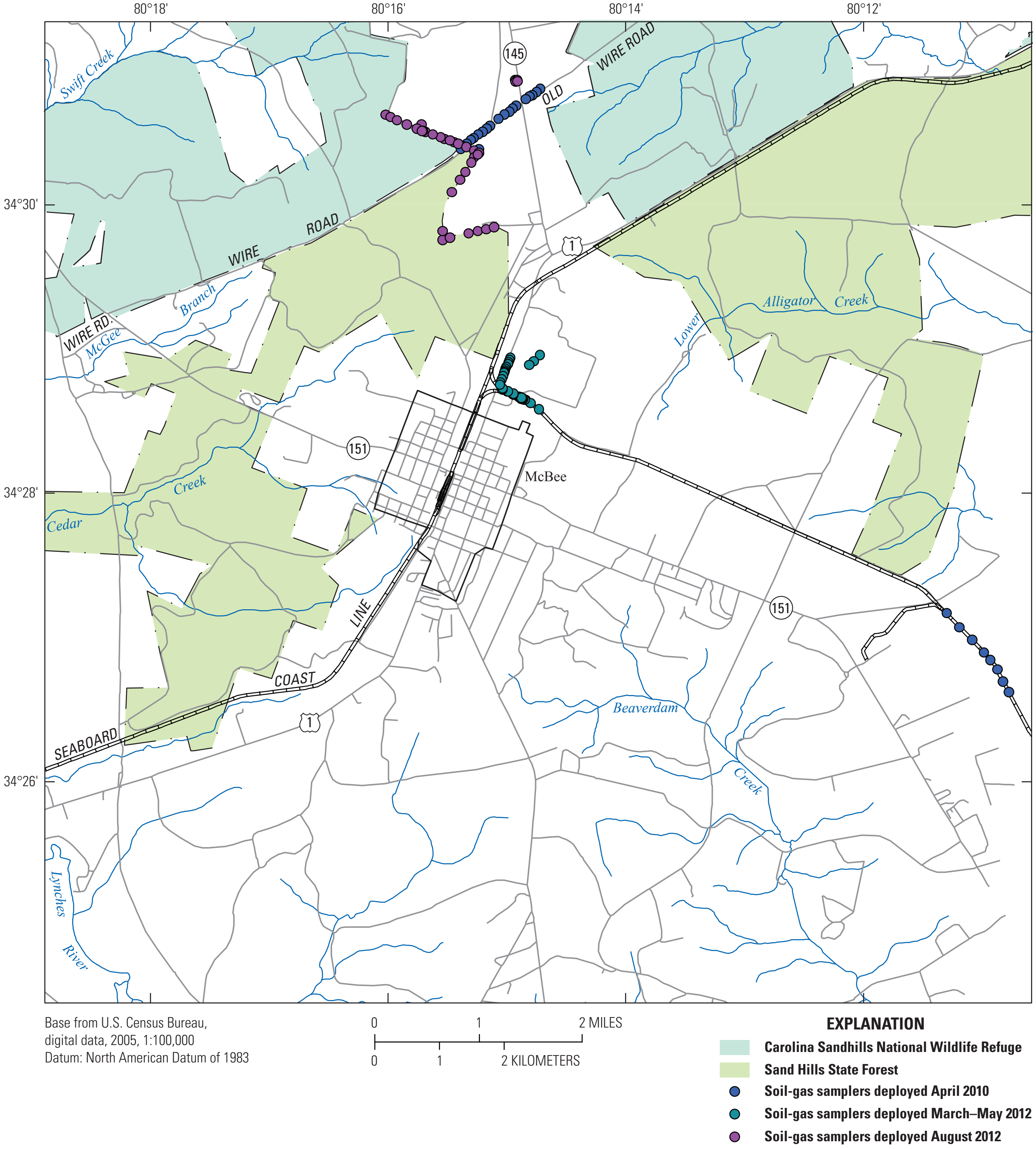


Figure 12. Locations of individual soil-gas samplers deployed in the shallow subsurface between 2010–2012, McBee, South Carolina.

The initial soil-gas survey was conducted during April 27–29, 2010, in areas where groundwater samples collected by DHEC officials had the highest EDB and DBCP concentrations; 28 soil-gas samplers were deployed and collected along Wire Road and a railroad easement north of S.C. Highway 151 East for a period of about 48 hours (no trip blanks, however, were used; Landmeyer and Campbell (2010)). Subsequent soil-gas surveys were deployed along a utility easement east of U.S. Highway 1 and slightly north of the railroad tracks during March 12–16, 2012, when 10 soil-gas samplers were deployed for a period of about 96 hours (two trip blanks were used); 30 soil-gas samplers were installed May 4–8, 2012 for a period of about 96 hours (one trip blank was used) along a utility right-of-way and easement east of U.S. Highway 1; and during August 24–30, 2012, when 42 soil-gas samplers were installed along an eastern property boundary of the Carolina Sandhills NWR and the Sand Hills State Forest north and south of Wire Road, respectively, for a period of about 144 hours (four trip blanks were used). All soil-gas samplers were collected and shipped to AGI, and analyzed by using EPA-verified methods (U.S. Environmental Protection Agency, 1998; American Society for Testing and Materials, 2006).

Groundwater-Age Dating

Groundwater samples were collected for the purpose of age dating from public-supply wells in the McBee area in 2010. The age date, or "apparent age," of groundwater is defined in this report as the length of time that has elapsed since the water sample first recharged the water table (in other words, the water was removed from contact with the atmosphere). The apparent age of groundwater pumped from the public-supply wells is necessary to determine if the age of the groundwater is commensurate with the timeframe when compounds such as EDB and DBCP were used and to facilitate the calibration of groundwater flow pathways to each well determined using the three-dimensional groundwater-flow model of Campbell and Landmeyer (2014).

Apparent-age dates can be determined indirectly by using the concentration of three different chlorofluorocarbons (CFC–11, –12, and –113) in groundwater. Their aqueous concentration reflects each compound's equilibration with that in air, prior to recharge (Busenberg and Plummer, 1992). The apparent age is determined by comparing the CFC concentrations in the groundwater sample to past atmospheric concentrations of each CFC, which have been recorded in North America since the 1940s. Ideally, each CFC should provide an independent way to determine groundwater apparent age for groundwater from a particular well. Also, the apparent age is more reliable if the ages from all three CFCs are in agreement.

The concentrations of CFCs can be used to interpret when the groundwater was recharged on the basis of a piston-type flow model (Plummer and Friedman, 1999). The piston-type flow model conceptualizes groundwater flow as a "plug" in a single-flow tube. Under the piston-type flow model, all groundwater-flow lines are assumed to have similar velocities with hydrodynamic dispersion and molecular diffusion assumed to be negligible. The accuracy of a CFC-concentration-based groundwater "age" is greatly improved when factors that affect the CFC concentrations once in groundwater other than recharge date are at a minimum. For example, decreases in the original CFC concentrations due to anaerobic microbial degradation, hydrodynamic dispersion in aquifers characterized by low hydraulic conductivity, or increases in CFC concentrations due to improper sampling techniques that permit modern, CFC-enriched, ambient air to contaminant the groundwater sample.

The groundwater samples were collected from public-supply wells by using an approach designed to eliminate the interaction of the groundwater sample with ambient air during sample collection. Sample vials (250-mL glass vials) were filled beneath a volume of groundwater pumped from the well into a 2-liter (L) graduated nylon cylinder. The sample tubing, made of nylon or copper to eliminate contact of the sample with air during pumping, was placed in each vial under water; the vial was allowed to overflow, and then each vial was capped under water using a metal screw cap with an aluminum foil liner. The samples then were removed from the cylinder, checked for the presence of air bubbles, and sealed with electrical tape around the bottle caps. The sample bottles were not stored on ice but were shipped directly to the USGS Chlorofluorocarbon (CFC) Laboratory in Reston, Virginia, where the CFC analyses were performed in triplicate by using gas chromatography/mass spectrometry.

As part of the sampling of the public-supply wells for the CFC analyses during 2010, samples were also collected for the determination of dissolved gases, specifically concentrations of methane, carbon dioxide, nitrogen, oxygen, and argon. The concentrations of oxygen, relative to methane, can provide information on the redox status of the water, which can be used to interpret the CFC-based age dates. Also, the concentrations of dissolved nitrogen and argon can indicate the air temperature during past recharge events, because the solubilities of nitrogen and argon vary substantially as a function of temperature (Weiss, 1970). Samples of groundwater for these dissolved gases were collected in a similar manner to those collected for the CFCs described above, except that the dissolved-gas sample bottles were sealed with a rubber stopper. A 21-gauge needle was inserted into the rubber stopper until the tip slightly exited through the bottom of the stopper; the rubber stopper with the needle was inserted into the bottle while the bottle was submerged in the water in the 2–L nylon cylinder, allowing any bubbles in the bottle to escape from the sample. The needle was removed from the stopper while the bottle was still submerged. Duplicate bottles were collected. All needles were properly disposed of or returned with the filled sample bottles. The sample name, water temperature, and estimated recharge altitude (the assumed altitude of the water table at the time of sampling) were recorded on the label attached to the foam sleeve used to protect the bottle during shipment. The samples were kept on ice or at least as cool as the temperature of the sampled groundwater to prevent the stoppers from popping due to sample warming. All sample bottles were stored upside down or on their side to keep any bubbles that formed away from the stopper. The sample bottles were shipped on ice to the USGS CFC Laboratory in Reston, Virginia, where the dissolved-gas analyses were performed in duplicate by using chromatograph/flame-ionization detection.

Particle-Tracking Analysis

A groundwater flow pathway was determined for public-supply wells and representative agricultural-supply, domestic-supply, and monitoring wells using the particle-tracking code MODPATH (Pollock, 2012). The groundwater flow pathway was determined by tracing the movement of imaginary "particles" placed in the groundwater flow field using a calibrated, transient, three-dimensional groundwater-flow model of the groundwater resources of Chesterfield County, S.C. (Campbell and Landmeyer, 2014). The imaginery particles were placed at 10-ft vertical intervals in model cells that correspond to the location and thickness of the entire screened interval for each well, as no data were available to indicate which part of the screened interval was responsible for providing the most water to the pumped well. Each imaginary particle was then traced backward in time, "upstream," along their respective particle flow pathway to a hydrologic boundary, the water table in a recharge area, or a final location determined by the total simulation time (Pollock, 2012). The pumping history of each well is included as part of these determinations. Although this approach does not estimate the three-dimensional capture zone for a well, it can help to assess potential source areas for chemical compounds detected in particular wells, especially when the groundwater flow pathways are evaluated in terms of previous land uses. Assumptions and limitations of this approach are described in a later section of this report.

Because the imaginary particles had to be placed across the entire screened interval of each well, each particle travelled "upstream" to a different location. To constrain which simulated groundwater flow pathways were the most representative of the groundwater velocity field for each well and its unique pumping history, the CFC-based groundwater age dates were used to calibrate the locations where the groundwater flow pathway for each well reached the simulated water table, similar to the approach used by Sandford (2011). Accurate depiction of the groundwater flow pathway for each public-supply well that had detections of EDB or DBCP was essential to assess whether or not potential sources of these compounds were located along each flow pathway. This approach was used for EDB-contaminated groundwater in Massachusetts where EDB in wells was tracked back in space and time to releases of fuel that contained EDB (Masterson and others, 1997), to assess public-supply well vulnerability to arsenic and uranium (Hinkle and others, 2009), and to investigate the transport of anthropogenic and natural compounds to public-supply wells as part of the USGS National Water-Quality Assessment Program study of the transport of anthropogenic and natural contaminants to public-supply wells (Clark and others, 2007).

The particle-tracking simulations also were performed on wells that had not been pumped (such as new public-supply Well 11), agricultural-supply wells that had been pumped and records of pumping were either unavailable or uncertain (CTF–60 and CTF–315), and monitoring wells (CTF–211). To determine the groundwater flow pathways for these wells, an infinitesimal amount of withdrawal was assigned to each well. The extent of the groundwater flow pathway for these wells could not be refined with CFC ages and, therefore, the maximum, uncalibrated, groundwater flow pathway is used.

Particle-tracking simulations generally are sensitive to horizontal hydraulic conductivities, model cell sizes, and effective porosities. There are no published values for porosity for the Crouch and McQueen Branch aquifers in the McBee area. Heath (1983) gives selected values of porosity for various geologic materials, including a value of 25 percent for sand. To account for the uncertainty of the porosity values within the Crouch and McQueen Branch aquifers, all particle-tracking simulations were evaluated for each public-supply well using uniform values that ranged from 25 to 35 percent porosity. Porosity only affects pore velocity and does not change the groundwater flow pathways (smaller porosity values increase the pore velocity and decrease the time of travel along the flow pathway).

The groundwater flow pathways determined by the particle-tracking simulations were mapped on available aerial photographs of the McBee area that spanned the timeframe of when EDB, DBCP, and other VOCs were used. The resolution between aerial photographs varied, and were in black and white until 2011, but most photographs examined could be used to delineate predominantly agricultural land uses relative to industrial or urban land uses, particularly where the land use has remained consistent and could be verified during the study.

Quality Assurance and Quality Control

Data quality for this study was ensured by using a variety of methods. All water samples were collected following written protocols described in the USGS National Field Manual (U.S. Geological Survey, variously dated). Quality control samples, such as trip blanks and duplicate samples, were collected in addition to groundwater and spring-water samples to provide information on possible sample contamination and to measure potential variability associated with the collection of data across a 2-year study. Moreover, samples were analyzed at the same laboratories to ensure consistency. Trip blanks for this study included VOC vials of laboratory blank water filled and sealed by the USGS NWQL. These trip blanks accompanied environmental sample vials to verify that

VOC contamination did not occur during storage, sampling, or shipment to or from the USGS NWQL. Any of the blanks described above could have been subjected to contamination during sample collection, processing, shipping, and analysis. Duplicates were collected immediately following collection of regular environmental samples and in the same manner to provide a measure of variability due to the effects of field and laboratory procedures.

Results of Sampling and Analysis

The results of groundwater and spring-water quality samples, soil-gas samples, groundwater-age dates, and particle-track simulations of groundwater flow pathways are presented and discussed in this section. To place the analytical results from each well or spring in the context of the groundwater-flow system near McBee, water-quality results are presented on maps showing the 2012 groundwater-flow system in the upper (fig. 13*A*) and lower (fig. 13*B*) units as simulated by using the three-dimensional groundwater-flow model presented in Campbell and Landmeyer (2014). The difference between the simulated potentiometric contours for when the first wells were sampled in 2010 is neglible compared to when the last water-quality samples were collected in 2012. In this section, areas of groundwater that are characterized by concentrations above the MRLs of individual compounds, such as EDB, collected over the 2010–2012 study period, are shown on these simulated potentiometric maps. This section also describes trends in compound concentrations over time in a particular well. Particle-tracking simulations of the groundwater flow pathway to public-supply wells using the groundwater-flow model of Campbell and Landmeyer (2014) are provided; for this analysis, the 2010 simulated potentiometric surface is used because the CFC data were collected in 2010. The groundwater flow pathways are superimposed on historical aerial photographs of land uses between 1961 and 2011 to assist in the assessment of potential sources of groundwater contamination detected in wells. Concentrations of EDB and DBCP detected during previous sampling events by DHEC officials are used and discussed for particular wells in the study area.

Physical Properties of Groundwater and Spring Water

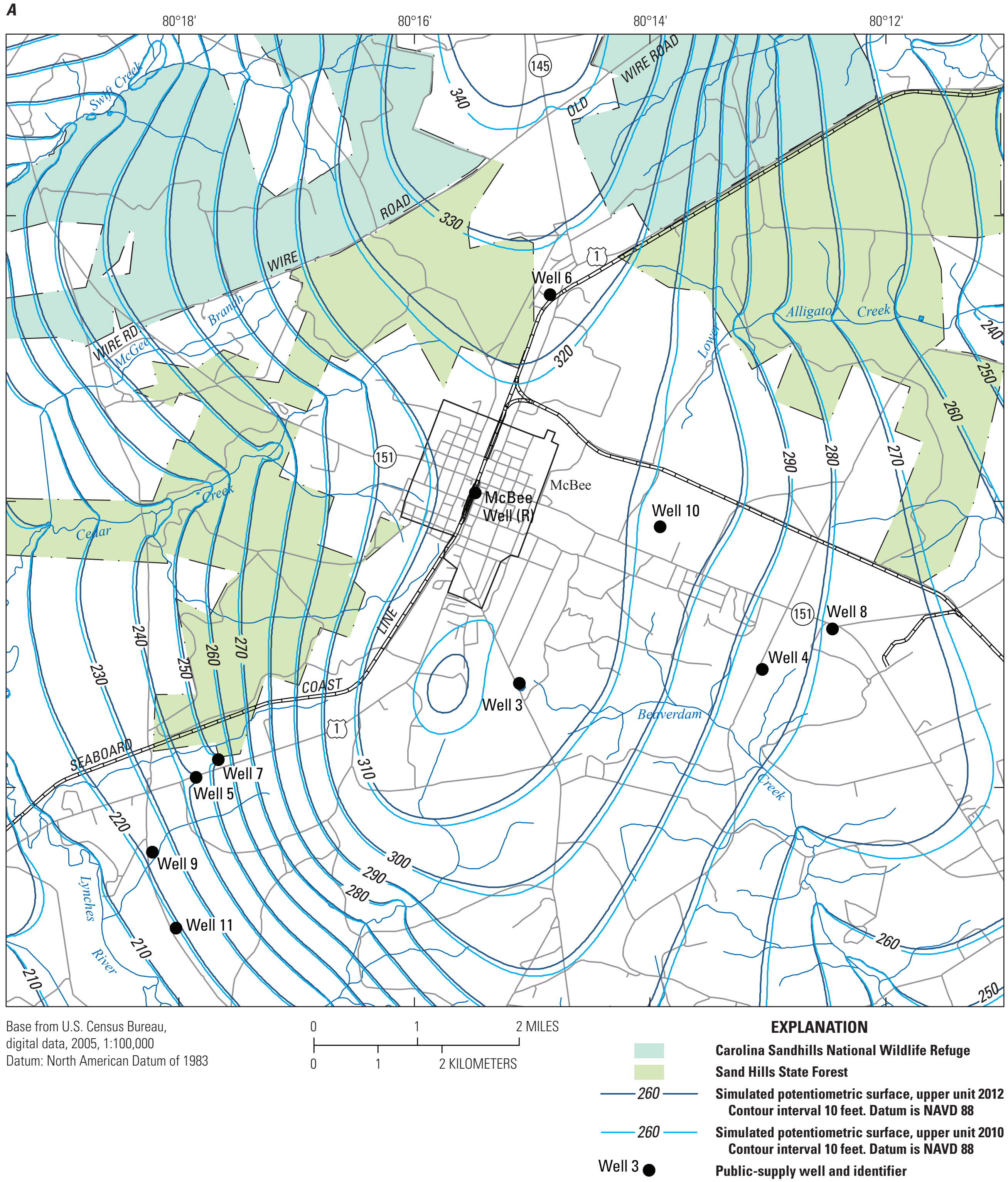
Groundwater samples collected between 2010 and 2012 from all wells in the McBee area that are screened in the Crouch and McQueen Branch aquifers were characterized by the following average values of water temperature (19.58 degrees Celsius (°C)), specific conductance (25.63 microsiemens per centimeter at 25 degrees Celsius (µS/cm)), pH (4.89), dissolved oxygen (9.21 mg/L), dissolved oxygen percent saturation at the groundwater sample temperature (99.82 percent), and turbidity (5.91 NTUs; table 4). Data for some monitoring wells are included in table 4 but were not used to calculate these averages because a monitoring well (CTF–228) had been recently installed, and three monitoring wells (W1, W2, and W3) represented shallow groundwater and were not, therefore, representative of the entire Crouch Branch aquifer. In general, groundwater temperatures measured at a particular well over time tended to be highest during the hot summer months and lowest during the cool winter months, and the difference approached 4 to 5 °C.

The physical properties and chemical composition of groundwater in the McBee area are similar to those of rainwater. In general, most wells have groundwater that is dilute, oxygenated, and acidic; groundwater samples from some wells, however, have compositions of specific conductance above the average of 25.63 µS/cm. The elevated specific conductance indicates that after infiltration groundwater interacted with a source(s) that would act to increase the specific conductance of the water, most likely aquifer minerals, septic tank leachate, or fertilizers applied at land surface. The average low pH can be explained as a result of ambient, naturally acidic rainwater caused by the dissolution of atmospheric carbon dioxide during precipitation and the fact that the sediments in the subsurface have been highly weathered since the Late Cretaceous period. As such, there is little buffering capacity in the subsurface, as the dissolution minerals such as feldspars (that would tend to increase the pH of water) have already been weathered.

Samples of water collected from four springs in the Cedar Creek Basin in December 2010 were characterized by the following average values for temperature (15.17 °C), specific conductance (23.75 µS/cm), pH (5.38), dissolved oxygen (6.59 mg/L), dissolved oxygen percent saturation at the sample temperature (66.73 percent), and turbidity (7.1 NTUs; table 4). The spring-water samples are cooler than the groundwater samples because the spring-water samples were collected in December whereas most of the groundwater samples were collected in August. The similar average specific conductance value of spring water compared to groundwater reflects flow through highly weathered sands to wells or springs in the Cedar Creek Basin, and other sources that are discussed in a later section. The average dissolved-oxygen concentration of the springs was lower than groundwater samples because each spring head was characterized by organic matter accumulation, decomposition, and consumption of dissolved oxygen.

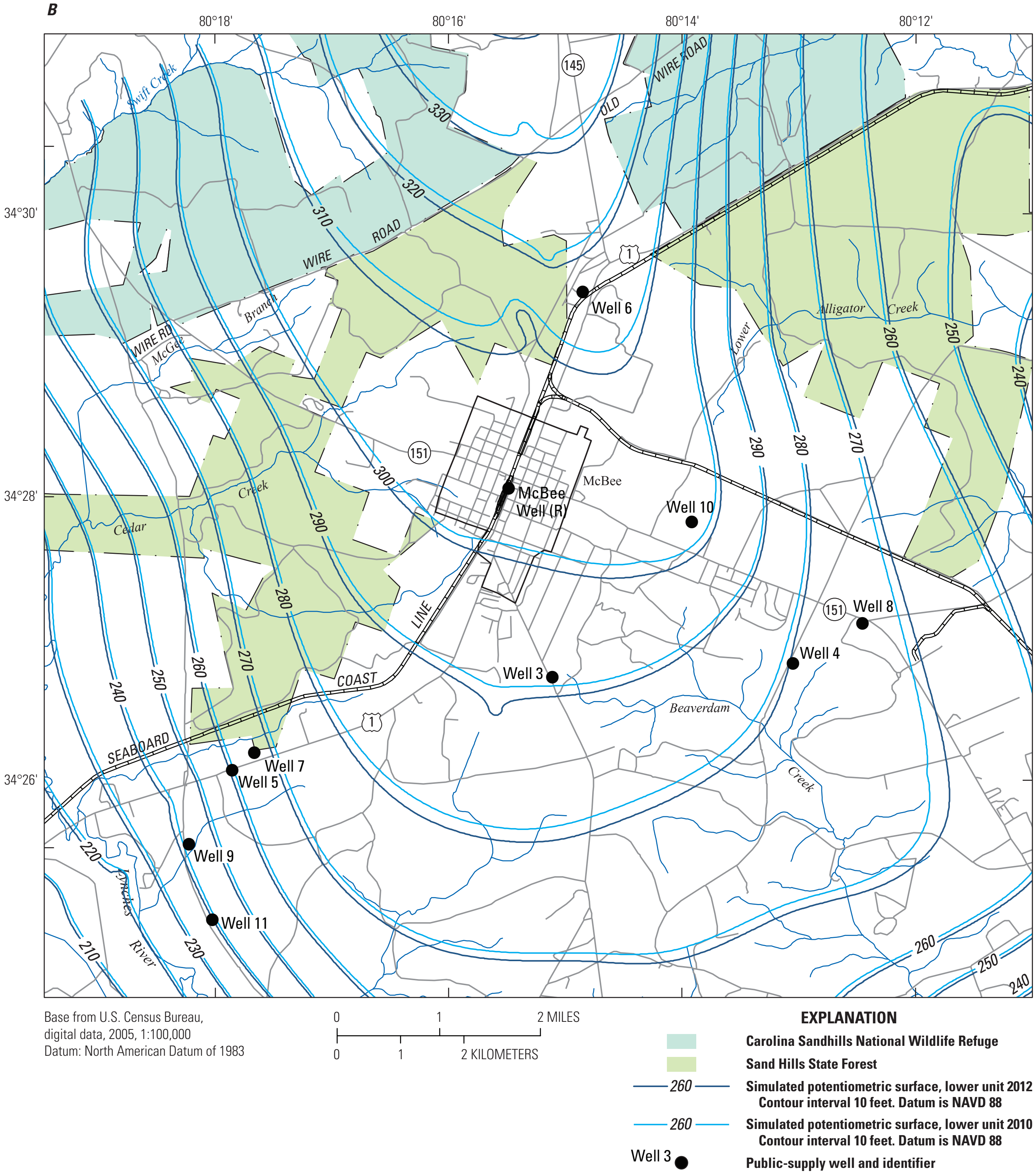
Anthropogenic Compounds

Concentrations of EDB, DBCP, and VOCs in groundwater and spring-water samples collected between 2010 and 2012 are listed in tables 5 and 6. The concentrations of EDB, DBCP, and other frequently detected VOCs are presented in terms of the times when the samples were collected and the location of the wells along groundwater flow pathways from recharge areas to discharge areas.



Base from U.S. Census Bureau,
digital data, 2005, 1:100,000
Datum: North American Datum of 1983

Figure 13. Simulated 2010 and 2012 potentiometric surfaces in the (*A*) upper and (*B*) lower units, near McBee, South Carolina. The potentiometric surfaces were simulated using the model described in Campbell and Landmeyer (2014).



Base from U.S. Census Bureau,
digital data, 2005, 1:100,000
Datum: North American Datum of 1983

Figure 13. Simulated 2010 and 2012 potentiometric surfaces in the (*A*) upper and (*B*) lower units, near McBee, South Carolina. The potentiometric surfaces were simulated using the model described in Campbell and Landmeyer (2014).—Continued

Table 4. Field measurements of physical properties and chemical composition during groundwater and spring-water sample collection, McBee, South Carolina, 2010–2012.

[ID, identification; CTF-, Chesterfield County prefix; n, unique county-well number; USGS, U.S. Geological Survey; (R), replacement well; S, shallow screened interval; D, deep screened interval; —, no data available; locations of wells are shown in figure 8; MG-, springs; PW, privately owned well; MW, monitoring well; *, early sample not used in computation of averages for water quality; **, samples representative of shallow groundwater and not used in computation of averages for water quality; °C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; NTU, nephelometric turbidity unit]

Field measurements of physical properties and chemical composition											
Well ID	**County number, CTF-n**	**USGS site ID number**	**Sample date**	**Sample time**	**Sample collection method**	**Water temperature (°C)**	**Specific conductance (µS/cm)**	**pH**	**Dissolved oxygen (mg/L)**	**Dissolved oxygen (percent saturation at sample temperature)**	**Turbidity (NTU)**
2010											
Public-supply wells											
Well 3	CTF–83	342642080150709	August 4, 2010	14:47	Wellhead	21.17	22	4.93	9.22	103.8	2.6
Well 4	CTF–88	342652080130109	August 4, 2010	12:17	Wellhead	19.26	32	4.74	9.73	105.5	2.8
Well 5	CTF–89	342559080180509	July 29, 2010	15:50	Wellhead	19.36	23	4.69	9.32	101.1	2.4
Well 6	CTF–106	342929080145009	July 29, 2010	13:10	Wellhead	18.38	14	4.74	9.69	103.1	2.3
Well 7	CTF–107	342711080174909	August 3, 2010	12:50	Wellhead	19.51	23	4.74	9.66	105.2	2.3
Well 8	CTF–108	342707080122909	August 4, 2010	13:48	Wellhead	19.42	42	4.67	9.77	106	2.6
Well 9	CTF–198	342532080181309	August 3, 2010	10:18	Wellhead	18.66	19	4.61	9.73	104.2	2.5
Well 10	CTF–219	342749080135509	August 4, 2010	11:17	Wellhead	18.68	39	4.54	9.88	105	2.2
McBee well(R)	CTF–179	342803080152909	August 3, 2010	15:10	Wellhead	19.67	44	4.95	9.16	100.1	3.1
Monitoring wells											
CTF–222(S)	CTF–222	342543080165800	August 18, 2010	11:35	Submersible	21.3	42	4.84	9.39	105.9	12.4
CTF–221(D)	CTF–221	342543080165801	August 18, 2010	—	—	—	—	—	—	—	—
CTF–189	CTF–189	343105080172100	August 30, 2010	13:15	Peristaltic	21.72	12	4.89	8.55	97.1	7.8
Cedar Creek Basin wells											
W1	CTF–230	342852080163900	December 13, 2010	11:41**	Waterra	11.24	10	5.12	11.17	101.7	11.24
W2	CTF–229	342853080163900	December 13, 2010	13:40**	Peristaltic	17.01	10	5.33	9.75	100	10.5
W3	CTF–231	342854080163700	December 13, 2010	14:50**	Peristaltic	16.68	10	5.2	9.95	102.3	16
Cedar Creek Basin Springs											
MG–015	–	342842080163800	December 7, 2010	11:11	Spring	15.52	20	5.06	6.28	64.9	7.3
MG–001	–	342847080164700	December 7, 2010	12:20	Spring	15.99	21	5.15	4.75	49	13.1
MG–006	–	342859080161800	December 7, 2010	14:10	Spring	14.68	42	5.85	6.34	64.7	4.2
MG–003	–	342851080164200	December 7, 2010	14:50	Spring	14.52	12	5.47	8.99	88.3	3.8

Table 4. Field measurements of physical properties and chemical composition during groundwater and spring-water sample collection, McBee, South Carolina, 2010–2012.—Continued

[ID, identification; CTF-, Chesterfield County prefix; n, unique county-well number; USGS, U.S. Geological Survey; (R), replacement well; S, shallow screened interval; D, deep screened interval; —, no data available; locations of wells are shown in figure 8; MG-, springs; PW, privately owned well; MW, monitoring well; *, early sample not used in computation of averages for water quality; **, samples representative of shallow groundwater and not used in computation of averages for water quality; °C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; NTU, nephelometric turbidity unit]

Field measurements of physical properties and chemical composition											
Well ID	**County number, CTF-n**	**USGS site ID number**	**Sample date**	**Sample time**	**Sample collection method**	**Water temperature (°C)**	**Specific conductance (µS/cm)**	**pH**	**Dissolved oxygen (mg/L)**	**Dissolved oxygen (percent saturation at sample temperature)**	**Turbidity (NTU)**
2011											
Monitoring wells											
CTF–228(S)	CTF–228	342828080131900	June 14, 2011	13:50	Bladder	—	18	5.11	—	—	—
CTF–228(D)	CTF–228	342828080131900	June 20, 2011	13:01	Bladder	—	17	4.73	—	—	—
Sand Hills State Forest wells											
MW1	CTF–224	342929080155300	June 15, 2011	17:04	Bladder	—	19	6.65	—	—	—
MW3	CTF–226	342912080160300	June 15, 2011	14:52	Bladder	—	18	6.45	—	—	—
MW4	CTF–227	342905080155900	June 14, 2011	16:53	Bladder	—	10	5.24	—	—	—
Public-supply wells											
Well 3	CTF–83	342642080150709	August 23, 2011	13:00*	Wellhead	19.68	23	6.53	6.49	69.8	58
Well 3	CTF–83	342642080150709	August 23, 2011	13:20	Wellhead	19.02	17	4.6	9.2	99.3	2.5
Well 4	CTF–88	342652080130109	August 23, 2011	12:30	Wellhead	19.18	34	4.52	9.94	109.7	1.2
Well 5	CTF–89	342559080180509	August 24, 2011	11:57	Wellhead	19.63	24	4.51	9.72	106.1	1.5
Well 6	CTF–106	342929080145009	August 23, 2011	14:40	Wellhead	18.78	19	4.39	9.91	106.3	1.7
Well 7	CTF–107	342711080174909	August 24, 2011	12:11	Wellhead	19.41	23	4.65	9.93	107.8	1.5
Well 8	CTF–108	342707080122909	August 23, 2011	11:01*	Wellhead	22.15	65	7.22	3.27	38.2	39.3
Well 8	CTF–108	342707080122909	August 23, 2011	11:30	Wellhead	19.55	44	4.56	9.46	103	1
Well 9	CTF–198	342532080181300	August 24, 2011	11:31	Wellhead	19.5	21	4.38	9.82	106.7	1.4
Well 10	CTF–219	342749080135509	August 23, 2011	14:00	Wellhead	19.08	42	4.23	10.11	109	1.2
Agricultural-supply wells											
CTF–60	CTF–60	343044080145200	August 23, 2011	15:00	Wellhead	18.83	58	4.43	10.52	113	2.6
CTF–315	CTF–315	343027080144400	August 24, 2011	15:00	Wellhead	18.43	55	4.12	10.22	108.9	1.2
CTF–316	CTF–316	342920080144300	August 25, 2011	14:25	Wellhead	18.51	28	4.65	9.97	106.4	1.2
CTF–209	CTF–209	342954080143900	August 25, 2011	12:22	Wellhead	19.7	33	4.48	9.79	107	3.9
CTF–207	CTF–207	343027080151400	August 25, 2011	12:55*	Wellhead	19.16	77	4.09	9.91	107.2	11

Table 4. Field measurements of physical properties and chemical composition during groundwater and spring-water sample collection, McBee, South Carolina, 2010–2012.—Continued

[ID, identification; CTF-, Chesterfield County prefix; n, unique county-well number; USGS, U.S. Geological Survey; (R), replacement well; S, shallow screened interval; D, deep screened interval; —, no data available; locations of wells are shown in figure 8; MG-, springs; PW, privately owned well; MW, monitoring well; *, early sample not used in computation of averages for water quality; **, samples representative of shallow groundwater and not used in computation of averages for water quality; °C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; NTU, nephelometric turbidity unit]

						Field measurements of physical properties and chemical composition					
Well ID	**County number, CTF-n**	**USGS site ID number**	**Sample date**	**Sample time**	**Sample collection method**	**Water temperature (°C)**	**Specific conductance (µS/cm)**	**pH**	**Dissolved oxygen (mg/L)**	**Dissolved oxygen (percent saturation at sample temperature)**	**Turbidity (NTU)**
2012											
Public-supply wells											
Well 11	CTF–313	342500080180200	February 8, 2012	13:45	Wellhead	18.55	11	4.78	10.09	107.8	11
Well 6	CTF–106	342929080145009	August 14, 2012	11:11*	Wellhead	19.36	16	4.87	8.84	95.9	4.7
Well 6	CTF–106	342929080145009	August 14, 2012	11:25	Wellhead	18.3	15	4.42	9.49	101.2	0
Well 10	CTF–219	342749080135509	August 14, 2012	13:45	Wellhead	18.5	35	4.15	9.34	99.7	0
Monitoring wells											
CTF–228(S)	CTF–228	342828080131900	February 8, 2012	16:25	Bladder	17.69	14	4.76	10.07	105.7	3.2
CTF–228(D)	CTF–228	342828080131900	February 23, 2012	13:30	Submersible	18.5	15	4.41	10.11	107.8	14.1
CTF–221(R)	CTF–221(R)	342543080165801	February 9, 2012	11:50	Bladder	17.65	10	5.55	10.29	102.9	13
CTF–211	CTF–211	343023080130600	February 9, 2012	14:25	Bladder	17	22	6.3	1.55	16.1	57
CTF–228(D)	CTF–228	342828080131900	August 15, 2012	16:11	Bladder	22.49	15	4.85	9.08	104.8	8
CTF–228(S)	CTF–228	342828080131900	August 15, 2012	16:45	Bladder	23.14	14	4.49	9.06	105.9	2.3
CTF–211	CTF–211	343023080130600	August 15, 2012	19:40	Bladder	19.5	32	5.79	1.89	20.6	35.2
Domestic-supply wells											
PW1	CTF–317	342839080170601	August 14, 2012	15:44	Wellhead	18.34	8	4.18	9.57	101.7	0
PW2	CTF–318	342826080165201	August 14, 2012	16:30	Wellhead	18.5	24	4.11	9.33	99.5	0
PW3	CTF–319	342758080144601	August 15, 2012	11:06	Wellhead	18.96	41	3.99	9.22	99.4	0

Ethylene Dibromide

During sampling in August 2011, groundwater from agricultural-supply well CTF–209 had 18.6 µg/L EDB, the highest concentration of EDB measured during the 2-year study (table 5). This concentration was a twofold increase from 9.1 µg/L EDB detected in groundwater from this well when sampled by DHEC officials in 2008 (Paula Brown, Department of Health and Environmental Control, written commun., March 2, 2010). Hydrologically downgradient from well CTF–209, EDB was detected above the MCL of 0.05 µg/L in groundwater from public-supply Well 6 during all three sampling events, at concentrations of 0.118 µg/L in July 2010, at 0.460 µg/L in August 2011, and at 0.502 µg/L in August 2012 (table 5). The consistent detection of EDB in groundwater from Well 6 between 2010 and 2012 confirms the previous detection of EDB in raw groundwater from this well when sampled prior to 2010 by DHEC officials (fig. 14; only those groundwater samples collected by DHEC officials before the installation of the GAC system are shown because some samples had been collected following filtration). The observed decrease in EDB detection in raw water from Well 6 between 2009 and 2010 may have been due to dilution associated with higher pumping rates or longer periods of pumping and, conversely, the observed increase in EDB concentration after 2010 may have been due to lower pumping rates and less dilution (Glenn Odum, Alligator Rural Water and Sewer Company, oral commun., May 15, 2012). Groundwater samples from agricultural-supply well CTF–316 located near Well 6 had 0.108 µg/L EDB. The pumping history of this agricultural-supply well could not be determined.

Six monitoring wells (MW1, MW3, MW4, W1, W2, and W3) are located downgradient from EDB-contaminated agricultural-supply well CTF–209 and public-supply Well 6. All six wells had detections of EDB in groundwater samples that ranged from 0.023 to 0.057 µg/L (table 5). Four springs (MG–015, –001, –006, and –003) located just downgradient from these six wells did not, however, have EDB above the MRL of 0.018 µg/L (table 5).

Groundwater samples not characterized by EDB detections provided useful information to assess the extent of the EDB contamination in the subsurface. For example, groundwater from agricultural-supply well CTF–60 sampled in August 2011 did not have EDB present above the MRL of 0.018 µg/L; this well is located to the northeast of (and upgradient from) EDB-contaminated agricultural-supply well CTF–209. Monitoring well CTF–189 also was sampled in August 2010, and EDB was not present above the MRL. The lack of EDB detection in groundwater from this well is most likely related to the fact that the well is screened in the upper part of the Crouch Branch aquifer and is located in the Swift Creek Basin, which lies west of the monitoring wells in the Cedar Creek Basin that contained EDB. No EDB was detected above the MRL in groundwater from monitoring well CTF–211, located east of any wells located north of McBee that contained EDB. To the south of these wells, EDB was not detected above the MRL in groundwater samples from either the shallow or deep screens at monitoring well CTF–228 during June 2011 and February and August 2012. Also EDB was not detected above the MRL in groundwater from Well 10 during August 2010, August 2011, and July 2012. In August 2012, domestic-supply well PW3 was sampled, and EDB was not present above the MRL. In the McBee Well(R) sampled in August 2010, no EDB was detected in groundwater above the MRL. Well 3 had an estimated EDB detection of 0.013 µg/L in August 2010, but not in August 2011 (table 5). Farther to the east and the south of McBee, groundwater from Wells 4, 5, 7, and 9 did not contain EDB above the MRL.

An area of groundwater in the Crouch Branch aquifer near McBee that is characterized by concentrations of EDB greater than the MRL of 0.018 µg/L in groundwater samples collected between 2010 and 2012 was delineated (fig. 15). The area of EDB contamination, or plume, is generally located in the Crouch Branch aquifer in the upper part of the Cedar Creek Basin, and is bounded by the recharge area near Wire Road to the north, the Sand Hills State Forest and discharge area of the Cedar Creek Basin springs to the west and south, and to the east by S.C. Highway 145 North (fig. 15). Because the higher concentrations of EDB are located in areas of higher groundwater altitudes, this area is the most likely source of the EDB detected in these wells and in downgradient wells in the Cedar Creek Basin. The detection of EDB in public-supply Well 6 most likely indicates EDB transport toward this well under forced hydraulic gradients since installation in 2002. The lack of EDB detection in wells located to the east of S.C. Highway 145 North and south of Wire Road suggests that the potential EDB source area, most likely related to past soil fumigation using EDB, is limited to agricultural areas west of S.C. Highway 145 North.

Dibromochloropropane

Dibromochloropropane was detected at 0.281 µg/L in a groundwater sample from agricultural-supply well CTF–60 in August 2011; this concentration exceeds the MCL of 0.20 µg/L for DBCP. Additionally, DBCP was detected above the MCL in groundwater from agricultural-supply well CTF–209 at 0.893 µg/L in August 2011 (table 5), and above the MRL in groundwater from Well 6 in July 2010, August 2011, and August 2012 at 0.340, 0.032, and 0.031 µg/L, respectively. Lastly, DBCP was detected in groundwater from public-supply Well 3 at 0.734 µg/L in August 2010 and 0.490 µg/L in August 2011 (table 5; fig. 16).

The distribution of DBCP concentrations in groundwater from 2010 to 2012 were mapped as areas characterized by DBCP concentrations greater than the MRL of 0.030 µg/L. The areas of DBCP contamination, or plumes, depict DBCP-contaminated groundwater in the upper unit (fig. 17) and lower unit (fig. 18). The plume of DBCP in the upper unit is located north of McBee, near the boundary of the Cedar Creek Basin, and is generally co-located with the highest concentrations of EDB (fig. 15). Because the higher concentrations of

Table 5. Concentrations of ethylene dibromide and dibromochloropropane in groundwater and spring-water samples, McBee, South Carolina, 2010–2012.

[ID, identification; n, unique county-well number; USGS, U.S. Geological Survey; PW, privately owned well; (R), replacement well; MRL, minimum reporting level; —, no data available; MCL, maximum contaminant level; µg/L, micrograms per liter; <, less than, meaning the compound was not detected; E, estimated concentration is less than the laboratory reporting level but equal to or greater than the laboratory method detection level; values in bold face exceed the MCL]

Well ID	County number, CTF-n	USGS site ID	Sample date	Sample time	Ethylene dibromide (µg/L), lower MRL	Dibromochloropropane (µg/L), lower MRL	Ethylene dibromide (µg/L),	Dibromochloropropane (µg/L)	Duplicate sample result for ethylene dibromide (µg/L)	Duplicate sample result for dibromochloropropane (µg/L)
MRL					0.018	0.03	0.028	0.40	0.018	0.03
MCL					0.05	0.20	0.05	0.20	0.05	0.20
2010										
Public-supply wells										
Well 3	CTF–83	342642080150709	August 4, 2010	15:00	<0.018	**0.588**	E0.013	**0.734**	<0.018	**0.568**
Well 4	CTF–88	342652080130109	August 4, 2010	12:25	<0.018	<0.030	<0.05	<0.34	—	—
Well 5	CTF–89	342559080180509	July 29, 2010	16:34	<0.018	<0.030	<0.05	<0.34	—	—
Well 6	CTF–106	342929080145009	July 29, 2010	13:20	**0.0608**	<0.030	**0.118**	**0.340**	—	—
Well 7	CTF–107	342711080174909	August 3, 2010	13:02	<0.018	E0.031	<0.05	<0.34	—	—
Well 8	CTF–108	342707080122909	August 4, 2010	14:00	<0.018	<0.030	<0.05	<0.34	—	—
Well 9	CTF–198	342532080181309	August 3, 2010	10:28	<0.018	<0.030	<0.05	<0.34	—	—
Well 10	CTF–219	342749080135509	August 4, 2010	11:30	<0.018	<0.030	<0.05	<0.34	—	—
McBee well(R)	CTF–179	342803080152909	August 3, 2010	15:18	<0.018	<0.030	E0.016	<0.34	—	—
Monitoring wells										
CTF–222(S)	CTF–222	342543080165800	August 18, 2010	11:45	<0.018	<0.030	<0.05	<0.34	—	—
CTF–221(D)	CTF–221	342543080165801	August 18, 2010	—	—	—	—	—	—	—
CTF–189	CTF–189	343105080172100	August 30, 2010	13:10	<0.018	<0.030	<0.05	<0.34	—	—
Cedar Creek Basin wells										
W1	CTF–230	342852080163900	December 13, 2010	11:54	0.027	<0.030	0.034	<0.40	—	—
W2	CTF–229	342853080163900	December 13, 2010	13:52	0.023	<0.030	0.039	<0.40	—	—
W3	CTF–231	342854080163700	December 13, 2010	14:40	0.034	<0.030	0.046	<0.40	—	—
Cedar Creek Basin Springs										
MG–015	—	342842080163800	December 7, 2010	11:01	<0.018	<0.030	<0.028	<0.40	—	—
MG–001	—	342847080164700	December 7, 2010	12:13	<0.018	<0.030	<0.028	<0.40	—	—
MG–006	—	342859080161800	December 7, 2010	14:05	<0.018	<0.030	<0.028	<0.40	—	—
MG–003	—	342851080164200	December 7, 2010	14:40	<0.018	<0.030	<0.028	<0.40	—	—

Table 5. Concentrations of ethylene dibromide and dibromochloropropane in groundwater and spring-water samples, McBee, South Carolina, 2010–2012.—Continued

[ID, identification; n, unique county-well number; USGS, U.S. Geological Survey; PW, privately owned well; (R), replacement well; MRL, minimum reporting level; —, no data available; MCL, maximum contaminant level; µg/L, micrograms per liter; <, less than, meaning the compound was not detected; E, estimated concentration is less than the laboratory reporting level but equal to or greater than the laboratory method detection level; values in bold face exceed the MCL]

Well ID	County number, CTF-n	USGS site ID	Sample date	Sample time	Ethylene dibromide (µg/L), lower MRL	Dibromo-chloropro-pane (µg/L), lower MRL	Ethylene dibromide (µg/L),	Dibromo-chloro-propane (µg/L)	Duplicate sample result for ethylene dibro-mide (µg/L)	Duplicate sample result for dibromo-chloropropane (µg/L)
MRL					0.018	0.03	0.028	0.40	0.018	0.03
MCL					0.05	0.20	0.05	0.20	0.05	0.20
					2011					
					Monitoring wells					
CTF–228(S)	CTF–228	342828080131900	June 14, 2011	13:58	<0.018	<0.030	<0.028	<0.40	—	—
CTF–228(D)	CTF–228	342828080131900	June 20, 2011	13:22	<0.018	<0.030	<0.028	<0.40	—	—
					Sand Hills State Forest wells					
MW1	CTF–224	342929080155300	June 15, 2011	17:55	**0.057**	<0.030	**0.06**	<0.40	**0.0507**	<0.03
MW3	CTF–226	342912080160300	June 15, 2011	14:50	0.036	<0.030	0.048	<0.40	—	—
MW4	CTF–227	342905080155900	June 14, 2011	17:05	0.030	<0.030	0.029	<0.40	—	—
					Public-supply wells					
Well 3	CTF–83	342642080150709	August 23, 2011	13:20	<0.018	**0.490**	<0.028	**0.367**	—	—
Well 4	CTF–88	342652080130109	August 23, 2011	12:30	<0.018	<0.030	<0.028	<0.40	—	—
Well 5	CTF–89	342559080180509	August 24, 2011	11:57	<0.018	<0.030	<0.028	<0.40	—	—
Well 6	CTF–106	342929080145009	August 23, 2011	14:50	**0.363**	0.032	**0.460**	<0.40	—	—
Well 7	CTF–107	342711080174909	August 24, 2011	12:11	<0.018	0.032	<0.028	<0.40	—	—
Well 8	CTF–108	342707080122909	August 23, 2011	11:30	<0.018	0.035	<0.028	<0.40	—	—
Well 9	CTF–198	342532080181309	August 24, 2011	11:31	<0.018	<0.030	<0.028	<0.40	—	—
Well 10	CTF–219	342749080135509	August 23, 2011	14:00	<0.018	<0.030	<0.028	<0.40	—	—
					Agricultural-supply wells					
CTF–60	CTF–60	343044080145200	August 23, 2011	15:00	<0.018	**0.281**	<0.028	**0.235**	—	—
CTF–315	CTF–315	343027080144400	August 24, 2011	14:25	<0.018	<0.030	<0.028	<0.40	—	—
CTF–316	CTF–316	342920080144300	August 25, 2011	12:22	**0.108**	<0.030	**0.077**	<0.40	—	—
CTF–209	CTF–209	343027080151400	August 25, 2011	13:24	**E1.07**	**E0.650**	**18.6**	**0.893**	—	—
CTF–207	CTF–207	342954080143900	August 25, 2011	12:55	—	—	—	—	—	—

Table 5. Concentrations of ethylene dibromide and dibromochloropropane in groundwater and spring-water samples, McBee, South Carolina, 2010–2012.—Continued

[ID, identification; n, unique county-well number; USGS, U.S. Geological Survey; PW, privately owned well; (R), replacement well; MRL, minimum reporting level; —, no data available; MCL, maximum contaminant level; µg/L, micrograms per liter; <, less than, meaning the compound was not detected; E, estimated concentration is less than the laboratory reporting level but equal to or greater than the laboratory method detection level; values in bold face exceed the MCL]

Well ID	County number, CTF-n	USGS site ID	Sample date	Sample time	Ethylene dibromide (µg/L), lower MRL	Dibromo-chloropro-pane (µg/L), lower MRL	Ethylene dibromide (µg/L),	Dibromo-chloro-propane (µg/L)	Duplicate sample result for ethylene dibromide (µg/L)	Duplicate sample result for dibromo-chloropropane (µg/L)
MRL					0.018	0.03	0.028	0.40	0.018	0.03
MCL					0.05	0.20	0.05	0.20	0.05	0.20
2012										
Public-supply wells										
Well 11	CTF–313	342500080180200	February 8, 2012	13:40	<0.018	<0.030	<0.028	<0.40	—	—
Well 6	CTF–106	342929080145009	August 14, 2012	11:25	**0.502**	0.031	**0.454**	<0.40	—	—
Well 10	CTF–219	342749080135509	August 14, 2012	13:45	<0.018	<0.030	<0.028	<0.40	—	—
Monitoring wells										
CTF–228(S)	CTF–228	342828080131900	February 8, 2012	16:30	<0.018	<0.030	<0.028	<0.40	—	—
CTF–228(D)	CTF–228	342828080131900	February 23, 2012	14:00	<0.018	<0.030	<0.028	<0.40	—	—
CTF–221(R)	CTF–221	342543080165801	February 9, 2012	11:58	<0.018	<0.030	<0.028	<0.40	—	—
CTF–211	CTF–211	343023080130600	February 9, 2012	14:20	<0.018	<0.030	<0.028	<0.40	—	—
CTF–228(D)	CTF–228	342828080131900	August 15, 2012	16:11	<0.018	<0.030	<0.028	<0.40	—	—
CTF–228(S)	CTF–228	342828080131900	August 15, 2012	16:45	<0.018	<0.030	<0.028	<0.40	—	—
CTF–211	CTF–211	343023080130600	August 15, 2012	19:40	<0.018	<0.030	<0.028	<0.40	—	—
Domestic-supply wells										
PW1	CTF–317	342839080170601	August 14, 2012	15:44	<0.018	<0.030	<0.028	<0.40	—	—
PW2	CTF–318	342826080165201	August 14, 2012	16:30	<0.018	<0.030	<0.028	<0.40	—	—
PW3	CTF–319	342758080144601	August 15, 2012	11:06	<0.018	<0.030	<0.028	<0.40	—	—

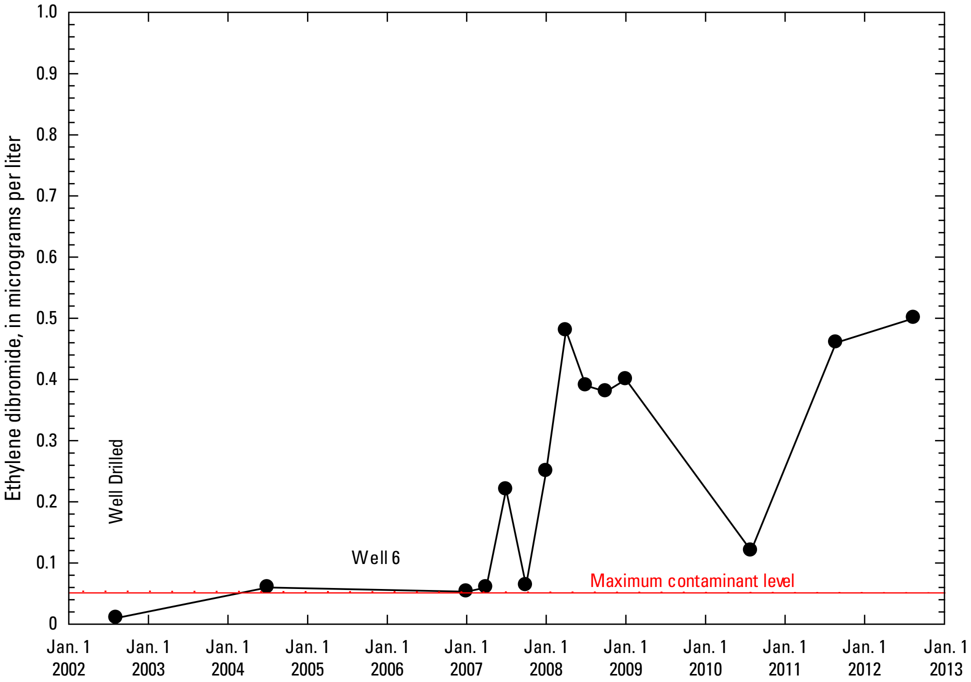


Figure 14. Concentration of ethylene dibromide detected in groundwater from public-supply Well 6, 2002–2012. Sample results of raw water prior to 2010 were collected by the Department of Health and Environmental Control. The U.S. Environmental Protection Agency National Primary Drinking Water Regulation maximum contaminant level for ethylene dibromide is 0.05 microgram per liter.

DBCP are located in areas of higher groundwater altitudes, this area is the most likely source of the DBCP detected in these wells and in downgradient public-supply Well 6. The lack of DBCP detection in wells located to the east of S.C. Highway 145 North and south of Wire Road suggests that the potential DBCP source area, most likely related to past soil fumigation using DBCP, is limited to agricultural areas west of S.C. Highway 145 North. In the lower unit, three generally lower concentration plumes of DBCP are located to the south of McBee (fig. 18). The highest concentrations of DBCP detected in the lower unit were from groundwater samples from public-supply Well 3, where DBCP was detected in groundwater at concentrations ranging from 0.367 to 0.734 µg/L (table 5). Groundwater samples from public-supply Well 7 contained an estimated concentration of 0.031 µg/L DBCP in August 2010 and 0.032 µg/L DBCP in August 2011. Groundwater samples from public-supply Well 8 had 0.035 µg/L DBCP. Concentrations of DBCP were below the MRL of 0.03 µg/L in all other wells sampled between 2010 and 2012. The extent of each DBCP plume shown in figs. 17 and 18 were determined using the DBCP concentrations measured and particle-track analyses that are discussed in a subsequent section of the report.

The detection of DBCP in groundwater from wells around the rural area of McBee is not the first report of DBCP-contaminated groundwater in South Carolina. An early investigation in the late 1970s concerning the effect of DBCP on groundwater resources in South Carolina (Carter and others, 1984) was initiated following the detection of DBCP in groundwater in areas of Arizona, California, Hawaii, and Maryland characterized by the agricultural use of DBCP as a soil fumigant (Oki and Giambelluca, 1987). Howard (1991) states that “municipal drinking water supplies were sampled in South Carolina in 1979 and 1980 in areas of high DBCP use and where DBCP was not used.” Carter and Riley (1981) reported the detection of DBCP at concentrations greater than 1 µg/L in 5 out of 95 well-water samples collected in South Carolina (Carter and Riley, 1981). Carter and others (1984) investigated a peach orchard in Edgefield County, S.C., where DBCP had been applied in the early 1970s. Concentrations of DBCP were detected in well-water samples at that orchard at levels greater than 1 µg/L. Concentrations of DBCP in soil at the site were less than 1 microgram per kilogram (µg/kg) and does not explain the higher level of DBCP found in the well water. A rusty can that had contained DBCP was discovered near the well, and Carter and others (1984) concluded that a possible spill from this can could explain the DBCP detected in the groundwater from this well.

Other Volatile Organic Compounds

Chloroform was the most frequently detected VOC in groundwater and spring-water samples in the McBee area (table 6). Chloroform was detected above the MRL in every groundwater and spring-water sample collected between 2010 and 2012 at an average concentration of 0.073 µg/L. This concentration is similar to the median chloroform concentration of 0.08 µg/L reported for groundwater in the United States (Zogorski and others, 2006). The frequency of detection of chloroform at low concentrations in groundwater and spring-water samples in the McBee area and elsewhere is believed to be a consequence of the almost century-long and widespread use of chlorine to disinfect drinking water and wastewater. The disinfection process produces trihalomethanes, such

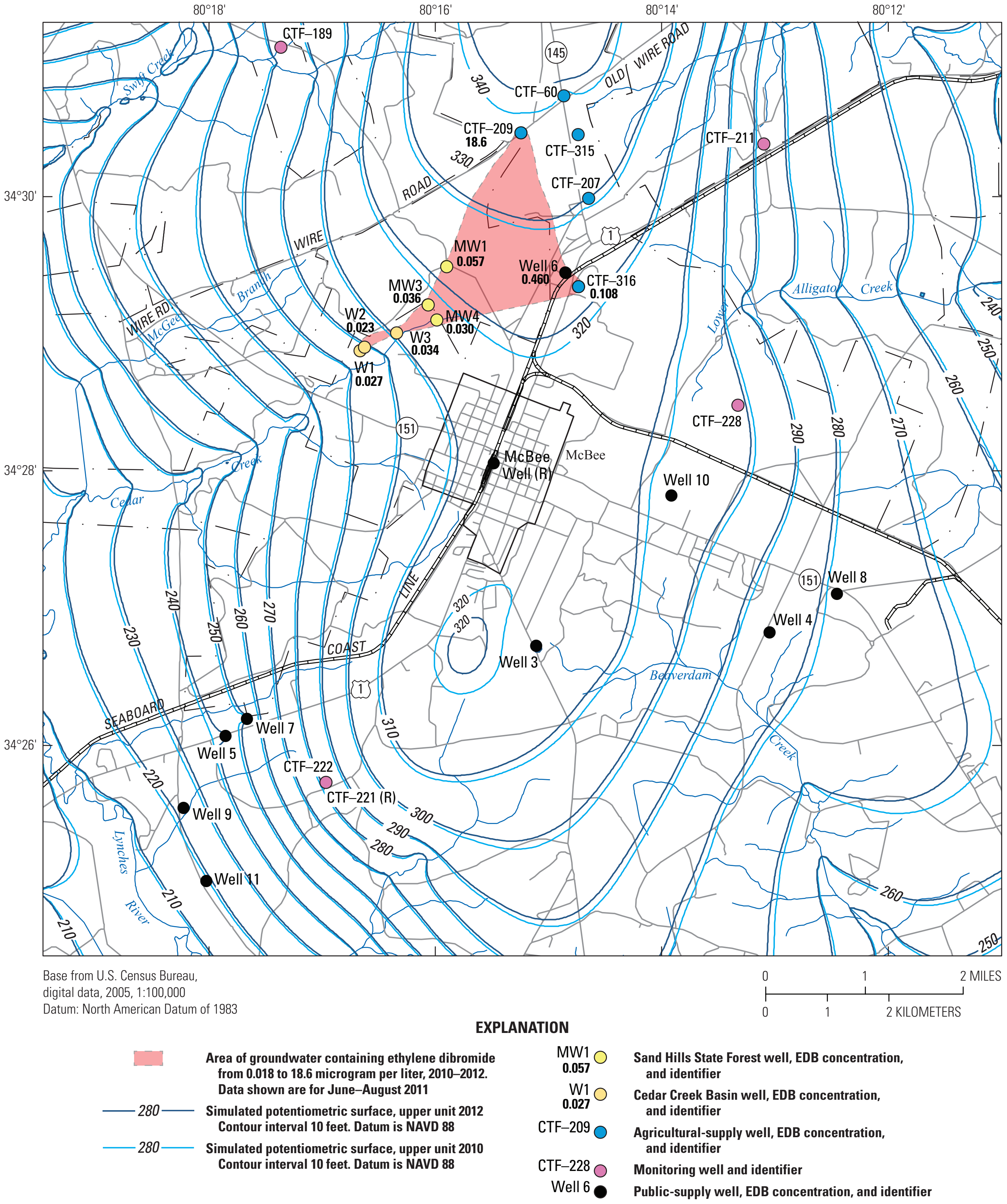


Figure 15. Area of groundwater containing ethylene dibromide concentrations from 0.018 to 18.6 microgram per liter between 2010–2012, McBee, South Carolina. The potentiometric surfaces were simulated using the model described in Campbell and Landmeyer (2014). The boundaries of the Carolina Sandhills National Wildlife Refuge and the Sand Hills State Forest are not shown in order to increase the clarity of the plume boundaries.

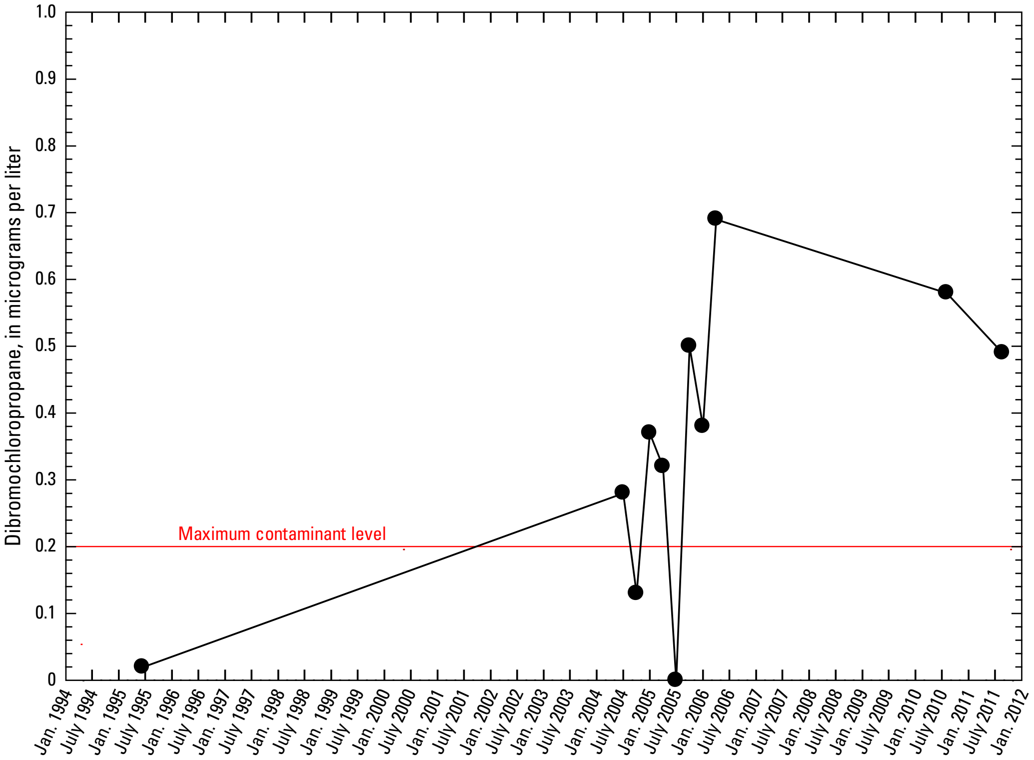


Figure 16. Concentration of dibromochloropropane detected in groundwater from public-supply Well 3, 2002–2012. Sample results of raw water prior to 2010 were collected by the Department of Health and Environmental Control. The U.S. Environmental Protection Agency National Primary Drinking Water Regulations maximum contaminant level is 0.20 microgram per liter.

as chloroform, that may have entered the hydrologic cycle and may have been delivered to groundwater by recharge of chloroform-containing precipitation (Ivahnenko and Zogorski, 2006; Zogorski and others, 2006). Chloroform concentrations above the average value of 0.073 µg/L for McBee groundwater were detected in springs and shallow wells, most likely as a result of a high percentage of shallow groundwater flow pathways of recently recharged water. In contrast, deep wells had chloroform concentrations lower than the average chloroform concentration of 0.073 µg/L.

The second most frequently detected VOC in groundwater and spring-water samples in the McBee area between 2010 and 2012 was toluene (table 6). Toluene was detected above the MRL of 0.018 µg/L in 2010 (and above the MRL of 0.02 µg/L in 2012) in 28 of 49 groundwater and spring-water samples. The highest toluene concentration (1.80 µg/L) was detected in groundwater from the deepest screened interval of monitoring well CTF–228(D) during sampling in February 2012. The second and third highest toluene concentrations (1.12 and 1.21 µg/L in February and August 2012, respectively) were detected in groundwater from monitoring well CTF–211 located near the Carolina Sandhills NWR. Monitoring well CTF–211 was the only well that had benzene detected with toluene, although at low concentrations of 0.160 and 0.394 µg/L. The fourth highest toluene concentration (0.783 µg/L) was detected in groundwater from the shallow monitoring well CTF–189. The toluene most likely resulted from well-construction methods associated with PVC-type wells, as groundwater from this well also contained tetrahydrofuran (3.09 µg/L), acetone (estimated 0.350 µg/L), and styrene (estimated 0.0122 µg/L). Groundwater from this well also contained an estimated 0.020 µg/L of carbon disulfide, which may not be related to well construction but rather to historical land uses that are discussed in a following section.

Various chlorinated compounds were detected in groundwater from wells in the McBee area. The compound 1,2-dichloropropane (1,2–DCP), once used as a soil fumigant but also used as a paint stripper and solvent (Zogorski and others, 2006), was detected in groundwater from six wells in the McBee area (fig. 19). For example, 1,2–DCP was detected in groundwater from monitoring wells MW1, MW3, and MW4 located in the Sand Hills State Forest during June 2011 at 0.077, 0.045, and 0.024 µg/L, respectively, which are concentrations considerably lower than the MCL of 5 µg/L. Additionally, 1,2–DCP was detected at 0.042 and 0.235 µg/L in groundwater from agricultural-supply wells CTF–60 and CTF–315, respectively, during August 2011. The highest concentration of 1,2–DCP (1.29 µg/L) was detected in EDB-contaminated groundwater from agricultural-supply well CTF–209. A groundwater sample collected from well CTF–209 during August 2011 was characterized by having the only detection of 1,3-dichloropropane (1,3–DCP) at 0.088 µg/L; the co-detection of 1,3–DCP and EDB in this well may reflect the occurrence of 1,3–DCP as an impurity of EDB when used as a soil fumigant. The chlorinated compound 1,2-dichloroethane (1,2–DCA), used variously to synthesize PVC, as a solvent, as a soil fumigant, and has been added in the past to gasoline fuels that contained tetraethyl lead (Zogorski and others, 2006), was detected in groundwater from only one well, public-supply Well 3, in August 2010 and 2011 at 0.225 and 0.116 µg/L, respectively

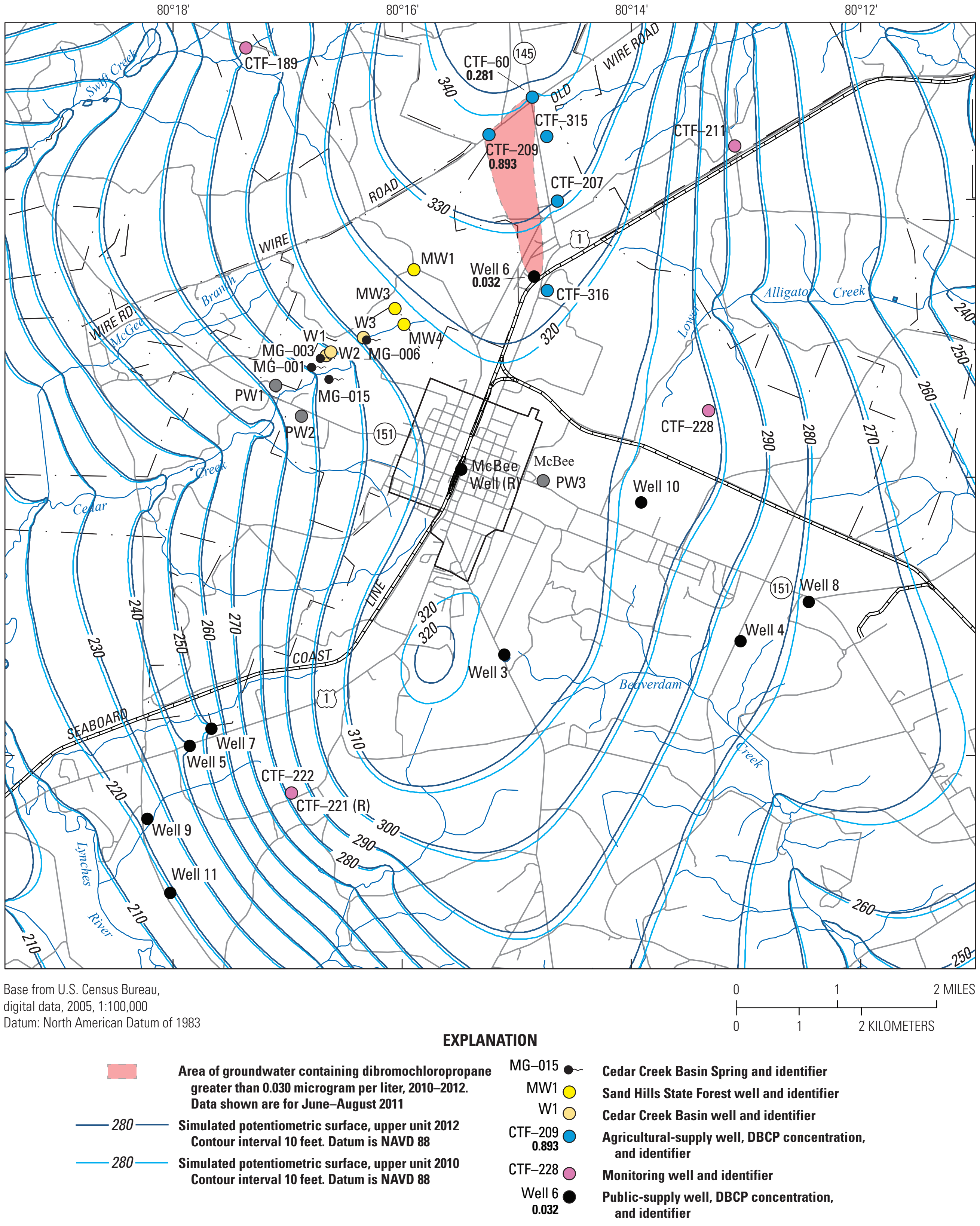
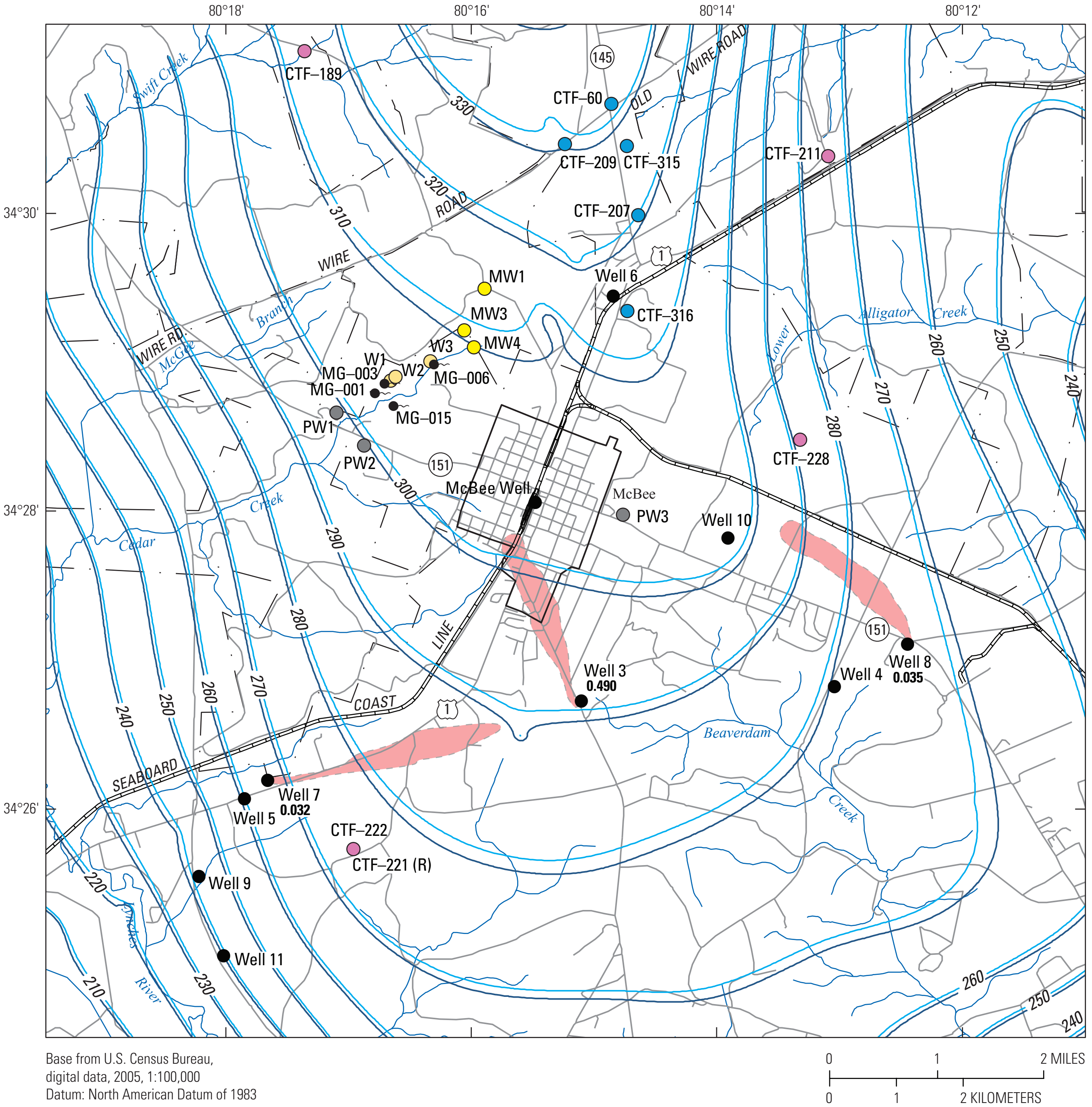


Figure 17. Area of groundwater in the upper unit containing dibromochloropropane greater than 0.030 microgram per liter between 2010–2012, McBee, South Carolina. The potentiometric surfaces were simulated using the model described in Campbell and Landmeyer (2014). The boundaries of the Carolina Sandhills National Wildlife Refuge and the Sand Hills State Forest are not shown in order to increase the clarity of the plume boundaries.



Base from U.S. Census Bureau,
digital data, 2005, 1:100,000
Datum: North American Datum of 1983

EXPLANATION

▨	Area of groundwater containing dibromochloropropane greater than 0.030 microgram per liter. Data shown are for June–August 2011
—280—	Simulated potentiometric surface, lower unit 2012 Contour interval 10 feet. Datum is NAVD 88
—280—	Simulated potentiometric surface, lower unit 2010 Contour interval 10 feet. Datum is NAVD 88
MG-015 •	Cedar Creek Basin Spring and identifier
MW1 ●	Sand Hills State Forest well and identifier
W1 ●	Cedar Creek Basin well and identifier
CTF–209 ●	Agricultural-supply well and identifier
CTF–228 ●	Monitoring well and identifier
Well 6 0.032 ●	Public-supply well, DBCP concentration, and identifier

Figure 18. Areas of groundwater in the lower unit that contain dibromochloropropane greater than 0.030 microgram per liter between 2010–2012, McBee, South Carolina. The potentiometric surfaces were simulated using the model described in Campbell and Landmeyer (2014).

Table 6. Concentrations of other volatile organic compounds in groundwater and spring-water samples, McBee, South Carolina, 2010–2012.

[ID, identification; n, unique county-well number; (R), replacement well; USGS, U.S. Geological Survey; MRL, minimum reporting level; —, no data available; MCL, maximum contaminant level; <, less than; E, estimated concentration is less than the laboratory reporting level but equal to or greater than the laboratory method detection level; concentrations are in micrograms per liter]

Well ID	County number, CTF-n	USGS site ID	Sample date	Sample time	1,2–Di-chloro-ethane (1,2–DCA)	1,1–Di-chloro-ethane (1,1–DCA)	Perchloro-ethylene (PCE)	Trichloro-ethylene (TCE)	1,1–Di-chloro-ethylene (1,1–DCE)	Dichloro-methane (DCM)	1,1,2–Tri-chloro-ethane (1,1,2–TCA)
MRL					0.080	0.044	0.026	0.022	0.022	0.038	0.046
MCL					5.00	—	5.00	5.00	7.00	5.00	5.00
2010											
Public-supply wells											
Well 3	CTF–83	342642080150709	August 4, 2010	15:00	0.225	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Well 4	CTF–88	342652080130109	August 4, 2010	12:20	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Well 5	CTF–89	342559080180509	July 29, 2010	16:34	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Well 6	CTF–106	342929080145009	July 29, 2010	13:20	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Well 7	CTF–107	342711080174909	August 3, 2010	13:00	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Well 8	CTF–108	342707080122909	August 4, 2010	13:48	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Well 9	CTF–198	342532080181309	August 3, 2010	10:28	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Well 10	CTF–219	342749080135509	August 4, 2010	11:24	<0.080	E0.042	<0.026	0.032	0.077	<0.038	<0.046
McBee well(R)	CTF–179	342803080152909	August 3, 2010	15:16	<0.080	<0.044	0.115	E0.019	<0.022	<0.038	<0.046
Monitoring wells											
CTF–222(S)	CTF–222	342543080165800	August 18, 2010	11:40	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
CTF–221(D)	CTF–221	342543080165801	August 18, 2010	—	—	—	—	—	—	—	—
CTF–189	CTF–189	343105080172100	August 30, 2010	13:00	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Trip blank			August 5, 2010	15:00	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Cedar Creek Basin wells											
W1	CTF–230	342852080163900	December 13, 2010	11:52	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
W2	CTF–229	342853080163900	December 13, 2010	13:48	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
W3	CTF–231	342854080163700	December 13, 2010	14:35	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Cedar Creek Basin Springs											
MG–015	—	342842080163800	December 7, 2010	10:56	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
MG–001	—	342847080164700	December 7, 2010	12:10	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
MG–006	—	342859080161800	December 7, 2010	14:00	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
MG–003	—	342851080164200	December 7, 2010	14:30	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046

Table 6. Concentrations of other volatile organic compounds in groundwater and spring-water samples, McBee, South Carolina, 2010–2012.—Continued

[ID, identification; n, unique county-well number; (R), replacement well; USGS, U.S. Geological Survey; MRL, minimum reporting level; —, no data available; MCL, maximum contaminant level; <, less than; E, estimated concentration is less than the laboratory reporting level but equal to or greater than the laboratory method detection level; concentrations are in micrograms per liter]

Well ID	County number, CTF-n	USGS site ID	Sample date	Sample time	1,2–Di-chloro-propane (1,2–DCP)	1,3–Di-chloro propane (1,3–DCP)	Tetra-hydro-furan	Chloro-form	Carbon disulfide (CS_2)	Acetone	Styrene
MRL					0.026	0.06	1.4	0.080	0.04	3.4	0.03
MCL					5.00	—	—	—	—	—	—
2010—Continued											
Public-supply wells											
Well 3	CTF–83	342642080150709	August 4, 2010	15:00	<0.026	<0.06	<1.4	0.0403	<0.04	<3.4	<0.03
Well 4	CTF–88	342652080130109	August 4, 2010	12:20	<0.026	<0.06	<1.4	0.0937	<0.04	<3.4	<0.03
Well 5	CTF–89	342559080180509	July 29, 2010	16:34	<0.026	<0.06	<1.4	0.131	<0.04	<3.4	<0.03
Well 6	CTF–106	342929080145009	July 29, 2010	13:20	<0.026	<0.06	<1.4	0.0828	<0.04	<3.4	<0.03
Well 7	CTF–107	342711080174909	August 3, 2010	13:00	<0.026	<0.06	<1.4	0.1	<0.04	<3.4	<0.03
Well 8	CTF–108	342707080122909	August 4, 2010	13:48	<0.026	<0.06	<1.4	E0.0134	<0.04	<3.4	<0.03
Well 9	CTF–198	342532080181309	August 3, 2010	10:28	<0.026	<0.06	<1.4	0.0653	<0.04	<3.4	<0.03
Well 10	CTF–219	342749080135509	August 4, 2010	11:24	<0.026	<0.06	<1.4	E0.0111	<0.04	<3.4	<0.03
McBee well(R)	CTF–179	342803080152909	August 3, 2010	15:16	<0.026	<0.06	<1.4	0.175	<0.04	<3.4	<0.03
Monitoring wells											
CTF–222(S)	CTF–222	342543080165800	August 18, 2010	11:40	<0.026	<0.06	<1.4	E0.0273	<0.04	<3.4	<0.03
CTF–221(D)	CTF–221	342543080165801	August 18, 2010	—	—	—	—	—	—	—	—
CTF–189	CTF–189	343105080172100	August 30, 2010	13:00	<0.026	<0.06	3.09	0.193	E0.020	E0.35	E0.012
Trip blank			August 5, 2010	15:00	<0.026	<0.06	<1.4	<0.080	<0.04	<3.4	<0.03
Cedar Creek Basin wells											
W1	CTF–230	342852080163900	December 13, 2010	11:52	<0.026	<0.06	<1.4	0.127	0.063	<3.4	<0.03
W2	CTF–229	342853080163900	December 13, 2010	13:48	<0.026	<0.06	<1.4	0.142	<0.04	<3.4	<0.03
W3	CTF–231	342854080163700	December 13, 2010	14:35	<0.026	<0.06	<1.4	0.133	<0.04	<3.4	<0.03
Cedar Creek Basin Springs											
MG–015	—	342842080163800	December 7, 2010	10:56	<0.026	<0.06	<1.4	0.161	0.024	<3.4	<0.03
MG–001	—	342847080164700	December 7, 2010	12:10	<0.026	<0.06	<1.4	0.206	0.022	<3.4	<0.03
MG–006	—	342859080161800	December 7, 2010	14:00	<0.026	<0.06	<1.4	0.0385	<0.04	<3.4	<0.03
MG–003	—	342851080164200	December 7, 2010	14:30	<0.026	<0.06	<1.4	0.0995	<0.04	<3.4	<0.03

Table 6. Concentrations of other volatile organic compounds in groundwater and spring-water samples, McBee, South Carolina, 2010–2012.—Continued

[ID, identification; n, unique county-well number; (R), replacement well; USGS, U.S. Geological Survey; MRL, minimum reporting level; —, no data available; MCL, maximum contaminant level; <, less than; E, estimated concentration is less than the laboratory reporting level but equal to or greater than the laboratory method detection level; concentrations are in micrograms per liter]

Well ID	County number, CTF-n	USGS site ID	Sample date	Sample time	Methyl tert-butyl ether (MTBE)	Benzene	Toluene	1,2,4–Trimethyl-benzene (1,2,4–TMB)	m,p-xylenes	Ethyl-benzene	4-iso-propyl-1-methyl-benzene
MRL					0.1	0.026; 0.020; 0.018	0.018	0.032	0.08	0.036	0.06
MCL					—	5.00	100	—	—	—	—
2010—Continued											
Public-supply wells											
Well 3	CTF–83	342642080150709	August 4, 2010	15:00	<0.1	<0.026	0.0433	<0.032	<0.08	<0.036	<0.06
Well 4	CTF–88	342652080130109	August 4, 2010	12:20	<0.1	<0.026	0.0404	<0.032	<0.08	<0.036	<0.06
Well 5	CTF–89	342559080180509	July 29, 2010	16:34	<0.1	<0.026	<0.018	<0.032	<0.08	<0.036	<0.06
Well 6	CTF–106	342929080145009	July 29, 2010	13:20	<0.1	<0.026	<0.018	<0.032	<0.08	<0.036	<0.06
Well 7	CTF–107	342711080174909	August 3, 2010	13:00	<0.1	<0.026	0.0476	<0.032	<0.08	<0.036	<0.06
Well 8	CTF–108	342707080122909	August 4, 2010	13:48	<0.1	<0.026	0.126	<0.032	<0.08	<0.036	<0.06
Well 9	CTF–198	342532080181309	August 3, 2010	10:28	<0.1	<0.026	0.0414	<0.032	<0.08	<0.036	<0.06
Well 10	CTF–219	342749080135509	August 4, 2010	11:24	<0.1	<0.026	0.0484	<0.032	<0.08	<0.036	<0.06
McBee well(R)	CTF–179	342803080152909	August 3, 2010	15:16	E0.027	<0.026	0.0349	<0.032	<0.08	<0.036	<0.06
Monitoring wells											
CTF–222(S)	CTF–222	342543080165800	August 18, 2010	11:40	<0.1	<0.026	0.0258	<0.032	E0.039	<0.036	<0.06
CTF–221(D)	CTF–221	342543080165801	August 18, 2010	—	—	—	—	—	—	—	—
CTF–189	CTF–189	343105080172100	August 30, 2010	13:00	<0.1	<0.026	0.783	<0.032	<0.08	<0.036	<0.06
Trip blank			August 5, 2010	15:00	<0.1	<0.026	<0.018	<0.032	<0.08	<0.036	<0.06
Cedar Creek Basin wells											
W1	CTF–230	342852080163900	December 13, 2010	11:52	<0.1	0.0168	<0.018	<0.032	<0.08	<0.036	<0.06
W2	CTF–229	342853080163900	December 13, 2010	13:48	<0.1	<0.026	<0.018	<0.032	<0.08	<0.036	<0.06
W3	CTF–231	342854080163700	December 13, 2010	14:35	<0.1	<0.026	<0.018	<0.032	<0.08	<0.036	<0.06
Cedar Creek Basin Springs											
MG–015	—	342842080163800	December 7, 2010	10:56	<0.1	<0.026	<0.018	<0.032	<0.08	<0.036	<0.06
MG–001	—	342847080164700	December 7, 2010	12:10	<0.1	<0.026	<0.018	<0.032	<0.08	<0.036	<0.06
MG–006	—	342859080161800	December 7, 2010	14:00	<0.1	<0.026	0.105	<0.032	<0.08	<0.036	0.033
MG–003	—	342851080164200	December 7, 2010	14:30	<0.1	<0.026	<0.018	<0.032	<0.08	<0.036	<0.06

Table 6. Concentrations of other volatile organic compounds in groundwater and spring-water samples, McBee, South Carolina, 2010–2012.—Continued

[ID, identification; n, unique county-well number; (R), replacement well; USGS, U.S. Geological Survey; MRL, minimum reporting level; —, no data available; MCL, maximum contaminant level; <, less than; E, estimated concentration is less than the laboratory reporting level but equal to or greater than the laboratory method detection level; concentrations are in micrograms per liter]

Well ID	County number, CTF-n	USGS site ID	Sample date	Sample time	1,2–Di-chloro-ethane (1,2–DCA)	1,1–Di-chloro-ethane (1,1–DCA)	Perchloro-ethylene (PCE)	Trichloro-ethylene (TCE)	1,1–Di-chloro-ethylene (1,1–DCE)	Dichloro-methane (DCM)	1,1,2–Tri-chloro-ethane (1,1,2–TCA)
MRL					0.080	0.044	0.026	0.022	0.022	0.038	0.046
MCL					5.00	—	5.00	5.00	7.00	5.00	5.00
2011											
Monitoring wells											
CTF–228(S)	CTF–228	342828080131900	June 14, 2011	13:58	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
CTF–228(D)	CTF–228	342828080131900	June 20, 2011	13:22	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Sand Hills State Forest wells											
MW1	CTF–224	342929080155300	June 15, 2011	17:55	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
MW3	CTF–226	342912080160300	June 15, 2011	14:50	<0.080	<0.044	<0.026	0.016	<0.022	<0.038	<0.046
MW4	CTF–227	342905080155900	June 14, 2011	17:05	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Public-supply wells											
Well 3	CTF–83	342642080150709	August 23, 2011	13:20	0.116	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Well 4	CTF–88	342652080130109	August 23, 2011	12:30	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Well 5	CTF–89	342559080180509	August 24, 2011	11:57	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Well 6	CTF–106	342929080145009	August 23, 2011	14:50	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Well 7	CTF–107	342711080174909	August 24, 2011	12:11	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Well 8	CTF–108	342707080122909	August 23, 2011	11:30	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Well 9	CTF–198	342532080181309	August 24, 2011	11:31	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Well 10	CTF–219	342749080135509	August 23, 2011	14:00	<0.080	0.021	<0.026	0.019	0.052	<0.038	<0.046
Agricultural-supply wells											
CTF–60	CTF–60	343044080145200	August 23, 2011	15:00	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
CTF–315	CTF–315	343027080144400	August 24, 2011	14:25	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
CTF–316	CTF–316	342920080144300	August 25, 2011	12:22	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
CTF–209	CTF–209	343027080151400	August 25, 2011	13:24	<0.080	<0.044	<0.026	<0.022	<0.022	2.09	0.028
CTF–207	CTF–207	342954080143900	August 25, 2011	12:55	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046

Table 6. Concentrations of other volatile organic compounds in groundwater and spring-water samples, McBee, South Carolina, 2010–2012.—Continued

[ID, identification; n, unique county-well number; (R), replacement well; USGS, U.S. Geological Survey; MRL, minimum reporting level; —, no data available; MCL, maximum contaminant level; <, less than; E, estimated concentration is less than the laboratory reporting level but equal to or greater than the laboratory method detection level; concentrations are in micrograms per liter]

Well ID	County number, CTF-n	USGS site ID	Sample date	Sample time	1,2–Di-chloro-propane (1,2–DCP)	1,3–Di-chloro propane (1,3–DCP)	Tetra-hydro-furan	Chloro-form	Carbon disulfide (CS_2)	Acetone	Styrene
MRL					0.026	0.06	1.4	0.080	0.04	3.4	0.03
MCL					5.00	—	—	—	—	—	—
2011—Continued											
Monitoring wells											
CTF–228(S)	CTF–228	342828080131900	June 14, 2011	13:58	<0.026	<0.06	<1.4	0.0165	<0.04	<3.4	<0.03
CTF–228(D)	CTF–228	342828080131900	June 20, 2011	13:22	<0.026	<0.06	<1.4	<0.080	<0.04	<3.4	<0.03
Sand Hills State Forest wells											
MW1	CTF–224	342929080155300	June 15, 2011	17:55	0.077	<0.06	<1.4	0.0315	<0.04	<3.4	<0.03
MW3	CTF–226	342912080160300	June 15, 2011	14:50	0.045	<0.06	<1.4	0.0291	0.017	<3.4	<0.03
MW4	CTF–227	342905080155900	June 14, 2011	17:05	0.024	<0.06	<1.4	0.0521	<0.04	<3.4	<0.03
Public-supply wells											
Well 3	CTF–83	342642080150709	August 23, 2011	13:20	<0.026	<0.06	<1.4	0.0627	<0.04	<3.4	<0.03
Well 4	CTF–88	342652080130109	August 23, 2011	12:30	<0.026	<0.06	<1.4	0.0854	<0.04	<3.4	<0.03
Well 5	CTF–89	342559080180509	August 24, 2011	11:57	<0.026	<0.06	<1.4	0.114	<0.04	<3.4	<0.03
Well 6	CTF–106	342929080145009	August 23, 2011	14:50	<0.026	<0.06	<1.4	0.0443	<0.04	<3.4	<0.03
Well 7	CTF–107	342711080174909	August 24, 2011	12:11	<0.026	<0.06	<1.4	0.105	<0.04	<3.4	<0.03
Well 8	CTF–108	342707080122909	August 23, 2011	11:30	<0.026	<0.06	<1.4	0.0186	<0.04	<3.4	<0.03
Well 9	CTF–198	342532080181309	August 24, 2011	11:31	<0.026	<0.06	<1.4	0.0644	<0.04	<3.4	<0.03
Well 10	CTF–219	342749080135509	August 23, 2011	14:00	<0.026	<0.06	<1.4	0.0158	<0.04	<3.4	<0.03
Agricultural-supply wells											
CTF–60	CTF–60	343044080145200	August 23, 2011	15:00	0.042	<0.06	<1.4	0.0266	<0.04	<3.4	<0.03
CTF–315	CTF–315	343027080144400	August 24, 2011	14:25	0.235	<0.06	<1.4	0.0238	<0.04	<3.4	<0.03
CTF–316	CTF–316	342920080144300	August 25, 2011	12:22	<0.026	<0.06	<1.4	0.0885	<0.04	<3.4	<0.03
CTF–209	CTF–209	343027080151400	August 25, 2011	13:24	1.29	0.088	3.54	0.019	<0.04	<3.4	<0.03
CTF–207	CTF–207	342954080143900	August 25, 2011	12:55	<0.026	<0.06	<1.4	<0.080	<0.04	<3.4	<0.03

Table 6. Concentrations of other volatile organic compounds in groundwater and spring-water samples, McBee, South Carolina, 2010–2012.—Continued

[ID, identification; n, unique county-well number; (R), replacement well; USGS, U.S. Geological Survey; MRL, minimum reporting level; —, no data available; MCL, maximum contaminant level; <, less than; E, estimated concentration is less than the laboratory reporting level but equal to or greater than the laboratory method detection level; concentrations are in micrograms per liter]

Well ID	County number, CTF-n	USGS site ID	Sample date	Methyl tert-butyl ether (MTBE)	Benzene	Toluene	1,2,4–Trimethyl-benzene (1,2,4–TMB)	m,p-xylenes	Ethyl-benzene	4-isopropyl-1-methyl benzene
MRL				0.1	0.026; 0.020; 0.018	0.018	0.032	0.08	0.036	0.06
MCL				—	5.00	100	—	—	—	—
2011—Continued										
Monitoring wells										
CTF–228(S)	CTF–228	342828080131900	June 14, 2011	<0.1	<0.026	0.0772	0.0205	0.048	<0.036	<0.06
CTF–228(D)	CTF–228	342828080131900	June 20, 2011	<0.1	<0.026	<0.018	<0.032	<0.08	<0.036	<0.06
Sand Hills State Forest wells										
MW1	CTF–224	342929080155300	June 15, 2011	<0.1	<0.026	0.0524	<0.032	0.043	<0.036	<0.06
MW3	CTF–226	342912080160300	June 15, 2011	<0.1	<0.026	0.0963	<0.032	0.062	<0.036	<0.06
MW4	CTF–227	342905080155900	June 14, 2011	<0.1	<0.026	0.0391	0.0207	0.041	<0.036	<0.06
Public-supply wells										
Well 3	CTF–83	342642080150709	August 23, 2011	<0.1	<0.026	0.178	<0.032	<0.08	<0.036	<0.06
Well 4	CTF–88	342652080130109	August 23, 2011	<0.1	<0.026	0.221	<0.032	<0.08	<0.036	<0.06
Well 5	CTF–89	342559080180509	August 24, 2011	<0.1	<0.026	0.0256	<0.032	<0.08	<0.036	<0.06
Well 6	CTF–106	342929080145009	August 23, 2011	<0.1	<0.026	0.112	<0.032	<0.08	<0.036	<0.06
Well 7	CTF–107	342711080174909	August 24, 2011	<0.1	<0.026	0.0201	<0.032	<0.08	<0.036	<0.06
Well 8	CTF–108	342707080122909	August 23, 2011	<0.1	<0.026	0.283	<0.032	<0.08	<0.036	<0.06
Well 9	CTF–198	342532080181309	August 24, 2011	<0.1	<0.026	0.0446	<0.032	<0.08	<0.036	<0.06
Well 10	CTF–219	342749080135509	August 23, 2011	<0.1	<0.026	0.222	<0.032	<0.08	<0.036	<0.06
Agricultural-supply wells										
CTF–60	CTF–60	343044080145200	August 23, 2011	<0.1	<0.026	0.205	<0.032	<0.08	<0.036	<0.06
CTF–315	CTF–315	343027080144400	August 24, 2011	<0.1	<0.026	<0.018	<0.032	<0.08	<0.036	<0.06
CTF–316	CTF–316	342920080144300	August 25, 2011	<0.1	<0.026	0.0201	<0.032	<0.08	<0.036	<0.06
CTF–209	CTF–209	343027080151400	August 25, 2011	<0.1	<0.026	0.0157	<0.032	<0.08	<0.036	<0.06
CTF–207	CTF–207	342954080143900	August 25, 2011	<0.1	<0.026	<0.018	<0.032	<0.08	<0.036	<0.06

Table 6. Concentrations of other volatile organic compounds in groundwater and spring-water samples, McBee, South Carolina, 2010–2012.—Continued

[ID, identification; n, unique county-well number; (R), replacement well; USGS, U.S. Geological Survey; MRL, minimum reporting level; —, no data available; MCL, maximum contaminant level; <, less than; E, estimated concentration is less than the laboratory reporting level but equal to or greater than the laboratory method detection level; concentrations are in micrograms per liter]

Well ID	County number, CTF-n	USGS site ID	Sample date	Sample time	1,2–Di-chloro-ethane (1,2–DCA)	1,1–Di-chloro-ethane (1,1–DCA)	Perchloro-ethylene (PCE)	Trichloro-ethylene (TCE)	1,1–Di-chloro-ethylene (1,1–DCE)	Dichloro-methane (DCM)	1,1,2–Tri-chloro-ethane (1,1,2–TCA)
MRL					0.080	0.044	0.026	0.022	0.022	0.038	0.046
MCL					5.00	—	5.00	5.00	7.00	5.00	5.00
2012											
Public-supply wells											
Well 11	CTF–313	342500080180200	February 8, 2012	13:40	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Well 6	CTF–106	342929080145009	August 14, 2012	11:25	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Well 10	CTF–219	342749080135509	August 14, 2012	13:45	<0.080	0.150	<0.026	0.101	0.367	<0.038	<0.046
Monitoring wells											
CTF–228(S)	CTF–228	342828080131900	February 8, 2012	16:30	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
CTF–228(D)	CTF–228	342828080131900	February 23, 2012	14:00	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
CTF–221(R)	CTF–221	342543080165801	February 9, 2012	11:58	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
CTF–211	CTF–211	343023080130600	February 9, 2012	14:20	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Domestic-supply wells											
PW1	CTF–317	342839080170601	August 14, 2012	15:44	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
PW2	CTF–318	342826080165201	August 14, 2012	16:30	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
PW3	CTF–319	342758080144601	August 15, 2012	11:06	<0.080	0.053	<0.026	<0.022	0.046	<0.038	<0.046
Monitoring wells											
CTF–228(D)	CTF–228	342828080131900	August 15, 2012	16:11	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
CTF–228(S)	CTF–228	342828080131900	August 15, 2012	16:45	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
CTF–211	CTF–211	343023080130600	August 15, 2012	19:40	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Trip blank		343023080130601	February 9, 2012	14:40	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046
Trip blank		343023080130601	August 20, 2012	14:50	<0.080	<0.044	<0.026	<0.022	<0.022	<0.038	<0.046

Table 6. Concentrations of other volatile organic compounds in groundwater and spring-water samples, McBee, South Carolina, 2010–2012.—Continued

[ID, identification; n, unique county-well number; (R), replacement well; USGS, U.S. Geological Survey; MRL, minimum reporting level; —, no data available; MCL, maximum contaminant level; <, less than; E, estimated concentration is less than the laboratory reporting level but equal to or greater than the laboratory method detection level; concentrations are in micrograms per liter]

Well ID	County number, CTF-n	USGS site ID	Sample date	Sample time	1,2–Di-chloro-propane (1,2–DCP)	1,3–Di-chloro propane (1,3–DCP)	Tetra-hydro-furan	Chloro-form	Carbon disulfide (CS_2)	Acetone	Styrene
MRL					0.026	0.06	1.4	0.080	0.04	3.4	0.03
MCL					5.00	—	—	—	—	—	—
2012—Continued											
Public-supply wells											
Well 11	CTF–313	342500080180200	February 8, 2012	13:40	<0.026	<0.06	<1.4	0.0943	<0.04	<3.4	<0.03
Well 6	CTF–106	342929080145009	August 14, 2012	11:25	<0.026	<0.06	<1.4	0.0365	<0.04	<3.4	<0.03
Well 10	CTF–219	342749080135509	August 14, 2012	13:45	<0.026	<0.06	<1.4	0.0142	<0.04	<3.4	<0.03
Monitoring wells											
CTF–228(S)	CTF–228	342828080131900	February 8, 2012	16:30	<0.026	<0.06	<1.4	0.0172	<0.04	<3.4	<0.03
CTF–228(D)	CTF–228	342828080131900	February 23, 2012	14:00	<0.026	<0.06	<1.4	0.0186	<0.04	<3.4	<0.03
CTF–221(R)	CTF–221	342543080165801	February 9, 2012	11:58	<0.026	<0.06	0.68	0.0684	<0.04	<3.4	<0.03
CTF–211	CTF–211	343023080130600	February 9, 2012	14:20	<0.026	<0.06	<1.4	<0.080	<0.04	5.50	<0.03
Domestic-supply wells											
PW1	CTF–317	342839080170601	August 14, 2012	15:44	<0.026	<0.06	<1.4	0.0787	<0.04	<3.4	<0.03
PW2	CTF–318	342826080165201	August 14, 2012	16:30	<0.026	<0.06	<1.4	0.072	<0.04	<3.4	<0.03
PW3	CTF–319	342758080144601	August 15, 2012	11:06	<0.026	<0.06	<1.4	0.0581	<0.04	<3.4	<0.03
Monitoring wells											
CTF–228(D)	CTF–228	342828080131900	August 15, 2012	16:11	<0.026	<0.06	<1.4	0.0158	<0.04	<3.4	0.052
CTF–228(S)	CTF–228	342828080131900	August 15, 2012	16:45	<0.026	<0.06	<1.4	0.0148	<0.04	<3.4	0.057
CTF–211	CTF–211	343023080130600	August 15, 2012	19:40	<0.026	<0.06	<1.4	<0.080	<0.04	<3.4	<0.03
Trip blank		343023080130601	February 9, 2012	14:40	<0.026	<0.06	<1.4	<0.080	<0.04	<3.4	<0.03
Trip blank		343023080130601	August 20, 2012	14:50	<0.026	<0.06	<1.4	<0.080	<0.04	<3.4	<0.03

Table 6. Concentrations of other volatile organic compounds in groundwater and spring-water samples, McBee, South Carolina, 2010–2012.—Continued

[ID, identification; n, unique county-well number; (R), replacement well; USGS, U.S. Geological Survey; MRL, minimum reporting level; —, no data available; MCL, maximum contaminant level; <, less than; E, estimated concentration is less than the laboratory reporting level but equal to or greater than the laboratory method detection level; concentrations are in micrograms per liter]

Well ID	County number, CTF-n	USGS site ID	Sample date	Sample time	Methyl tertbutyl ether (MTBE)	Benzene	Toluene	1,2,4–Trimethyl-benzene (1,2,4–TMB)	m,p-xylenes	Ethyl-benzene	4-iso-propyl-1-methyl-benzene
MRL					0.1	0.026; 0.020; 0.018	0.018	0.032	0.08	0.036	0.06
MCL					—	5.00	100	—	—	—	—
				2012—Continued							
				Public-supply wells							
Well 11	CTF–313	342500080180200	February 8, 2012	13:40	<0.1	<0.026	<0.018	<0.032	<0.08	<0.036	<0.06
Well 6	CTF–106	342929080145009	August 14, 2012	11:25	<0.1	<0.026	<0.02	0.0176	<0.08	0.0132	<0.06
Well 10	CTF–219	342749080135509	August 14, 2012	13:45	<0.1	<0.026	<0.02	<0.032	<0.08	<0.036	<0.06
				Monitoring wells							
CTF–228(S)	CTF–228	342828080131900	February 8, 2012	16:30	<0.1	<0.026	<0.02	<0.032	<0.08	<0.036	<0.06
CTF–228(D)	CTF–228	342828080131900	February 23, 2012	14:00	<0.1	<0.026	1.8	<0.032	<0.08	<0.036	<0.06
CTF–221(R)	CTF–221	342543080165801	February 9, 2012	11:58	<0.1	<0.026	<0.02	<0.032	<0.08	<0.036	<0.06
CTF–211	CTF–211	343023080130600	February 9, 2012	14:20	<0.1	0.16	1.12	<0.032	0.057	0.0747	<0.06
				Domestic-supply wells							
PW1	CTF–317	342839080170601	August 14, 2012	15:44	<0.1	<0.026	<0.02	0.0244	<0.08	<0.036	<0.06
PW2	CTF–318	342826080165201	August 14, 2012	16:30	<0.1	<0.026	<0.02	0.0276	<0.08	<0.036	<0.06
PW3	CTF–319	342758080144601	August 15, 2012	11:06	<0.1	<0.026	<0.02	0.0225	<0.08	<0.036	<0.06
				Monitoring wells							
CTF–228(D)	CTF–228	342828080131900	August 15, 2012	16:11	<0.1	0.015	<0.02	0.0434	<0.08	<0.036	<0.06
CTF–228(S)	CTF–228	342828080131900	August 15, 2012	16:45	<0.1	0.012	<0.02	0.0434	<0.08	<0.036	<0.06
CTF–211	CTF–211	343023080130600	August 15, 2012	19:40	<0.1	0.394	1.21	<0.032	<0.08	0.161	<0.06
Trip blank		343023080130601	February 9, 2012	14:40	<0.1	<0.026	<0.018	<0.032	<0.08	<0.036	<0.06
Trip blank		343023080130601	August 20, 2012	14:50	<0.1	<0.026	<0.018	<0.032	<0.08	<0.036	<0.06

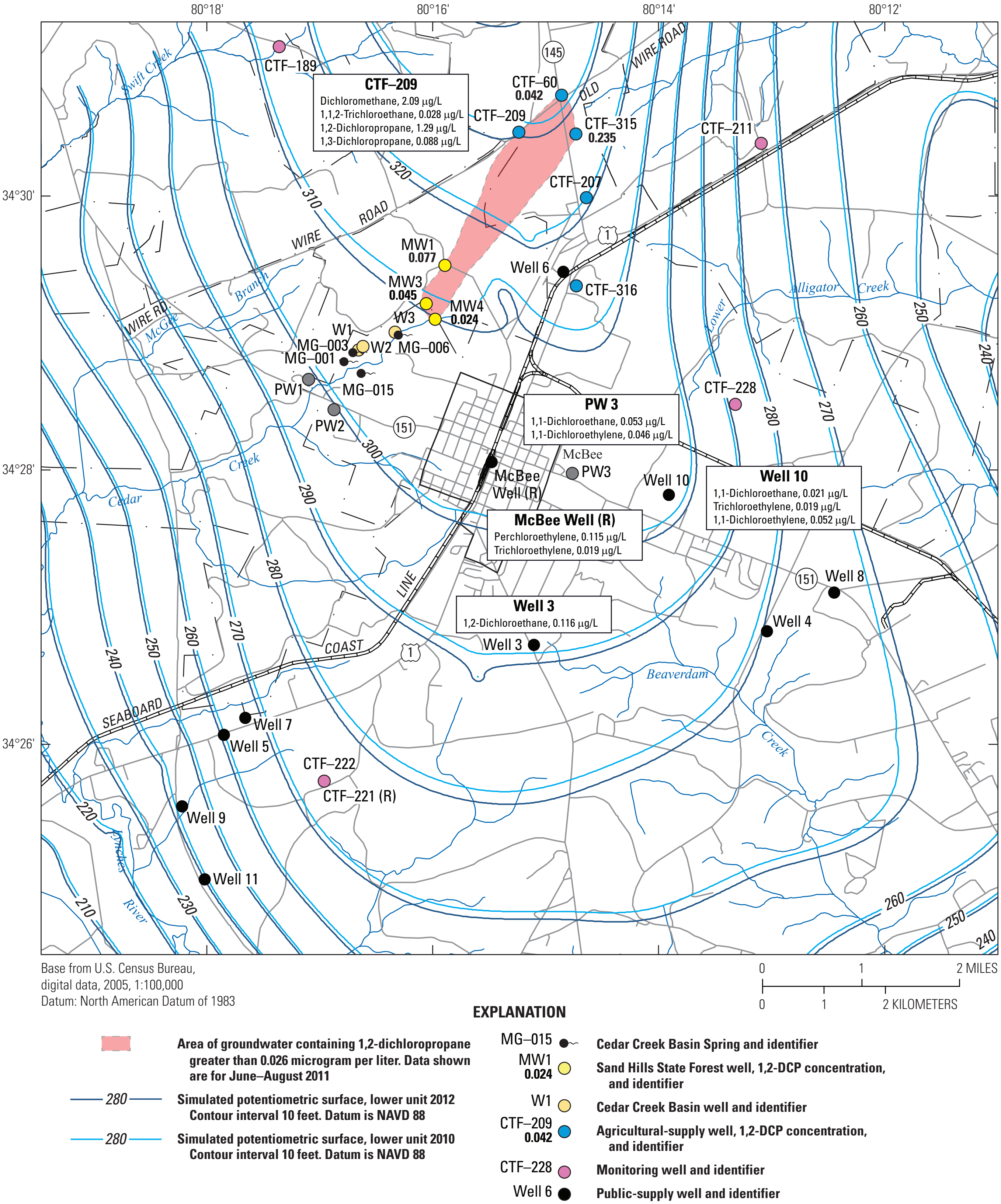


Figure 19. Area of groundwater containing 1,2-dichloropropane and 1,3-dichloropropane greater than 0.026 microgram per liter, between 2010–2012, McBee, South Carolina. Concentrations of other volatile organic compounds detected in groundwater also are shown. The potentiometric surfaces were simulated using the model described in Campbell and Landmeyer (2014). The boundaries of the Carolina Sandhills National Wildlife Refuge and the Sand Hills State Forest are not shown in order to increase the clarity of the plume boundaries.

(table 6; fig. 19); these concentrations are less than the MCL of 5 µg/L. Public-supply Well 3 is located south of McBee, where several older gasoline stations are located. One station was located just south of McBee and may be the source of the 1,2–DCA detected in groundwater from Well 3; this potential source of contamination is described in the section on particle-tracking analysis.

The chlorinated compound 1,1-dichloroethane (1,1–DCA), used as a solvent, degreaser, and fumigant (Zogorski and others, 2006), was detected in groundwater from two wells, public-supply Well 10 and domestic-supply well PW3. Between 2010 and 2012, groundwater from Well 10 had estimated concentrations of 1,1–DCA of 0.042 µg/L, 0.021 µg/L, and 0.150 µg/L. In 2012, 1,1–DCA was also detected in groundwater from nearby domestic-supply well PW3 at a concentration of 0.053 µg/L. The detection of 1,1–DCA in well PW3, most likely screened in the shallow, Crouch Branch aquifer, proximal to Well 10 (fig. 19), which is screened across the deeper McQueen Branch aquifer, indicates a potential common source of 1,1–DCA to both wells. The potential downward transport of 1,1–DCA from the shallow to deeper aquifer, or the existence of separate sources, was evaluated by using particle-tracking simulations, and the results are discussed in the section on particle tracking.

Dichloromethane (DCM), also known as methylene chloride, can dissolve a wide range of organic compounds making it a useful solvent and degreaser (Zogorski and others, 2006), and it has been used to weld certain plastics. In August 2011, DCM was detected in groundwater from agricultural-supply well CTF–209 at a concentration of 2.09 µg/L, which is just less than half the MCL of 5.0 µg/L. The compound 1,1,2-trichloroethane (1,1,2–TCA) also was detected in groundwater from well CTF–209 at 0.028 µg/L during August 2011; however, 1,1,2–TCA was not detected in groundwater from any other well in the McBee area during the study period between 2010 and 2012. Perchloroethylene (PCE), a common solvent and degreaser and used widely as a dry cleaning fluid (Zogorski and others, 2006), was detected at 0.115 µg/L, below the MCL of 5 µg/L, in groundwater from the McBee Well(R) (table 6).

Another commonly used solvent and degreaser, trichloroethylene (TCE), was detected in groundwater from public-supply Well 10, the McBee Well(R), and monitoring well MW3 located in the Sand Hills State Forest (fig. 19). The TCE concentrations in Well 10 were 0.032, 0.019, and 0.101 µg/L, in August of 2010, 2011, and 2012, respectively (table 6). In addition to the detection of PCE already described, TCE was detected at an estimated concentration of 0.019 µg/L in a groundwater sample from the McBee Well(R) during August 2010. Groundwater from monitoring well MW3 had 0.016 µg/L TCE in June 2011. The compound 1,1-dichloroethylene (1,1–DCE) was detected in groundwater from public-supply Well 10 during each sampling event of August 2010, 2011, and 2012, at concentrations of 0.077, 0.052, and 0.367 µg/L, respectively. Also, 1,1–DCE was detected in groundwater from domestic-supply well PW3 located near Well 10 at a concentration of 0.046 µg/L. The compound, 1,1–DCE, was used initially in the manufacture of cling wrap, but is now commonly used as a polymerizer to manufacture fire-retardant fibers, as a coating for steel pipes, and in adhesives (Zogorski and others, 2006). The MCL for 1,1–DCE is 7 µg/L. Although present in groundwater at low concentrations in public-supply Well 10, the concentrations of TCE, 1,1–DCE, and 1,1–DCA all increased over time (fig. 20). It is not known why the concentrations increased, but may be related to a constant source of contaminants, increased pumping of Well 10, or a combination of these factors.

Tetrahydrofuran was detected in groundwater from monitoring wells CTF–189 and CTF–221(R) [replacement well] at concentrations of 3.09 and 0.68 µg/L, respectively, and in groundwater from agricultural-supply well CTF–209 at a concentration of 3.54 µg/L. Tetrahydrofuran is used in PVC adhesives (Zogorski and others, 2006), and leaching of tetrahydrofuran from the PVC-casing and screen construction of CTF–189 and CTF–209 may explain the relatively higher concentrations than those levels detected in CTF–221(R), which was constructed with a PVC screen but had metal casing.

Carbon disulfide (CS_2) was detected above the MRL of 0.04 µg/L in groundwater from three wells and two springs in the McBee area. Carbon disulfide was detected in

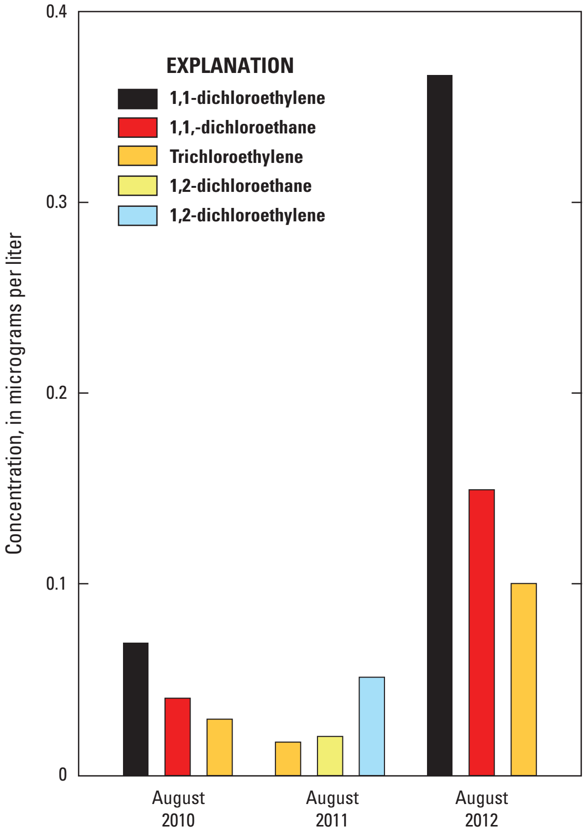


Figure 20. Concentration of 1,1-dichloroethane, 1,1-dichloroethylene, 1,2-dichloroethane, 1,2-dichloroethylene, and trichloroethylene detected in groundwater from public-supply Well 10, 2010–2012.

groundwater from monitoring wells CTF–189, W1, and MW3 at concentrations of 0.020 (estimated), 0.063, and 0.017 µg/L, respectively, and in spring water from springs MG–001 and MG–015 at concentrations of 0.022 and 0.024 µg/L, respectively. The potential source of carbon disulfide to groundwater and springs near McBee is described in the next section.

Other less frequently detected VOCs were found in groundwater in the McBee area: monitoring well CTF–189 had acetone at an estimated concentration of 0.350 µg/L and styrene at an estimated concentration of 0.012 µg/L; monitoring well CTF–211 had an acetone concentration of 5.50 µg/L; monitoring well CTF–228 had a styrene concentration of 0.052 µg/L in August 2012 in the groundwater sample from the deeper screened interval and a styrene concentration of 0.057 µg/L in August 2012 in the groundwater sample from the shallower screened interval. The compound MTBE, used in increasing concentrations in gasoline since the 1970s as an oxygenate (Zogorski and others, 2006), was detected in the McBee Well(R) at an estimated concentration of 0.027 µg/L. Benzene was detected in groundwater from monitoring well CTF–211 (0.16 µg/L during February 2012 and 0.394 µg/L in August 2012) and in the shallow and deep screened intervals of monitoring well CTF–228 (0.012 and 0.015 µg/L, respectively, in August 2012).

Trends in Soil Fumigant Usage

The organic compound carbon disulfide and the halogenated organic compounds 1,2–DCA, 1,1–DCA, 1,2–DCP, 1,3–DCP, EDB, and DBCP were detected in multiple groundwater and spring-water samples collected near McBee between 2010 and 2012 (see previous section and table 6). In addition to the use of EDB and DBCP as soil fumigants as previously described, the principle use of 1,2–DCA, 1,1–DCA, 1,2–DCP, and 1,3–DCP in the United States between the late 1800s and early 1980s was as soil fumigants (Lembright, 1990; fig. 21).

Because these fumigants were not available for use at the same time in the Southeastern United States, a systematic progression exists in the sequential use of these fumigants (fig. 21). Carbon disulfide was one of the first soil fumigants used on a large scale against nematodes (fig. 21), having gained notoriety after its successful use in 1869 to control grape phylloxera when injected into the soil, and has been used as a soil fumigant in the United States since the early 1930s (Newhall, 1955). The use of carbon disulfide declined after the 1940s with the introduction of less flammable, less costly chlorinated compounds, such as 1,2–DCP and 1,3–DCP (an impurity resulting from the production of 1,2–DCP). Thus, EDB and DBCP became popular soil fumigants after the 1950s (Newhall, 1955), until their ban in the early 1980s (fig. 21).

The history of the production and use of soil fumigants in the Southeastern United States appears to be reflected in the distribution and concentrations of these compounds in groundwater and spring-water samples collected in the Cedar Creek Basin near McBee (fig. 22). For example, carbon disulfide, which is the earliest soil fumigant used in the Southeastern United States, was detected only in samples of spring water and groundwater from the discharge area located far downgradient from areas of higher altitudes and agricultural land uses near Wire Road and S.C. Highway 145 North (fig. 22). Discharge areas, such as in Cedar Creek Basin, tend to be characterized by a large contribution of groundwater from long flow pathways that were recharged farther upgradient decades ago. Carbon disulfide was detected in two spring-water samples at concentrations of 0.022 and 0.024 µg/L (table 6), in a groundwater sample from well W1 at 0.063 µg/L, and at 0.017 µg/L in monitoring well MW3, which is upgradient from the two springs and well W1. Groundwater from public-supply Well 6 did not contain carbon disulfide because the use of this compound was most likely discontinued decades prior to the installation and pumping of Well 6 in 2002. No records of the use of carbon disulfide as a soil fumigant in the McBee area exist, so the detection and distribution of carbon disulfide

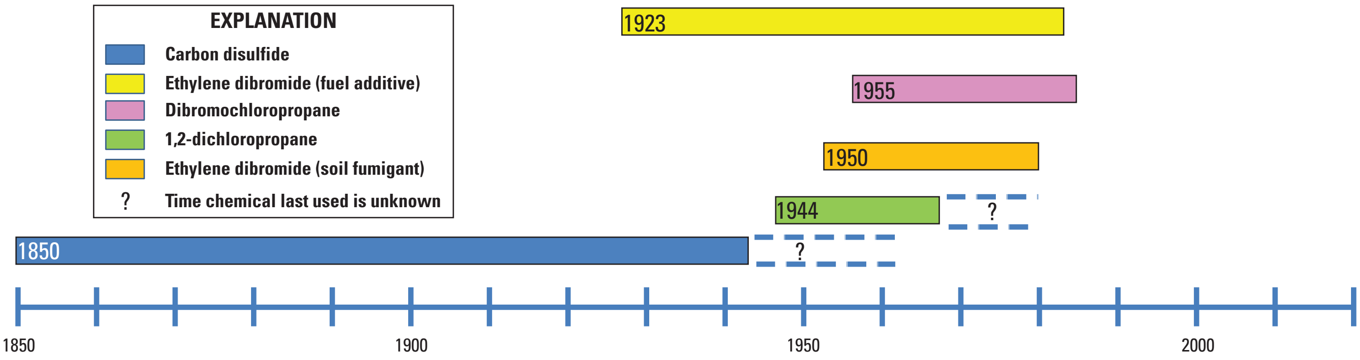


Figure 21. Timeline showing the use of carbon disulfide, ethylene dibromide, dibromochloropropane, and 1,2-dichloropropane as soil fumigants and ethylene dibromide as a fuel additive, 1850–2000.

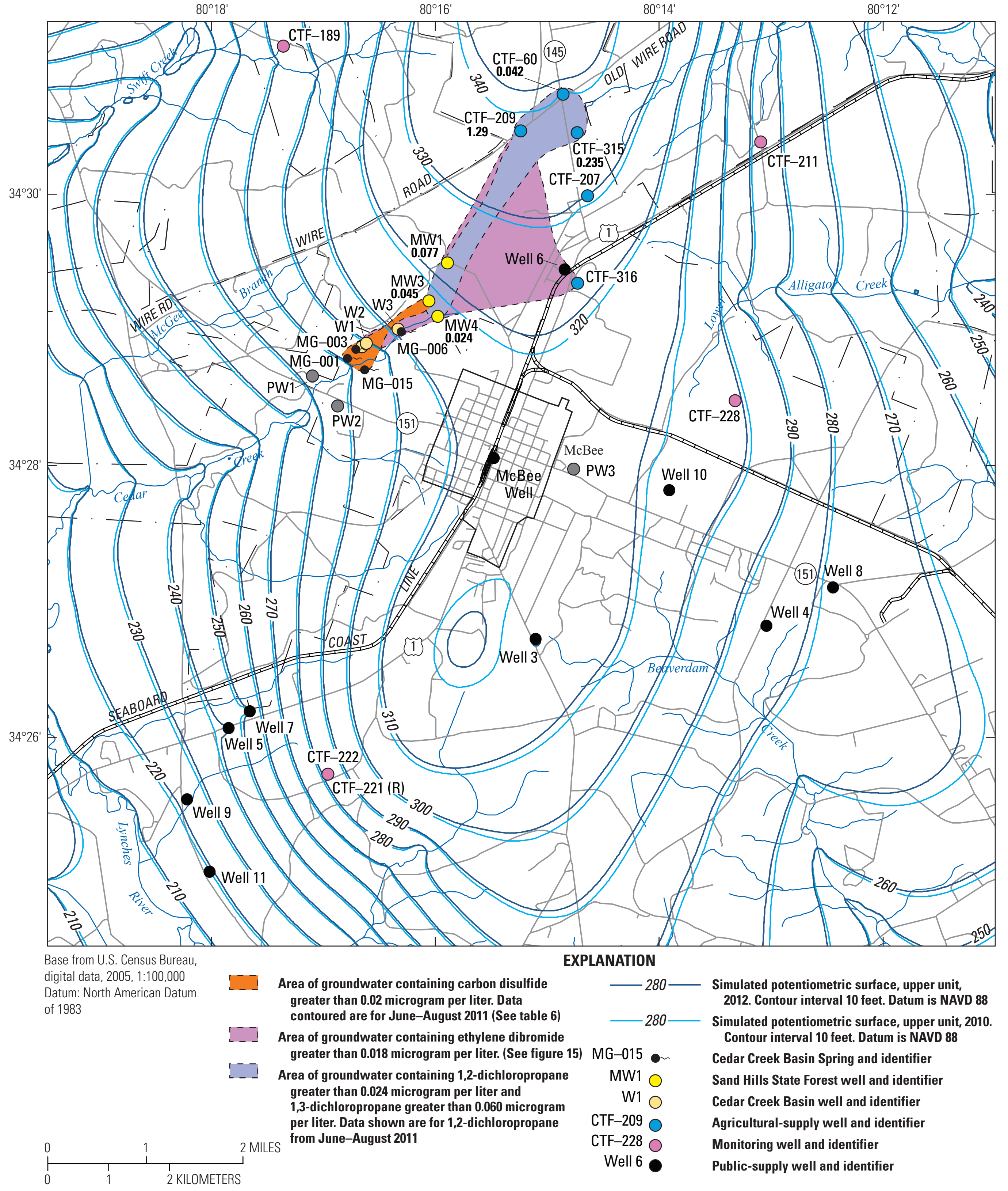


Figure 22. Areas of groundwater and spring water containing carbon disulfide concentrations greater than 0.02 microgram per liter, ethylene dibromide greater than 0.018 microgram per liter, 1,2-dichloropropane greater than 0.024 microgram per liter, and 1,3-dichloropropane greater than 0.060 microgram per liter, between 2010–2012, McBee, South Carolina. The potentiometric surfaces were simulated using the model described in Campbell and Landmeyer (2014). The boundaries of the Carolina Sandhills National Wildlife Refuge and the Sand Hills State Forest are not shown in order to increase the clarity of the plume boundaries.

in groundwater and spring water resulting from use as a soil fumigant cannot be confirmed. Currently (2014), there is no MCL for carbon disulfide. One monitoring well near the headwaters of Swift Creek Basin (CTF–189), adjacent to the Cedar Creek Basin, had an estimated concentration of carbon disulfide at 0.020 µg/L; this estimated detection may indicate that carbon disulfide has been transported from upgradient areas to this particular well. The use of carbon disulfide was most likely replaced by 1,2–DCP or EDB (fig. 21).

As previously described and shown in fig. 15, EDB was detected in groundwater samples from agricultural-supply wells located in the recharge area near Wire Road and in groundwater from monitoring wells located near discharge areas located by springs in Cedar Creek Basin (EDB plume is reproduced in fig. 22). Although the use of carbon disulfide as a soil fumigant preceeded the use of EDB by some 40 years (fig. 21), the co-detection of both soil fumigants in some groundwater samples could be due to either the higher solubility of EDB in water relative to carbon disulfide or the higher sorptive capacity of carbon disulfide on silicate minerals relative to EDB. The co-detection of EDB with 1,2- and 1,3–DCP in groundwater may reflect that EDB became a popular soil fumigant after the 1940s when 1,2–DCP also was being used (fig. 21; Newhall, 1955). The apparent separation of EDB from areas where it was applied, based on the lack of EDB detection in groundwater from agricultural-supply wells CTF–60 and CTF–315 that contained 1,2–DCP, may reflect the 1980s ban on EDB for use as a soil fumigant. The highest concentration of EDB in groundwater was detected in agricultural-supply well CTF–209, indicating that this well may be located close to the area where EDB had been applied for a long period of time, at high rates, or from a point-source leak or spill.

Groundwater samples collected from wells located upgradient from the Cedar Creek Basin springs and from the area of carbon disulfide detection contained 1,2–DCP and 1,3–DCP, but spring-water samples did not (fig. 22). The concentrations of 1,2–DCP ranged from 0.024 to 1.29 µg/L (table 6). The two highest concentrations of 1,2–DCP were detected in groundwater from two agricultural-supply wells (CTF–315 and CTF–209) located in an agricultural area near Wire Road; the lowest concentrations of 1,2–DCP were detected in wells located farther away from this area. Although 1,2–DCP has been used as a solvent and as a paint stripper, its use as a soil fumigant in the McBee area is indicated by co-detection in groundwater from the agricultural-supply well CTF–209 near Wire Road of 1,3–DCP at a concentration of 0.088 µg/L, an impurity often associated with 1,2–DCP. The detection of these compounds in groundwater from three agricultural-supply wells (CTF–209, CTF–60, and CTF–315) in an area that has been used for agriculture since the 1900s most likely reflects the use of 1,2–DCP as a soil fumigant after the mid 1940s, most likely as a replacement for carbon disulfide (Carter, 1943). The lack of detection of 1,2–DCP and 1,3–DCP in Cedar Creek Basin spring-water or nearby groundwater samples may indicate a lack of transport from upgradient source areas. Like carbon disulfide, the extent of 1,2–DCP detection appears to pre-date any pumping at public-supply Well 6.

As previously described and shown (figs. 17 and 18), the detection of DBCP in groundwater in the McBee area is constrained to two primary areas (1) near a recharge area for the upper unit located near Wire Road and S.C. Highway 145 North where carbon disulfide, 1,2–DCP and 1,3–DCP, and EDB had been detected, and (2) south of McBee in the lower unit near public-supply Well 3 (DBCP was detected in groundwater from public-supply Wells 7 and 8, but at lower concentrations). The detection of DBCP in wells near the recharge area near Wire Road and S.C. Highway 145 North ranging from estimated concentrations of 0.031 to 0.893 µg/L and the lack of detection in Cedar Creek Basin spring water may provide some evidence of the sources and time when DBCP was used as a soil fumigant in this area. For example, the DBCP concentration at agricultural-supply well CTF–209 (0.893 µg/L) located north of McBee is similar to the DBCP concentrations detected in Well 3 (0.588 to 0.734 µg/L) located south of McBee. The northern area appears to be the most likely source of DBCP detected in public-supply Well 6, or DBCP was used proximal to that public-supply well. For both cases, DBCP appears to have been transported toward Well 6 under forced hydraulic gradients. The area with the highest concentration of DBCP in groundwater located south of McBee is centered near public-supply Well 3.

To summarize the water-quality results for anthropogenic compounds related to soil fumigation, the ability of groundwater in the Crouch and McQueen Branch aquifers in the McBee area to preserve the record of past use between the early 1900s to the 1980s is relatively unique and made possible because

1. The various chemicals used for soil fumigation were developed at different times and used widely in the United States during unique time periods.
2. Groundwater flow along a flow pathway can be characterized by having the oldest water (longest time since last recharge) near discharge areas such as springs and lakes.
3. Groundwater flow along a flow pathway can be characterized by having the youngest water (shortest time since last recharge) near recharge areas at higher altitudes far from springs.
4. The oxic conditions of groundwater in the McBee area inhibits the bacterial destruction by dechlorination reactions of most of the compounds used for soil fumigation.
5. The McBee study area has a groundwater flow pathway characterized by a recharge area where agricultural activities have occurred since the early 1900s, and a downgradient, discharge area characterized by several springs.
6. The groundwater flow pathway had various monitoring wells that were sampled from recharge area to discharge area.

Naturally Occurring Radium Isotopes and Radon

In contrast to EDB, DBCP, and other VOCs detected in groundwater in the McBee area, the radium isotopes discussed in this section most likely originate from naturally occurring uranium and thorium minerals that compose part of the aquifer sediments through which groundwater flows (Szabo and dePaul, 1998). An additional source of radium isotopes to groundwater in agricultural areas could be the radium present in minerals used in fertilizers applied at land surface.

Radium Isotopes

The radium isotopes ^{226}Ra and ^{228}Ra were detected above MRLs in nearly all wells sampled between 2010 and 2012 in the McBee area (table 7). The average ^{226}Ra and ^{228}Ra concentration was 2.94 pCi/L, below the MCL of 5.0 pCi/L. The average ^{226}Ra concentration was 1.15 pCi/L, and the average ^{228}Ra concentration was slightly higher at 1.80 pCi/L.

Groundwater from six wells had radium isotope concentrations that exceeded the MCL (table 7); two are public-supply wells, one is a domestic-supply well, two are agricultural-supply wells, and one is a monitoring well. Groundwater from public-supply Well 8 had radium isotope concentrations of 7.21 and 6.29 pCi/L, respectively, during 2010 and 2011, and groundwater from public-supply Well 10 had radium isotope concentrations of 4.66, 5.01, and 5.59 pCi/L during 2010, 2011, and 2012, respectively. The highest radium isotope concentration measured in groundwater was for domestic-supply well PW3, which had a radium isotope concentration of 10.72 pCi/L. The agricultural-supply wells CTF–315 and CTF–60 had radium isotope concentrations of 7.39 and 8.30 pCi/L, respectively, in 2011. Groundwater from monitoring well CTF–222(S) had a concentration of 5.07 pCi/L during 2010.

Groundwater from wells with elevated radium concentrations is characterized by high concentrations of dissolved oxygen, whereas the one well in the study area that had low concentrations of dissolved oxygen (monitoring well CTF–211) had relatively low, average radium isotope concentrations of 0.985 pCi/L during sampling events in 2012. This direct relation between dissolved oxygen and radium in groundwater conflicts with the inverse relation between radium isotopes and dissolved oxygen reported for groundwater in the United States by Szabo, dePaul, and others (2012). They report that the geochemical status of groundwater (acidic, anoxic) is more important than lithology in determining the level of radium isotopes in wells installed in the principle aquifers across the Nation. In short, according to Szabo, dePaul, and others (2012), even though there may be an ample mineral source of these radium isotopes in the subsurface, the tendency is for these isotopes to remain adsorbed, especially onto iron and manganese oxides, if conditions are oxic and of neutral pH. Szabo and others (2012) state that, in general, aquifers with low sorptive capacity (limestone, mature sands) and anoxic, acidic groundwater that promotes desorption, correspond to an increased likeliness of elevated radium isotopes in wells. The results of elevated radium isotopes in the acidic, oxic groundwater near McBee, however, do not support that conclusion.

There is a fairly strong positive relation ($r^2 = 0.623$) between elevated radium isotopes and the specific conductance of groundwater in the McBee area (fig. 23). This relation between elevated radium isotopes and specific conductance has been observed in groundwater in the Atlantic Coastal Plain in other states (Szabo, dePaul, and others, 2012) and between elevated individual and radium isotopes and total dissolved solids (Herczeg and others, 1988; Sidhu and Breithart, 1998; Sturchio and others, 2001; Schrag and others, 2010). Conversely, Denham and others (2005) and Vengosh and others (2009) observed no positive relation between elevated individual and radium isotopes and specific conductance of groundwater in the Atlantic Coastal Plain.

In the McBee area, where ambient groundwater is characterized by dilute, low values of specific conductance (table 4), even small increases in specific conductance are notable and warrant assessment into the source of the increase. In general, elevated specific conductance values are detected in water samples (1) from wells located within or near areas that have agricultural land uses, such as along S.C. Highway 145 North as well as along S.C. Highway 151 West, (2) from wells located along S.C. Highway 151 East in urban to suburban areas that area characterized by domestic or industrial septic systems and drain fields, and (3) in a spring (MG–006) sampled in the Cedar Creek Basin (fig. 24).

The range of specific conductance measurements (12 to 42 µS/cm) in the spring-water samples from the Cedar Creek Basin was unexpected. The detection of above-average concentrations of specific conductance in these springs may be related to the co-occurrence of carbon disulfide. The elevated specific conductance of the spring-water samples may indicate the movement of carbon disulfide, as well as other agricultural chemicals such as fertilizers, from agricultural areas through the groundwater system to the springs. Agricultural fertilizers or lime can contain trace elements, such as nitrogen-phosphorus and potassium, that would tend to be sources of solutes that can increase the specific conductance of groundwater. Szabo and others (1997) and Szabo and dePaul (1998) reported that a higher percentage of wells located in agricultural areas contained higher concentrations of radium isotopes than wells not located in land used for agriculture. The elevated specific conductance in groundwater could be derived from leachate to groundwater of potassium chloride-type fertilizers (Szabo and others, 1997) rather than aquifer sediment weathering reactions. At this time, it is not possible to determine if the elevated specific conductance measured in groundwater samples from the public-supply wells (McBee Well(R), Well 3, Well 10, and Well 8) is from upgradient sources of specific conductance that have moved toward these wells or from the input of specific conductance from more localized sources. These hypotheses are tested and discussed in the particle-tracking analysis section of the report.

Table 7. Concentrations of radium-226 and radium-228 in groundwater samples, McBee, South Carolina, 2010–2012.

[ID, identification; n, unique county-well number; R, replacement well; USGS, U.S. Geological Survey; pCi/L, picocuries per liter; —, no data available; MCL, maximum contaminant level; MRL, minimum reporting level; values in boldface exceed the MCL; concentrations are in picocuries per liter]

Well ID	County number, CTF-n	USGS site ID	Sample date	Sample time	Radium-226 (^{226}Ra)	Radium-228 (^{228}Ra)	Radium-226 + Radium-228 (^{226}Ra + ^{228}Ra)	Radium-228/Radium-226 (^{228}Ra/^{226}Ra)
MRL					0.10	1.00	—	—
MCL					—	—	5.00	—
2010								
Public-supply wells								
Well 3	CTF–83	342642080150709	August 4, 2010	14:47	0.52	0.61	1.13	1.17
Well 4	CTF–88	342652080130109	August 4, 2010	12:17	1.45	2.14	3.59	1.48
Well 5	CTF–89	342559080180509	July 29, 2010	15:50	0.69	1.17	1.86	1.71
Well 6	CTF–106	342929080145009	July 29, 2010	13:10	0.49	0.54	1.03	1.11
Well 7	CTF–107	342711080174909	August 3, 2010	12:50	0.71	0.92	1.63	1.30
Well 8	CTF–108	342707080122909	August 4, 2010	13:48	2.56	4.65	**7.21**	1.82
Well 9	CTF–198	342532080181309	August 3, 2010	10:18	0.48	1.07	1.55	2.23
Well 10	CTF–219	342749080135509	August 4, 2010	11:17	2.14	2.52	4.66	1.18
McBee well(R)	CTF–179	342803080152900	August 3, 2010	15:10	1.49	1.92	3.41	1.29
Monitoring wells								
CTF–222(S)	CTF–222	342543080165800	August 18, 2010	11:35	1.77	3.30	**5.07**	1.86
CTF–221(D)	CTF–221	342543080165801	August 18, 2010	—	—	—	—	—
CTF–189	CTF–189	343105080172100	August 30, 2010	13:15	0.29	0.34	0.64	1.17
2011								
Monitoring wells								
CTF–228(S)	CTF–228	342828080131900	June 14, 2011	13:50	1.07	1.98	3.05	1.85
CTF–228(D)	CTF–228	342828080131900	June 20, 2011	13:01	0.88	2.44	3.32	2.77
Public-supply wells								
Well 3	CTF–83	342642080150709	August 23, 2011	13:00	0.26	0.28	0.54	1.09
Well 3	CTF–83	342642080150709	August 23, 2011	13:20	0.35	0.00	0.35	—
Well 4	CTF–88	342652080130109	August 23, 2011	12:30	1.14	2.02	3.16	1.77
Well 5	CTF–89	342559080180509	August 24, 2011	11:57	1.56	1.04	2.60	0.67
Well 6	CTF–106	342929080145009	August 23, 2011	14:40	0.48	0.55	1.03	1.14
Well 7	CTF–107	342711080174909	August 24, 2011	12:11	0.65	1.47	2.12	2.26
Well 8	CTF–108	342707080122909	August 23, 2011	11:01	2.30	3.80	**6.10**	1.65
Well 8	CTF–108	342707080122909	August 23, 2011	11:30	2.46	3.83	**6.29**	1.56
Well 9	CTF–198	342532080181309	August 24, 2011	11:31	0.47	1.05	1.06	2.22
Well 10	CTF–219	342749080135509	August 23, 2011	14:00	1.99	3.02	**5.01**	1.52
Agricultural-supply wells								
CTF–60	CTF–60	343044080145200	August 23, 2011	15:00	3.30	5.02	**8.30**	1.52
CTF–315	CTF–315	343027080144400	August 24, 2011	15:00	3.01	4.38	**7.39**	1.46
CTF–316	CTF–316	342920080144300	August 25, 2011	14:25	0.93	1.13	2.06	1.21
CTF–209	CTF–209	343027080151400	August 25, 2011	12:22	1.07	1.29	2.36	1.21
CTF–207	CTF–207	342954080143900	August 25, 2011	12:55	—	—	—	—

Table 7. Concentrations of radium-226 and radium-228 in groundwater samples, McBee, South Carolina, 2010–2012.—Continued

[ID, identification; n, unique county-well number; R, replacement well; USGS, U.S. Geological Survey; pCi/L, picocuries per liter; —, no data available; MCL, maximum contaminant level; MRL, minimum reporting level; values in boldface exceed the MCL; concentrations are in picocuries per liter]

Well ID	County number, CTF-n	USGS site ID	Sample date	Sample time	Radium-226 (^{226}Ra)	Radium-228 (^{228}Ra)	Radium-226 + Radium-228 (^{226}Ra + ^{228}Ra)	Radium-228/Radium-226 (^{228}Ra/^{226}Ra)
MRL					0.10	1.00	—	—
MCL					—	—	5.00	—
				2012				
				Public-supply wells				
Well 11	CTF–313	342500080180200	February 8, 2012	13:45	0.26	0.75	1.01	2.85
Well 6	CTF–106	342929080145009	August 14, 2012	11:11	0.47	0.68	1.16	1.44
Well 6	CTF–106	342929080145009	August 14, 2012	11:25	0.43	0.59	1.02	1.37
Well 10	CTF–219	342749080135509	August 14, 2012	13:45	1.97	3.62	**5.59**	1.84
				Monitoring wells				
CTF–228(S)	CTF–228	342828080131900	February 8, 2012	16:25	0.70	1.39	2.09	1.99
CTF–228(D)	CTF–228	342828080131900	February 23, 2012	13:30	2.08	2.81	4.89	1.35
CTF–221(R)	CTF–221	342543080165801	February 9, 2012	11:50	0.16	0.40	0.56	2.58
CTF–211	CTF–211	343023080130600	February 9, 2012	14:25	0.63	0.18	0.81	0.29
				Domestic-supply wells				
PW1	CTF–317	342839080170601	August 14, 2012	15:44	0.21	0.37	0.59	1.74
PW2	CTF–318	342826080165201	August 14, 2012	16:30	1.53	2.42	3.99	1.58
PW3	CTF–319	342758080144601	August 15, 2012	11:06	3.92	6.80	**10.72**	1.73
				Monitoring wells				
CTF–228(D)	CTF–228	342828080131900	August 15, 2012	16:11	0.66	0.95	1.61	1.44
CTF–228(S)	CTF–228	342828080131900	August 15, 2012	16:45	0.54	1.53	2.07	2.83
CTF–211	CTF–211	343023080130600	August 15, 2012	19:40	0.59	0.57	1.16	0.97

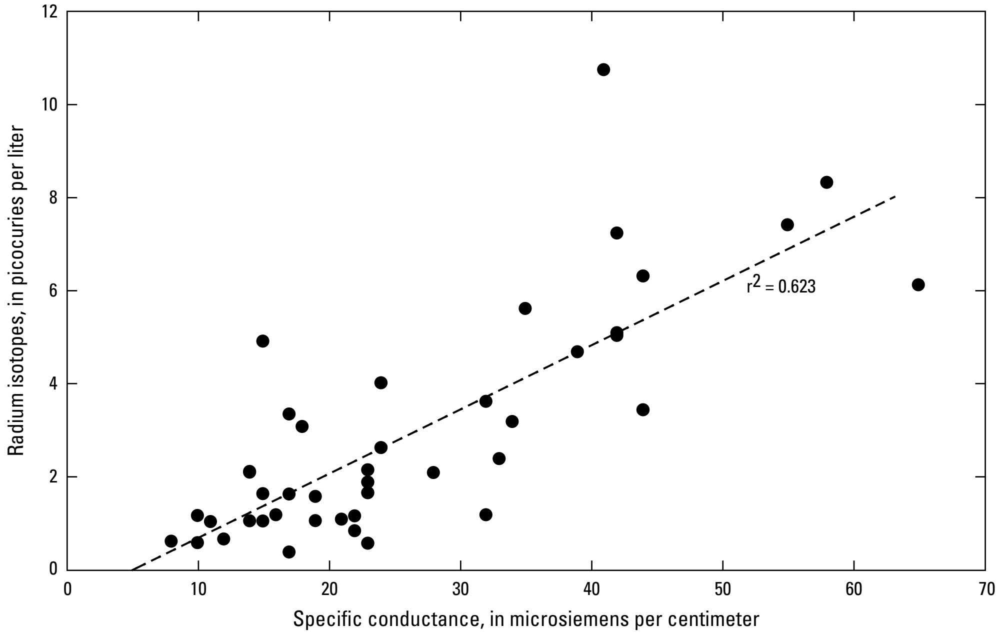


Figure 23. Relation between specific conductance and the concentration of radium isotopes in groundwater, McBee, South Carolina, 2010–2012.

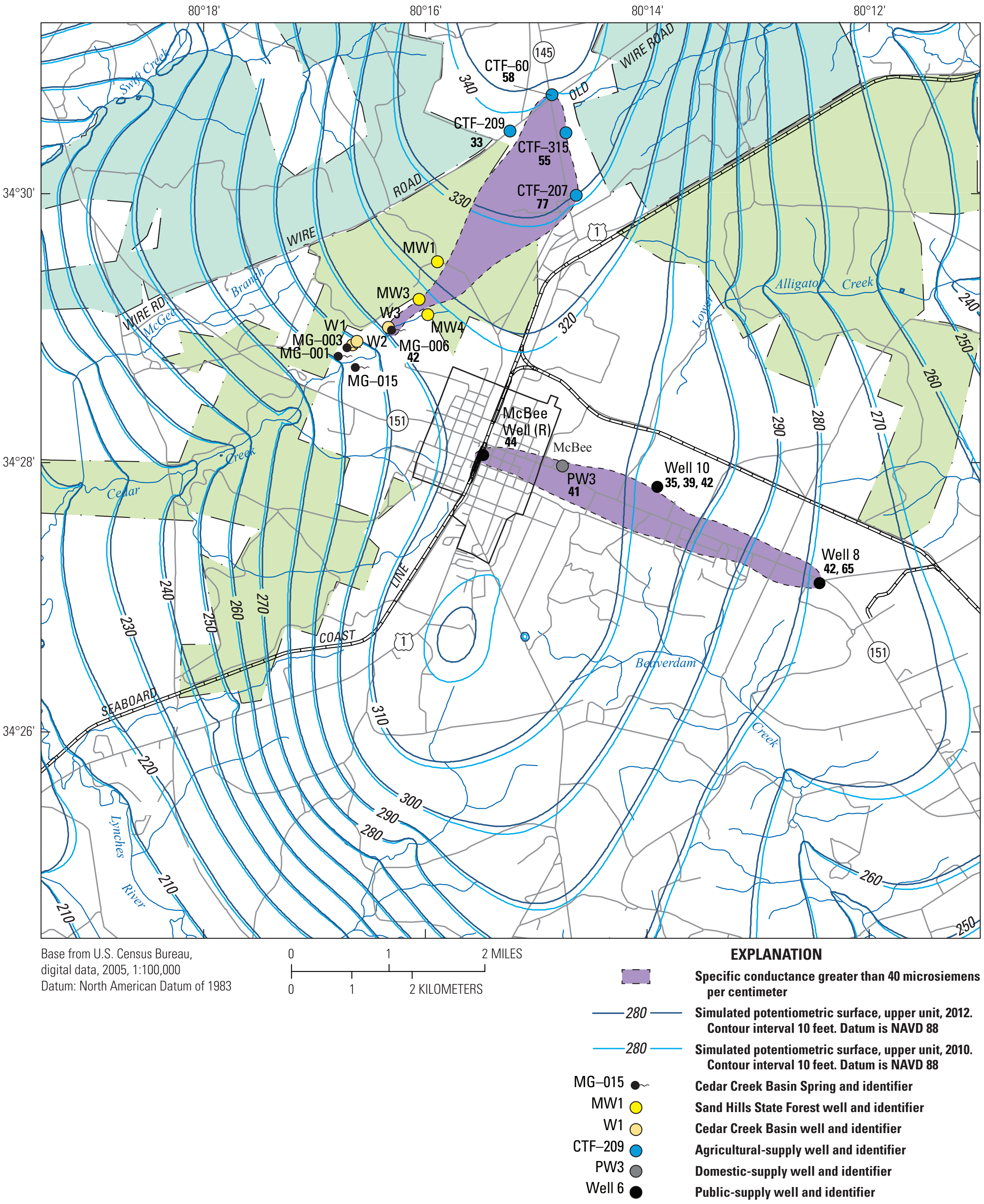


Figure 24. Areas of groundwater and spring water containing specific conductance greater than 40 microsiemens per centimeter, McBee, South Carolina, 2010–2012. The area of high specific conductance north of McBee is located in the upper unit; the area east of McBee is located in the upper and lower units. The potentiometric surfaces were simulated using the model described in Campbell and Landmeyer (2014).

There is a strong relation ($r^2 = 0.913$) between ^{226}Ra and ^{228}Ra isotopes in groundwater in the McBee area (fig. 25). A similar linear relation ($r^2 = 0.83$) was observed for 182 wells sampled in South Carolina and reported in King and others (1982). The relation, however, indicates that concentrations of ^{228}Ra are generally higher than would be expected if the processes that control radium release into water occurred in a 1:1 relation between ^{228}Ra and ^{226}Ra (fig. 25). Cecil and others (1987) reported that ^{228}Ra was higher in groundwater than ^{226}Ra, but they did not offer an explanation as to why. Because thorium is not soluble and ^{228}Ra has a much shorter half-life (5.75 years) than ^{226}Ra (1,601 years), the observed enrichment of ^{228}Ra relative to ^{226}Ra indicates a source of thorium local to the area.

A source of thorium near a well that could explain the higher concentrations of ^{228}Ra in a given water sample is indicated by the ratio of concentrations of ^{228}Ra to ^{226}Ra that exceed 1. The average ratio for all groundwater samples collected between 2010 and 2012 was 1.61 (table 7), which indicates that thorium and uranium are not present in equal proportions and that a nearby source of thorium exists. In contrast, groundwater samples collected in the New Jersey part of the Atlantic Coastal Plain were characterized by ratios near 1.0, which was interpreted by Szabo and dePaul (1998) as being an indication that both ^{228}Ra and ^{226}Ra were derived from aquifer sands. Heron and Johnson (1969) reported that the sediments of the Atlantic Coastal Plain, and specifically those in Chesterfield County, S.C., are characterized by low radioactivity.

The hypothesis of a local, constant source of thorium to well water also affected by high specific conductance was examined in the wells that were sampled multiple times between 2010 and 2012. The results are discussed in terms of groundwater samples collected from monitoring wells and public-supply wells. Monitoring well CTF–211 was sampled twice, in February and August 2012, during which the concentrations of ^{226}Ra and ^{228}Ra were consistently low, each less than 1 pCi/L (fig. 26*A*). Monitoring well CTF–228(S) was sampled three times between 2011 and 2012, during which the concentration of ^{228}Ra in groundwater was consistently higher than the concentration of ^{226}Ra (fig. 26*B*). Monitoring well CTF–228(D) also was sampled three times between 2011 and 2012, during which the concentration of ^{228}Ra in groundwater also was consistently higher than the concentration of ^{226}Ra (fig. 26*C*). The relatively consistent individual radium isotope concentrations over time in individual wells confirm similar results of King and others (1982), who suggest the consistency can be explained in terms of the long-term stability of a source of the isotopes to each water well.

Public-supply wells also had trends in radium concentrations over time. Well 3 was sampled twice, in August 2010 and August 2011, during which the concentrations of ^{226}Ra and ^{228}Ra in groundwater were consistently low, each less than 1 pCi/L (fig. 27*A*); this well had not been pumped much since installation of a GAC system. Public-supply Well 4 had been sampled multiple times by DHEC personnel since 2008 and for this study the concentration of ^{228}Ra was higher than the concentration of ^{226}Ra for most sampling events between 2010 and 2011 (fig. 27*B*). Public-supply Well 5 had been sampled multiple times by DHEC and for this study; up until 2011 the concentration of ^{228}Ra was higher than the concentration of ^{226}Ra, until this trend reversed in 2011, and both radium isotopes were less than 2 pCi/L (fig. 27*C*). In groundwater samples from public-supply Well 6, the concentration of ^{228}Ra was slightly higher than the concentration of ^{226}Ra, and both radium isotopes were less than 1 pCi/L (fig. 27*D*); earlier radium isotope data collected by DHEC are not shown because the samples were collected after the water had been filtered through the GAC system. Public-supply Well 7 had been sampled multiple times by DHEC personnel since 2008, and concentrations of both isotopes were less than 2 pCi/L through 2011 (fig. 27*E*). Public-supply Well 8 had been sampled multiple times by DHEC personnel since 2008 and concentrations of ^{228}Ra were higher than the concentration of ^{226}Ra for all sampling events

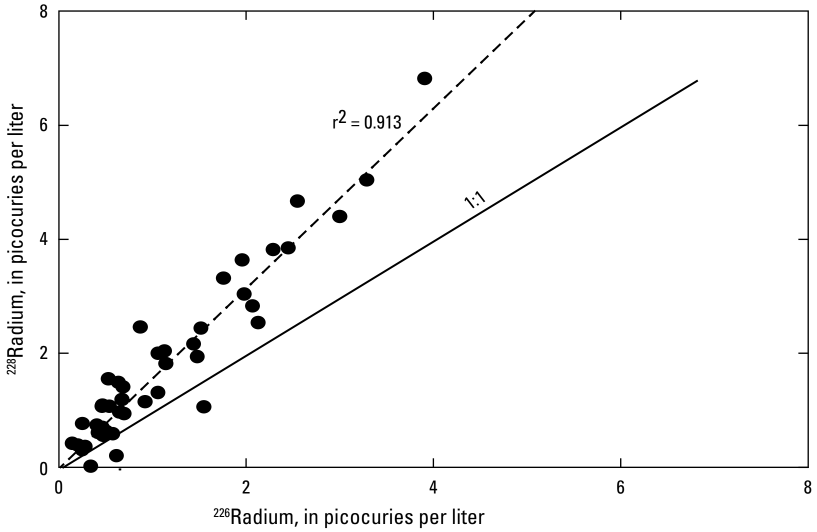


Figure 25. Relation between concentrations of radium-226 and radium-228 in groundwater, McBee, South Carolina, 2010–2012.

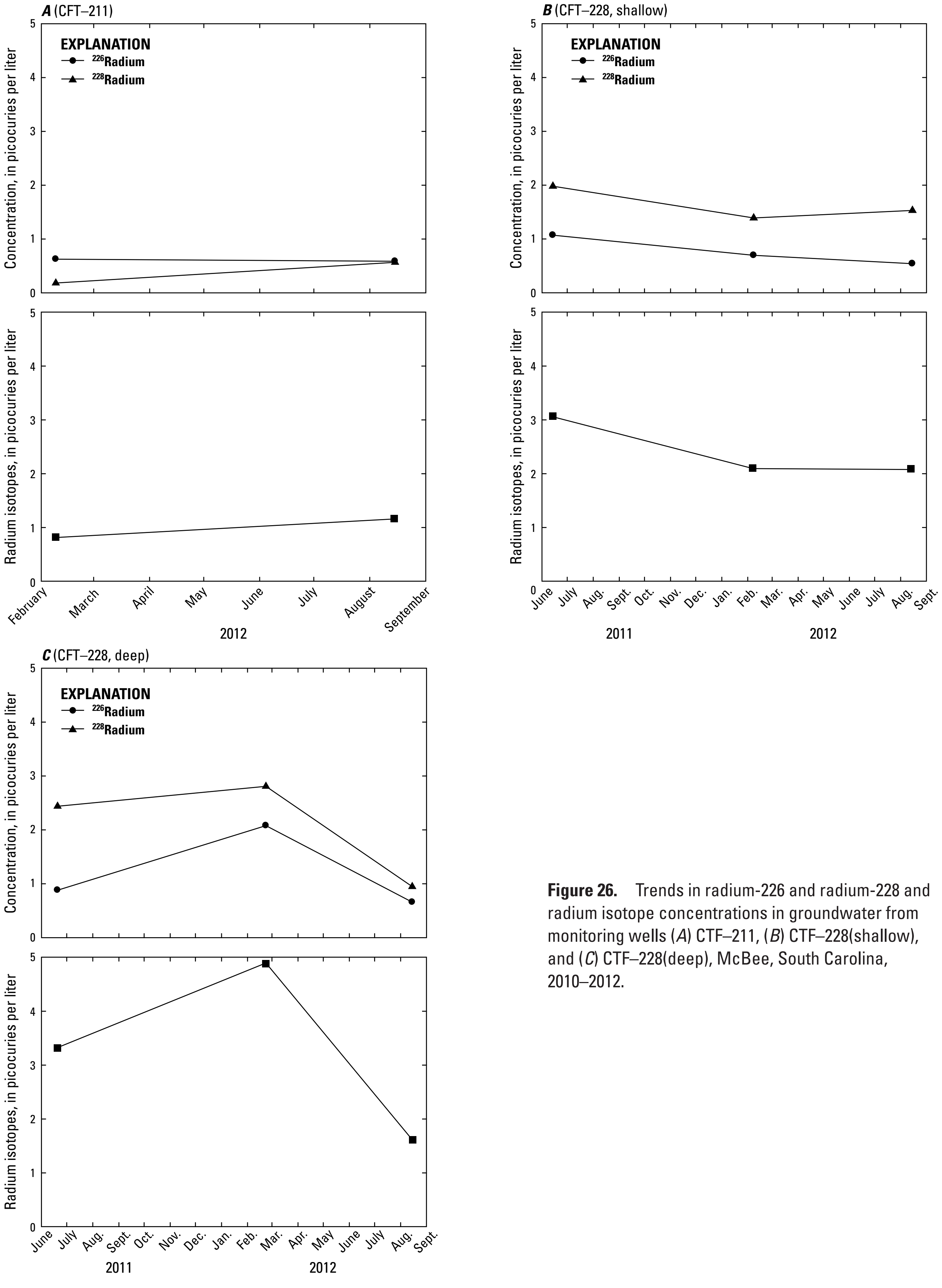


Figure 26. Trends in radium-226 and radium-228 and radium isotope concentrations in groundwater from monitoring wells (*A*) CTF–211, (*B*) CTF–228(shallow), and (*C*) CTF–228(deep), McBee, South Carolina, 2010–2012.

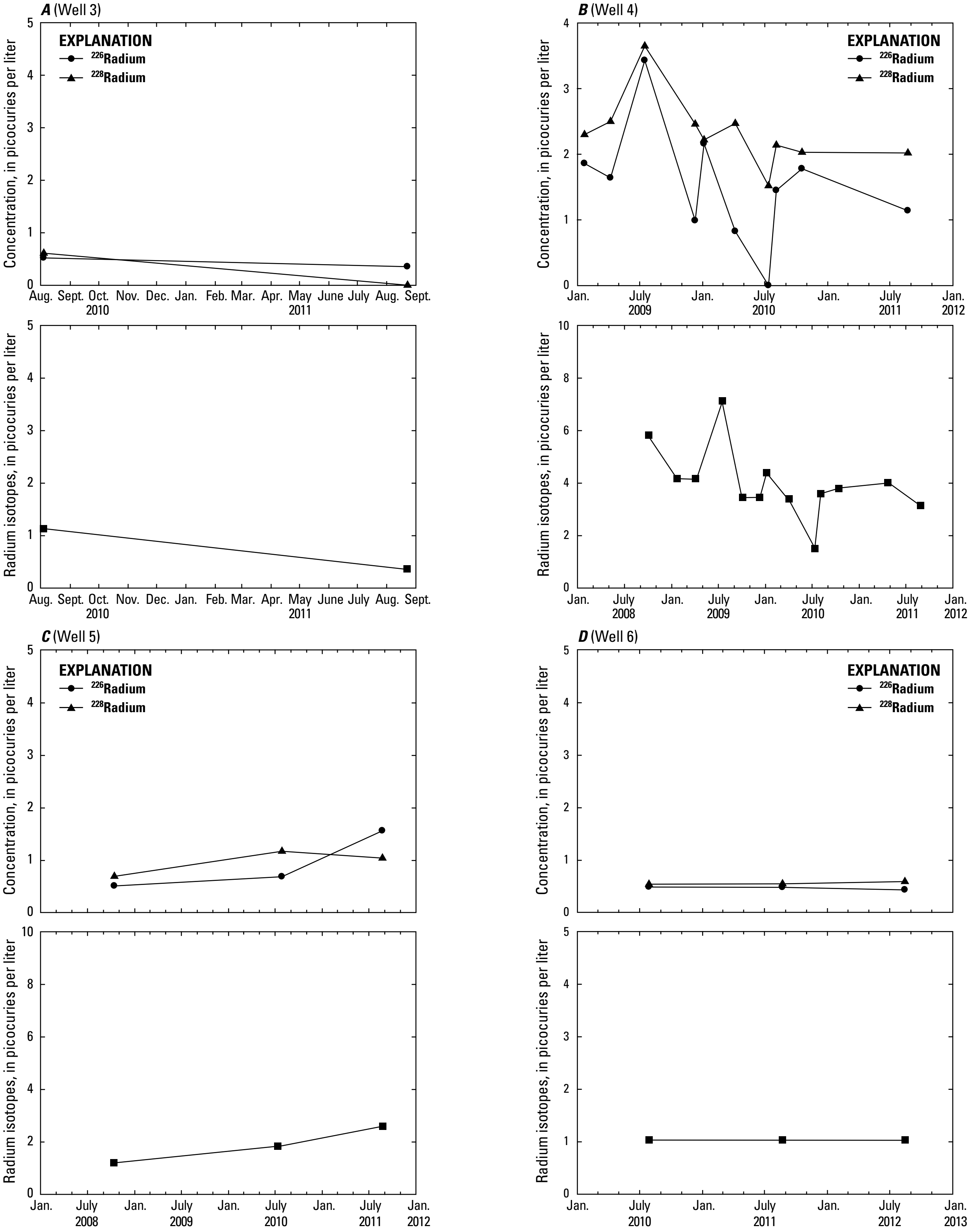


Figure 27. Trends in radium-226 and radium-228 and radium isotope concentrations in groundwater from public-supply (*A*) Well 3, (*B*) Well 4, (*C*) Well 5, (*D*) Well 6, (*E*) Well 7, (*F*) Well 8, (*G*) Well 9, and (*H*) Well 10, McBee, South Carolina, 2010–2012. Data collected by S.C. Department of Health and Environmental Control officials before 2010 are shown for those groundwater samples of raw water.

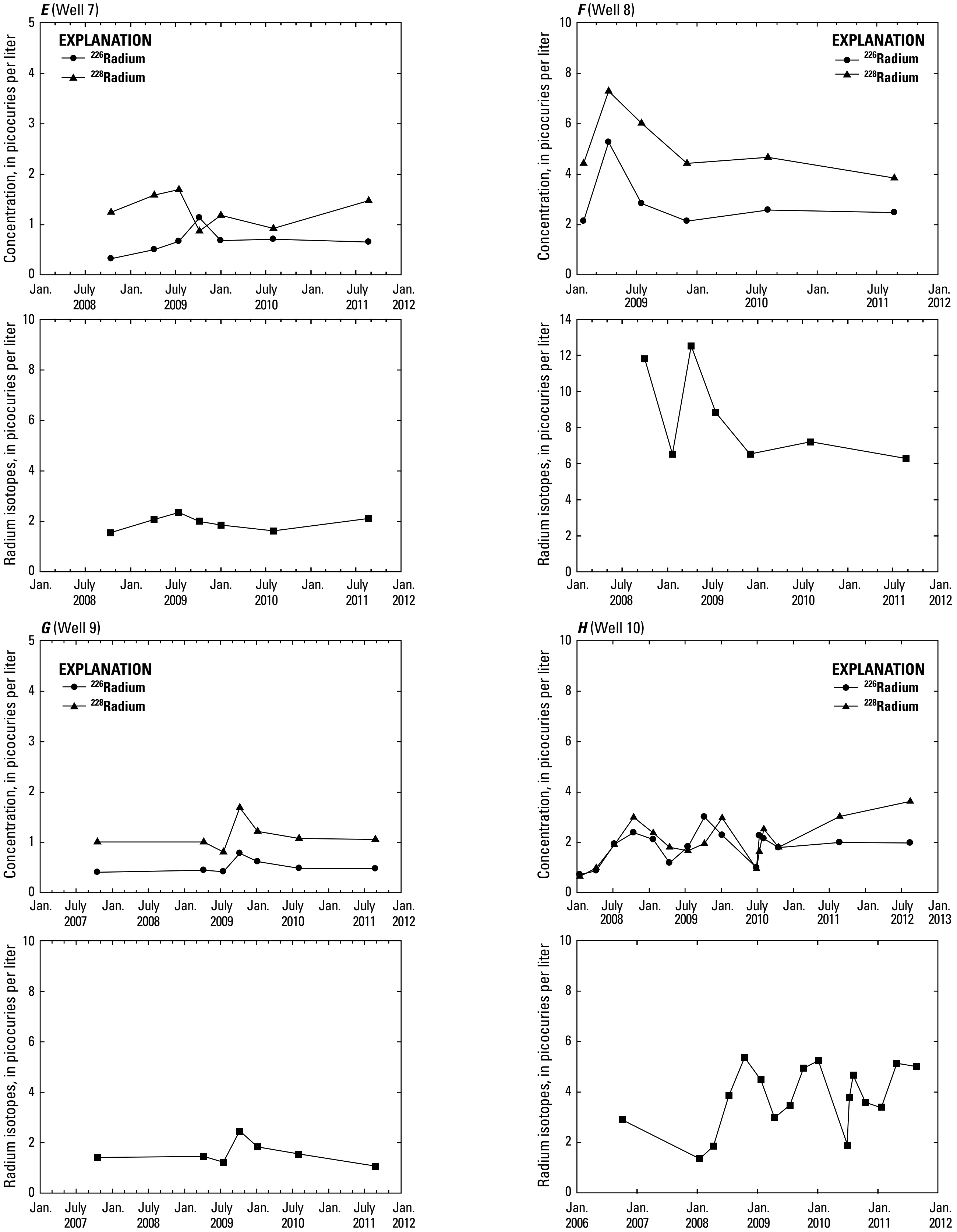


Figure 27. Trends in radium-226 and radium-228 and radium isotope concentrations in groundwater from public-supply (*A*) Well 3, (*B*) Well 4, (*C*) Well 5, (*D*) Well 6, (*E*) Well 7, (*F*) Well 8, (*G*) Well 9, and (*H*) Well 10, McBee, South Carolina, 2010–2012. Data collected by S.C. Department of Health and Environmental Control officials before 2010 are shown for those groundwater samples of raw water.—Continued

(fig. 27*F*). Public-supply Well 9 had been sampled multiple times by DHEC personnel since 2007 and the concentration of ^{228}Ra was consistently higher than the concentration of ^{226}Ra, and both measurements were less than 2 pCi/L (fig. 27*G*). Public-supply Well 10 had been sampled multiple times by DHEC personnel since 2006 and the concentration of ^{228}Ra was higher than the concentration of ^{226}Ra for most sampling events between 2010 and 2012 (fig. 27*H*). An increase is noted in both radium isotopes in the winter (October–November) of 2008–2010; whether this is true of only this well and not others cannot be determined, because a greater quantity of water-quality data were collected from public-supply Well 10.

Denham and others (2005) examined intermittent elevated levels of radium isotopes near a site on the Savannah River in the Atlantic Coastal Plain of South Carolina. They acknowledged that the dissolution of radium from aquifer minerals and alpha recoil would tend to occur consistently and produce consistent concentrations, which would explain the occurrence of elevated radium isotopes in wells. They were, however, most interested in why concentrations in some wells changed over time, especially since the intermittent values could not be attributed to sampling error. Their results pointed to the desorption of radium from hematite-coated sand grains when the groundwater pH was less than 5.8, with the low pH resulting from increased partial pressure of carbon dioxide.

The lowest concentrations of radium isotopes were detected in wells with screens completed at the lowest altitudes, and the highest concentrations of radium isotopes were detected in wells with screens completed at the highest altitudes, but the relation for all wells is weak (fig. 28*A*). Also, the lowest concentrations of radium isotopes were detected in the shallowest well drilled, and the highest concentrations of

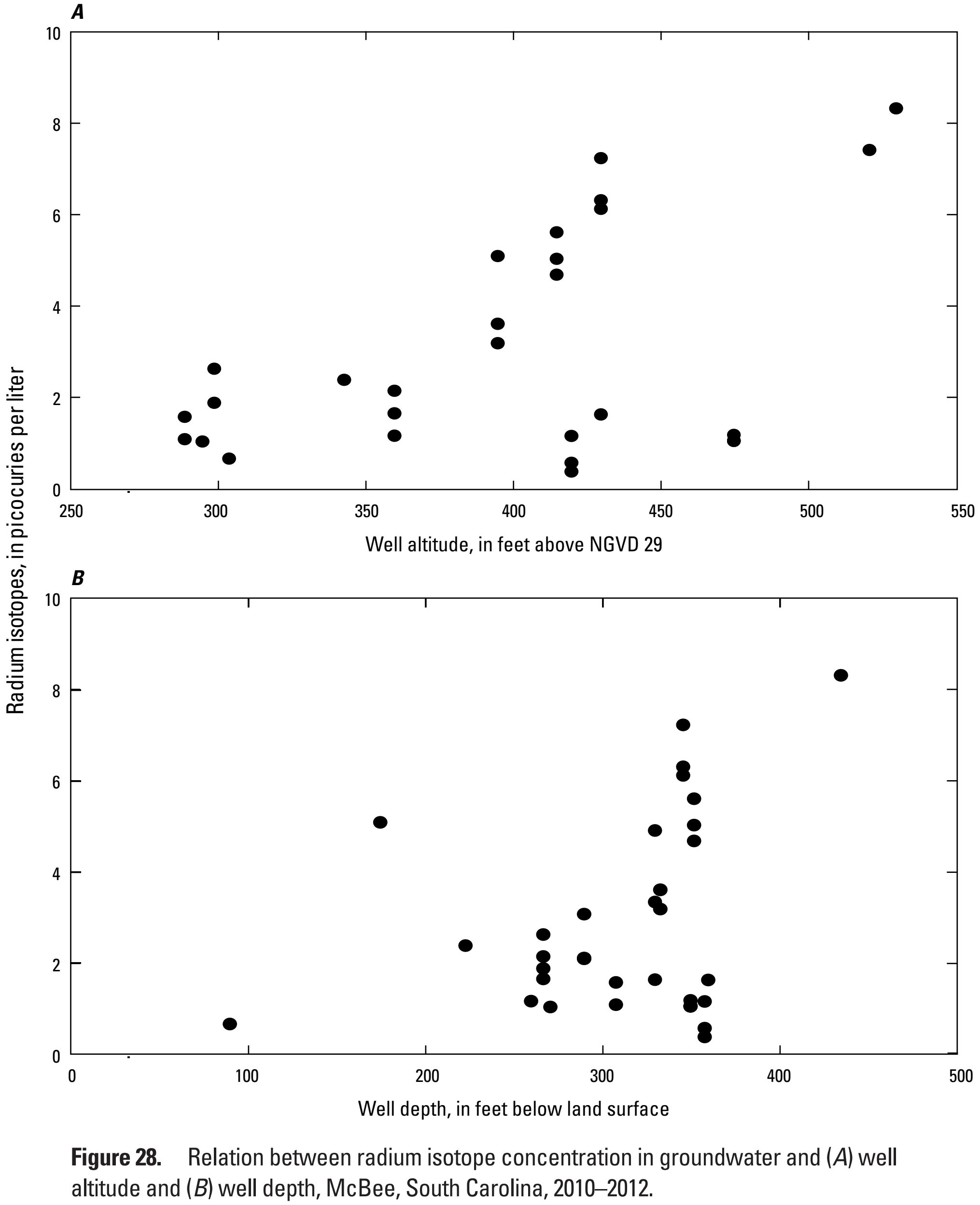


Figure 28. Relation between radium isotope concentration in groundwater and (*A*) well altitude and (*B*) well depth, McBee, South Carolina, 2010–2012.

radium isotopes were detected in the deepest well drilled, but the relation for all wells is weak (fig. 28*B*). In contrast, Szabo and dePaul (1998) reported an inverse relation between radium isotopes and well depth in the New Jersey part of the Atlantic Coastal Plain. The median depth of wells sampled in that study, however, was no greater than 93 ft below land surface. Moreover, they explained the low concentrations of radium isotopes in these deep wells as a result of the presence of old groundwater that predated the agricultural land uses in the area (Szabo and dePaul, 1998).

The highest concentrations of radium isotopes were detected in wells that had the lowest pH (fig. 29). Szabo and dePaul (1998) also observed a similar relation and may indicate weathering of radium from mineral sources. Kubilius (2007) reported that elevated ^{226}Ra in groundwater from the Atlantic Coastal Plain of South Carolina was due to the oxidation of sedimentary iron sulfides where oxic groundwater came into contact with anoxic, sulfate-reducing groundwater.

A possible non-localized mineral source of radium isotopes, especially ^{226}Ra, could be various non-fumigant chemicals used by the agricultural industry. Lime, as calcium hydroxide (CaOH), is derived from dolomite, and carbonate minerals can co-precipitate uranium relative to thorium. Thorium concentrations in groundwater were not measured, but if lime was the source of elevated radium isotopes in the McBee area, then ^{226}Ra would be elevated over ^{228}Ra; this scenario was not observed. Fertilizers commonly applied at land surface typically are phosphate-based formulations, and the source of the phosphate typically is clay deposits of a marine origin that also contain abundant uranium (Barišić and others, 1992).

Radon

Radon was detected in all groundwater samples collected from August 2011 to August 2012 in the McBee area (table 8). The radon concentrations ranged from 63.5 to 325 pCi/L. The average radon concentration was 200 pCi/L. Three wells had concentrations of radon that exceed the proposed MCL of 300 pCi/L for radon (table 8). A USGS study during 1995–1998 reported radon concentrations greater than 300 pCi/L in 47 percent of wells sampled in the Sandhills physiographic province located west of McBee in the adjacent Santee River Basin (Hughes and others, 2000). These high radon concentrations are among the highest measured in the Nation (Hughes and others, 2000), and the high concentrations are attributed primarily to the presence of crystalline rocks in the Piedmont of North and South Carolina. In the McBee study area, groundwater from monitoring well CTF–228 had radon levels above the proposed MCL in samples collected from the shallow screened interval (325 and 300 pCi/L for February 8, 2012, and August 15, 2012, respectively) and the deep screened interval (303 pCi/L for August 15, 2012).

The concentrations of radon measured in groundwater are considerably higher, by 2 to 3 orders of magnitude, than the concentrations of its parent, ^{226}Ra (table 8). This situation can exist only if there is an abundant source of ^{226}Ra in solid phases of the subsurface with greater ^{226}Ra concentrations than in the groundwater. Measurement of the ^{226}Ra, ^{228}Ra, uranium, or thorium content of the aquifer material beneath McBee was beyond the scope of the study.

Radon concentration showed a slight positive relation to the altitude and age of the well (fig. 30*A* and 30*B*), where age of the well is defined as the time elapsed since installation.

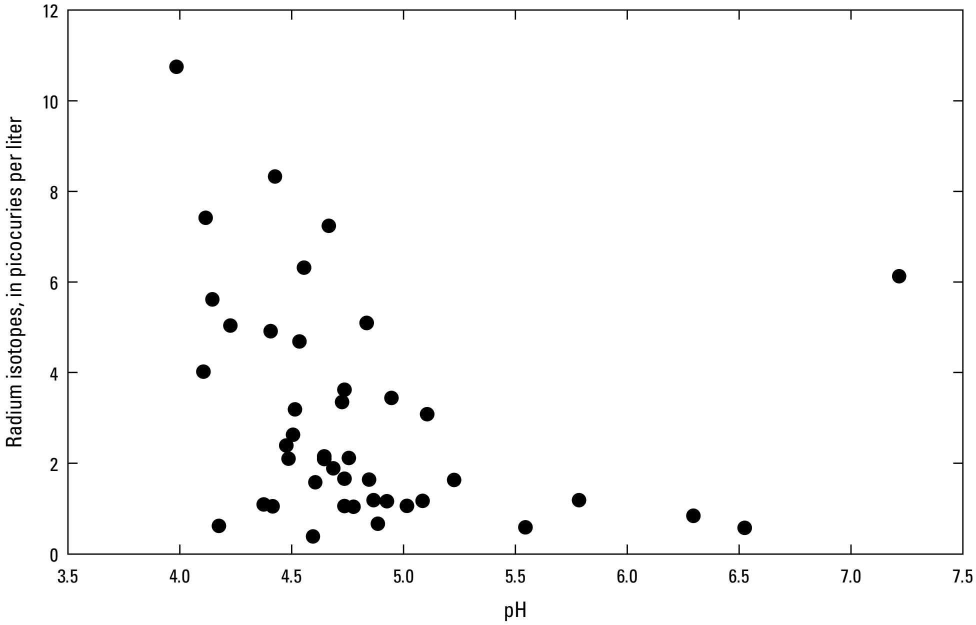


Figure 29. Relation between radium isotope concentration in groundwater and pH, McBee, South Carolina, 2010–2012.

Table 8. Concentrations of radon measured in groundwater samples, McBee, South Carolina, 2011–2012.

[ID, identification; n, unique county-well number; USGS, U.S. Geological Survey; pCi/L, picocuries per liter; MCL, maximum contaminant level; MRL, minimum reporting level; values in boldface exceed the proposed MCL; concentrations are in picocuries per liter]

Well ID	County number, CTF-n	USGS Site ID	Sample date	Sample time	Radon-222 (^{222}Rn)
Proposed MCL					300
MRL					20
2011					
Public-supply wells					
Well 3	CTF–83	342642080150709	August 26, 2011	13:00	254
Well 3	CTF–83	342642080150709	August 23, 2011	13:20	189
Well 4	CTF–88	342652080130109	August 23, 2011	12:30	206
Well 5	CTF–89	342559080180509	August 24, 2011	11:57	143
Well 6	CTF–106	342929080145009	August 23, 2011	14:40	249
Well 7	CTF–107	342711080174909	August 24, 2011	12:11	115
Well 8	CTF–108	342707080122909	August 23, 2011	11:01	206
Well 8	CTF–108	342707080122909	August 23, 2011	11:30	221
Well 9	CTF–198	342532080181309	August 22, 2011	11:31	175
Well 10	CTF–219	342749080135509	August 23, 2011	14:00	205
Agricultural-supply wells					
CTF–60	CTF–60	343044080145200	August 23, 2011	15:00	166
CTF–315	CTF–315	343027080144400	August 24, 2011	14:25	209
CTF–316	CTF–316	342920080144300	August 25, 2011	12:22	191
CTF–209	CTF–209	343027080151400	August 25, 2011	13:24	190
2012					
Public-supply wells					
Well 11	CTF–313	342500080180200	February 8, 2012	13:30	133
Well 6	CTF–106	342929080145009	August 14, 2012	11:11	219
Well 6	CTF–106	342929080145009	August 14, 2012	11:25	227
Well 10	CTF–219	342749080135509	August 14, 2012	13:45	192
Monitoring wells					
CTF–228(S)	CTF–228	342828080131900	February 8, 2012	16:15	**325**
CTF–228(D)	CTF–228	342828080131900	February 23, 2012	14:00	277
CTF–221(R)	CTF–221	342543080165801	February 9, 2012	11:50	187
CTF–211	CTF–211	343023080130600	February 9, 2012	14:10	63.5
Domestic-supply wells					
PW1	CTF–317	342839080170601	August 14, 2012	15:40	195
PW2	CTF–318	342826080165201	August 14, 2012	16:30	238
PW3	CTF–319	342758080144601	August 15, 2012	11:06	188
Monitoring wells					
CTF–228(D)	CTF–228	342828080131900	August 15, 2012	16:11	**303**
CTF–228(S)	CTF–228	342828080131900	August 15, 2012	16:45	**300**
CTF–211	CTF–211	343023080130600	August 15, 2012	19:40	86.2

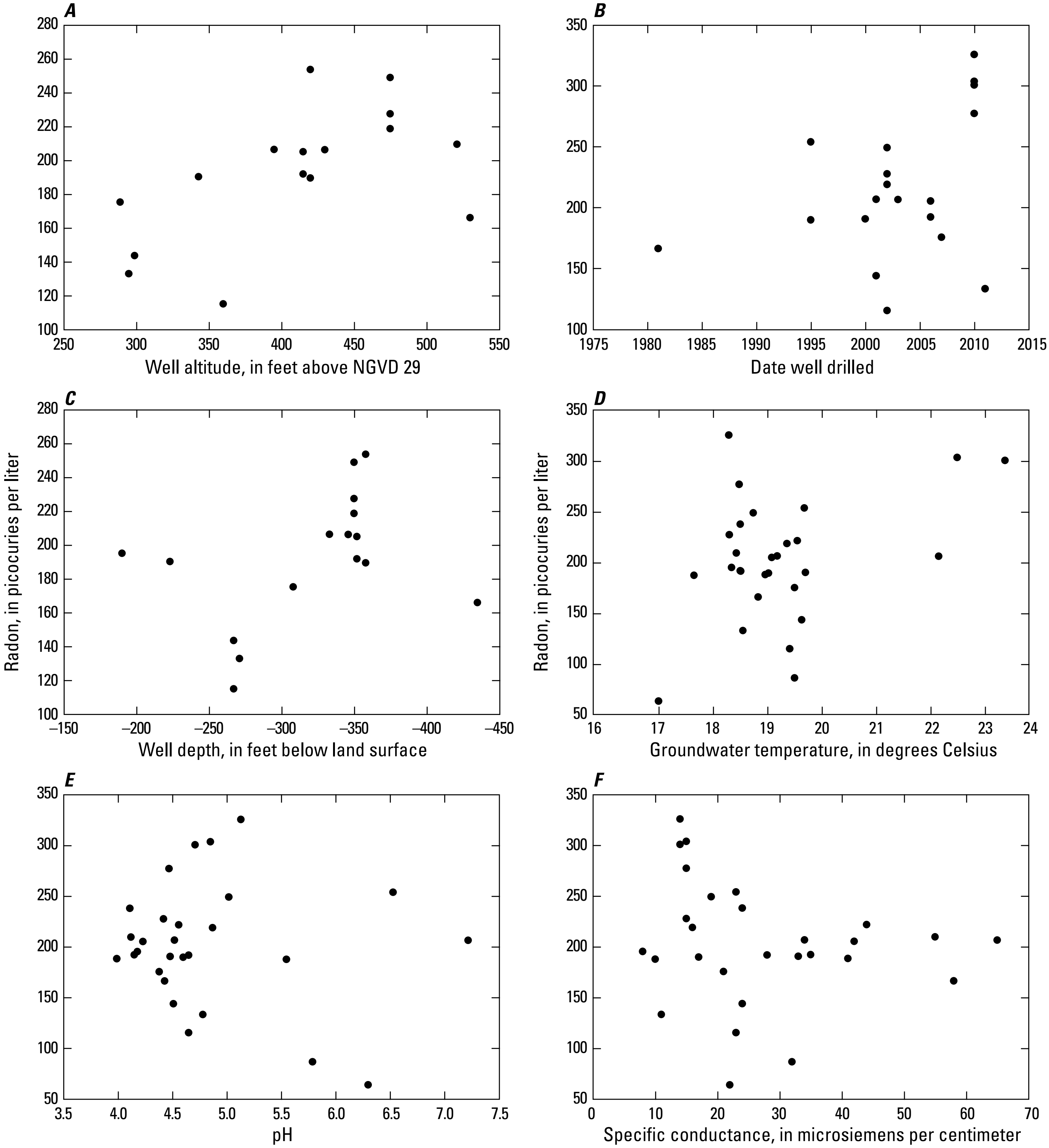


Figure 30. Relation between radon concentrations in groundwater and (*A*) well altitude, (*B*) date well drilled, (*C*) well depth, (*D*) groundwater temperature, (*E*) pH, and (*F*) specific conductance, McBee, South Carolina, 2010–2012.

Concentrations of radon were high in wells drilled at high altitudes and in wells more recently drilled; however, the installation dates for multiple wells that had varying radon concentrations could not be included in this comparison. Conversely, there was no positive relation observed between radon concentration and well depth (fig. 30*C*). There also was no positive correlation between radon concentration and groundwater temperature, pH, or specific conductance, which might be expected given the conservative nature of radon (figs. 30*D* to 30*F*).

The detection of radon in groundwater from all wells coupled with radon's short half-life indicates that the distribution of the parent, ^{226}Ra, is either widespread, proximal to each well screened interval, or both. To evaluate the relation between ^{226}Ra and ^{222}Rn, radon concentrations were compared to ^{226}Ra concentrations for the same well collected on the same day. No relation was observed between ^{226}Ra and ^{222}Rn (fig. 31). Hence, the potential use of radon as a less expensive alternative to determine radium in wells may not be valid in the McBee area or other similar locations in the Sandhills physiographic province of the Atlantic Coastal Plain.

The lack of a relation between ^{222}Rn and ^{226}Ra was unexpected, given that radon concentrations tend to be indicative of the radium content of the rocks in recent contact with the water (Otton and Reimer, 1991) and that King and others (1982) showed a positive relation between the log transforms of ^{222}Rn and ^{226}Ra. Other researchers, however, have shown no correlation between radon and radium concentrations in groundwater (Loomis, 1987) and no correlation of radon concentration with well discharge, specific capacity, or well depth (Loomis and others, 1988). The lack of consensus about these correlations may be due to radon being a gas or other hydrogeologic factors.

Inorganic Compounds

Lead was the only inorganic compound detected in groundwater at a concentration that exceeded the MCL during sampling in 2012 (table 9). Lead was detected in groundwater samples from monitoring well CTF–211 at 58.9 and 41.4 µg/L during sampling in February and August 2012, respectively (fig. 32). Both detections exceed the MCL of 15 µg/L and exceed the average lead concentration of 1.35 µg/L in groundwater from all other McBee area wells. Groundwater samples from well CTF–211 also were characterized by having the highest concentrations of cadmium, chromium, copper, manganese, nickel, zinc, and antimony compared to other wells sampled in the area.

A possible explanation for the elevated lead and other inorganics in groundwater samples from monitoring well CTF–211 may be related to the past storage and use at a nearby maintenance facility area of fuels that would have contained tetraethyl lead. An alternative explanation for the elevated inorganics in groundwater from well CTF–211, one of the older wells in the McBee area, could be corrosion of the steel well casing. Lead, however, is less corrosive than steel, and steel has been demonstrated to act as a sink for lead by absorption rather than as a source of dissolved lead to water (Uhlig, 1963). Moreover, groundwater samples collected from well CTF–211 in 2011 contained concentrations of hydrocarbon compounds, such as BTEX (table 6) commonly associated with gasoline releases to the subsurface.

Uranium was detected at levels above the MRL of 0.014 µg/L in all groundwater samples collected in February and August 2012 in the McBee area (table 9). The highest concentration (0.412 µg/L) was detected in the deep

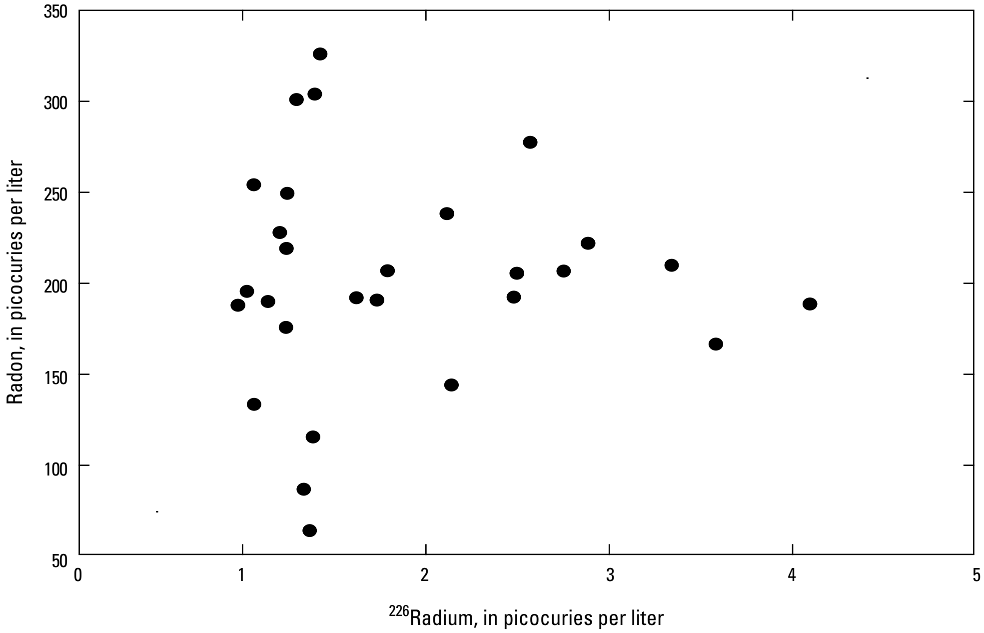


Figure 31. Relation between radon and radium-226 concentrations in groundwater, McBee, South Carolina, 2010–2012.

Table 9. Concentrations of inorganic compounds in unfiltered groundwater samples, McBee, South Carolina, 2012.

[<, less than; ID, identification; n, unique county-well number; USGS, U.S. Geological Survey; µg/L, micrograms per liter; MCL, maximum contaminant level; MRL, minimum reporting level; CTF, Chesterfield County; S, shallow screened interval; D, deep screened interval; PW, private well; —, no data available; values in boldface exceed the MCL; concentrations are in micrograms per liter]

Well ID	County number, CTF-n	USGS site ID	Sample date	Sample time	Barium	Beryllium	Cadmium	Chromium	Cobalt	Copper	Lead	Manganese	Thallium
MCL					2,000	4.00	5.00	100	—	1,300	15.00	—	2.00
MRL					0.060	0.020	0.016	0.300	0.020	0.700	0.040	0.400	0.060
Public-supply wells													
Well 11	CTF–313	342500080180200	February 8, 2012	13:40	5.400	<0.02	<0.016	<0.3	0.396	7.640	2.820	1.960	<0.06
Well 6	CTF–106	342929080145009	August 14, 2012	11:11	4.480	<0.02	<0.016	0.320	0.094	20.000	3.530	4.990	<0.06
Well 6	CTF–106	342929080145009	August 14, 2012	11:25	4.100	<0.02	<0.016	0.320	0.055	11.400	1.770	3.500	<0.06
Well 10	CTF–219	342749080135509	August 14, 2012	13:45	29.300	0.028	0.022	<0.3	0.528	9.530	1.270	5.200	<0.06
Monitoring wells													
CTF–228(S)	CTF–228	342828080131900	February 8, 2012	16:30	11.400	<0.02	0.032	0.396	0.097	<0.7	0.528	2.420	<0.06
CTF–228(D)	CTF–228	342828080131900	February 23, 2012	14:00	32.800	0.070	<0.016	0.855	0.227	<0.7	1.420	6.190	<0.06
CTF–221(R)	CTF–221	342543080165801	February 9, 2012	11:58	5.570	<0.02	<0.016	0.464	1.880	1.260	0.302	23.900	<0.06
CTF–211	CTF–211	343023080130600	February 9, 2012	14:20	5.660	0.022	0.360	5.360	1.230	41.900	**58.900**	269.000	<0.06
CTF–211	CTF–211	343023080130600	August 15, 2012	19:40	7.540	<0.02	0.265	3.530	0.928	35.800	**41.400**	303.000	<0.06
Domestic-supply wells													
PW1	CTF–317	342839080170601	August 14, 2012	15:44	1.690	<0.02	<0.016	<0.3	<0.02	0.965	0.405	<0.4	<0.06
PW2	CTF–318	342826080165201	August 14, 2012	16:30	19.100	0.044	0.019	<0.3	0.308	33.400	2.520	2.430	<0.06
PW3	CTF–319	342758080144601	August 15, 2012	11:06	38.900	0.058	0.038	<0.3	0.545	13.900	0.842	21.600	<0.06
Monitoring wells													
CTF–228(D)	CTF–228	342828080131900	August 15, 2012	16:11	8.080	<0.02	<0.016	0.834	0.119	1.020	0.536	5.910	<0.06
CTF–228(S)	CTF–228	342828080131900	August 15, 2012	16:45	7.860	<0.02	<0.016	0.326	0.074	<0.7	0.293	1.560	<0.06

Table 9. Concentrations of inorganic compounds in unfiltered groundwater samples, McBee, South Carolina, 2012.—Continued

[<, less than;ID, identification; n, unique county-well number; USGS, U.S. Geological Survey; µg/L, microgram per liter; MCL, maximum contaminant level; MRL, minimum reporting level; CTF, Chesterfield County; S, shallow screened interval; D, deep screened interval; PW, private well; —, no data available; values in boldface exceed the MCL; concentrations are in micrograms per liter]

Well ID	County number, CTF-n	USGS site ID	Sample date	Sample time	Molybdenum	Nickel	Silver	Strontium	Zinc	Antimony	Aluminum	Lithium	Selenium	Uranium
MCL					—	—	—	—	—	6.00	—	—	50	—
MRL					0.050	0.190	0.015	0.800	3.000	0.180	3.800	0.150	0.050	0.014
Public-supply wells														
Well 11	CTF–313	342500080180200	February 8, 2012	13:40	<0.05	0.246	<0.015	2.640	12.200	<0.18	70.400	0.158	<0.05	0.044
Well 6	CTF–106	342929080145009	August 14, 2012	11:11	<0.05	0.277	<0.015	3.340	18.700	<0.18	194.000	<0.15	<0.05	0.082
Well 6	CTF–106	342929080145009	August 14, 2012	11:25	<0.05	<0.19	<0.015	2.910	8.020	<0.18	20.300	<0.15	0.052	0.055
Well 10	CTF–219	342749080135509	August 14, 2012	13:45	<0.05	0.371	<0.015	16.100	10.300	<0.18	10.100	0.153	<0.05	0.061
Monitoring wells														
CTF–228(S)	CTF–228	342828080131900	February 8, 2012	16:30	0.713	0.841	<0.015	4.000	5.740	<0.18	108.000	<0.15	<0.05	0.056
CTF–228(D)	CTF–228	342828080131900	February 23, 2012	14:00	<0.05	0.288	0.028	9.680	10.400	<0.18	1,210.000	0.297	<0.05	0.412
CTF–221(R)	CTF–221	342543080165801	February 9, 2012	11:58	0.262	0.479	<0.015	9.690	11.500	<0.18	242.000	1.230	<0.05	0.084
CTF–211	CTF–211	343023080130600	February 9, 2012	14:20	0.173	6.940	0.039	1.920	698.000	0.285	22.200	<0.15	<0.05	0.156
CTF–211	CTF–211	343023080130600	August 15, 2012	19:40	0.073	5.770	0.028	1.970	515.000	0.234	11.300	<0.15	<0.05	0.120
Domestic-supply wells														
PW1	CTF–317	342839080170601	August 14, 2012	15:44	<0.05	<0.19	<0.015	1.260	8.710	<0.18	17.700	<0.15	0.072	0.030
PW2	CTF–318	342826080165201	August 14, 2012	16:30	<0.05	0.607	0.017	7.940	40.700	<0.18	23.600	0.151	<0.05	0.061
PW3	CTF–319	342758080144601	August 15, 2012	11:06	<0.05	0.561	<0.015	14.400	11.300	<0.18	29.500	0.203	<0.05	0.043
Monitoring wells														
CTF–228(D)	CTF–228	342828080131900	August 15, 2012	16:11	0.069	0.668	0.029	4.030	27.500	<0.18	182.000	<0.15	<0.05	0.089
CTF–228(S)	CTF–228	342828080131900	August 15, 2012	16:45	0.114	0.297	<0.015	3.520	4.190	<0.18	93.100	<0.15	0.055	0.036

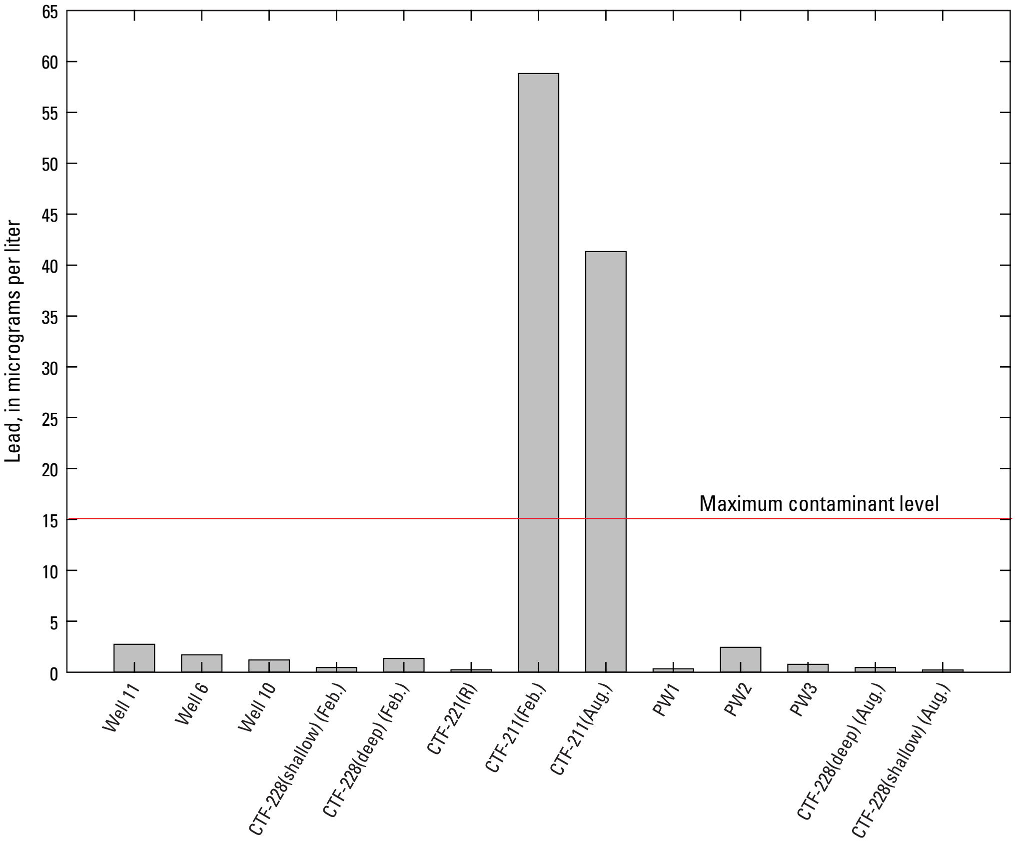


Figure 32. Concentrations of lead in groundwater samples collected from wells, McBee, South Carolina, 2012. The maximum contaminant level for lead of 15 micrograms per liter is shown.

screened interval of monitoring well CTF–228(D) during February 2012. The next highest uranium concentrations (0.156 and 0.120 µg/L) were detected in groundwater from monitoring well CTF–211 located near the maintenance facility; this well also had elevated lead concentrations. The average uranium concentration for all groundwater samples was 0.095 µg/L, and if these highest three uranium concentrations are not included in the average, an ambient "background" uranium concentration in groundwater of 0.055 µg/L can be estimated. This ambient uranium concentration is exceeded in groundwater samples collected from public-supply Well 6 and Well 10, monitoring wells CTF–221(R) and CTF–228(S), and domestic-supply well PW2.

Groundwater samples collected from the deep screened interval of well CTF–228(D) during August 2012 had more than twice the uranium (0.089 µg/L) as groundwater from the shallow screened interval (0.036 µg/L; table 9). The detection of the highest concentrations of uranium in groundwater from the deepest screened interval raises the possibility that a source of uranium to groundwater may be the pre-Paleozoic to Middle Cambrian rocks that lie beneath the Mesozoic and Cenozoic rocks of the Crouch and McQueen Branch aquifers. Although most public-supply wells in the McBee area are drilled to "bedrock" (generally the slightly metamorphosed clays (slates)), the use of multiple screened intervals in these wells precludes a closer examination of bedrock as a source of uranium to groundwater.

Alternatively, a potential, non-natural source of uranium to groundwater is from phosphate-based fertilizers applied at land surface, in which uranium is essentially an impurity present in phosphate-rich rocks, typically concentrated as uranium phosphate. Hence, uranium in groundwater can be from fertilizers (Otton and others, 1993), and higher concentrations of ^{226}Ra and ^{228}Ra have been related to increased nitrate concentrations in low pH groundwater indicative of agricultural land uses (Zsabo and dePaul, 1998). Spalding and Sackett (1972) traced high concentrations of uranium in surface waters of the Midwestern United States to the use of phosphate-bearing fertilizers in agricultural fields. Additionally, uranium concentrations in groundwater in the McBee area sampled during 2012 had little to no correlation with either ^{226}Ra or ^{228}Ra concentrations (fig. 33*A* and *B*), and uranium concentrations are generally lower in shallow wells. The lack of correlation between uranium and ^{226}Ra or ^{228}Ra concentrations is somewhat unexpected as uranium is the source of ^{226}Ra, which was elevated in some wells, groundwater was oxic, and uranium is mobile under oxic conditions. Moreover, the radium isotopes in fertilizers tend to be enriched in ^{226}Ra relative to ^{228}Ra, such that the ^{228}Ra/^{226}Ra ratios would be less than 1 if the uranium in McBee groundwater was derived entirely from fertilizers; however, this is not the case, as the ratios are greater than 1 (table 7).

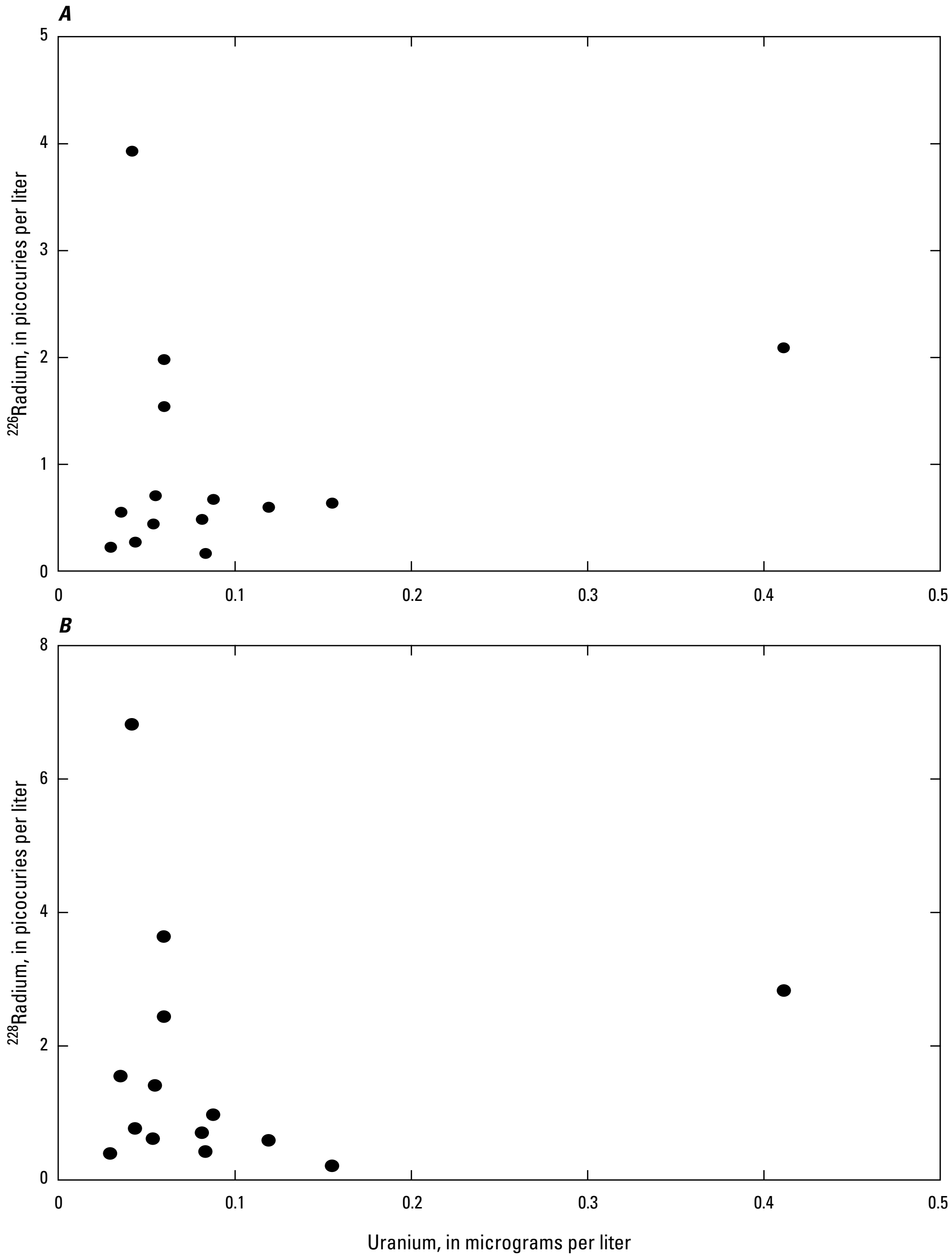


Figure 33. Relation between uranium concentration and concentrations of (*A*) radium-226 and (*B*) radium-228 in groundwater, McBee, South Carolina, 2010–2012.

Soil-Gas Samples

The compounds EDB and DBCP were not detected above the MRL of 0.02 microgram (µg) in any of the 103 soil-gas samplers deployed in the McBee area between 2010 and 2012 (table 10). The lack of EDB and DBCP detection in soil-gas samplers deployed in areas characterized by EDB- and DBCP-contaminated groundwater may be due to the following, in order of decreasing likeliness: (1) the past injection of liquid EDB and DBCP at shallow depths of the soil zone was followed by rapid gravity-driven removal from the soil zone to the water table some 160 ft below the injection sites; (2) EDB and DBCP vapors are present in the subsurface but at concentrations lower than the MRL of 0.02 µg; (3) the soil-gas samplers were deployed for an insufficient length of time to permit the equilibration of any low concentrations of EDB and DBCP vapors into the soil-gas samplers, in particular during the initial soil-gas survey in April 2010 where samplers were deployed for 2 days, including one sampler (no. 25) that was deployed for less than 2 hours; and (4) the soil-gas samplers were not deployed in areas where EDB and DBCP usage at land surface occurred recently or in the past.

Total petroleum hydrocarbons were detected above the MRLs in some soil-gas samplers deployed in the McBee

Table 10. Mass of ethylene dibromide, dibromochloropropane, total petroleum hydrocarbons, perchloroethylene, trichloroethylene, and chloroform detected in soil-gas samplers deployed April 2010, and March, May, and August 2012, McBee, South Carolina.

[EDB, ethylene dibromide; DBCP, dibromochloropropane; TPH, total petroleum hydrocarbons; PCE, perchloroethylene; TCE, trichloroethylene; ID, identification; MRL, minimum reporting limit; µg, micrograms; <, less than; Field IDs are generic and related to local landmarks for reference only; missing, sampler was deployed but could not be located for retrieval; –, no data available; samples are in micrograms]

Deploy date	Deploy time	Retrieval date	Retrieval time	Soil-gas sampler ID	Deploy sampler count	Field ID	Longitude	Latitude	Ethylene dibromide (EDB)	Dibromo-chloropropane (DBCP)	Total petroleum hydro-carbons (TPH)	Per-chloro-ethylene (PCE)	Tri-chloro-ethylene (TCE)	Chloro-form
MRL									0.02	0.02	0.5	0.02	0.02	0.02
April 27, 2010	12:30	April 29, 2010	12:05	622751	1	–	34 27 09.96	80 11 18.54	<0.02	<0.02	6.47	<0.02	<0.02	<0.02
April 27, 2010	12:40	April 29, 2010	12:10	622752	2	–	34 27 03.89	80 11 12.34	<0.02	<0.02	50.4	<0.02	<0.02	0.43
April 27, 2010	12:50	April 29, 2010	12:15	622753	3	–	34 26 58.86	80 11 05.84	<0.02	<0.02	2.39	<0.02	<0.02	<0.02
April 27, 2010	12:55	April 29, 2010	12:21	622754	4	–	34 26 53.51	80 11 00.02	<0.02	<0.02	3.54	<0.02	<0.02	<0.02
April 27, 2010	13:00	April 29, 2010	12:25	622755	5	–	34 26 50.51	80 10 56.60	<0.02	<0.02	9.7	<0.02	<0.02	0.35
April 27, 2010	13:05	April 29, 2010	12:30	622756	6	–	34 26 46.46	80 10 53.32	<0.02	<0.02	2.2	<0.02	<0.02	<0.02
April 27, 2010	13:12	April 29, 2010	12:31	622757	7	–	34 26 41.57	80 10 50.40	<0.02	<0.02	4.33	<0.02	<0.02	<0.02
April 27, 2010	13:16	April 29, 2010	12:26	622758	8	–	34 26 37.06	80 10 47.36	<0.02	<0.02	35.1	<0.02	<0.02	<0.02
April 27, 2010	14:00	April 29, 2010	14:49	622759	9	–	34 30 47.88	80 14 43.03	<0.02	<0.02	13.3	<0.02	<0.02	<0.02
April 27, 2010	14:05	April 29, 2010	14:47	622760	10	–	34 30 46.55	80 14 45.08	<0.02	<0.02	2.84	<0.02	<0.02	<0.02
April 27, 2010	14:07	April 29, 2010	14:46	622761	11	–	34 30 45.34	80 14 47.30	<0.02	<0.02	1.78	<0.02	<0.02	<0.02
April 27, 2010	14:12	April 29, 2010	14:45	622762	12	–	34 30 44.76	80 14 48.66	<0.02	<0.02	1.75	<0.02	<0.02	<0.02
April 27, 2010	14:15	April 29, 2010	14:43	622763	13	–	34 30 43.59	80 14 50.58	<0.02	<0.02	2.2	<0.02	<0.02	<0.02
April 27, 2010	14:20	April 29, 2010	14:41	622764	14	–	34 30 40.99	80 14 55.44	<0.02	<0.02	2.03	<0.02	<0.02	<0.02
April 27, 2010	14:24	April 29, 2010	14:35	622765	15	–	34 30 39.76	80 14 56.93	<0.02	<0.02	1.72	<0.02	<0.02	<0.02
April 27, 2010	14:26	April 29, 2010	14:32	622766	16	–	34 30 38.51	80 14 58.73	<0.02	<0.02	1.51	<0.02	<0.02	<0.02
April 27, 2010	14:30	April 29, 2010	14:30	622767	17	–	34 30 37.25	80 15 01.15	<0.02	<0.02	1.1	<0.02	<0.02	<0.02
April 27, 2010	14:33	April 29, 2010	14:28	622768	18	–	34 30 35.45	80 15 04.26	<0.02	<0.02	0.97	<0.02	<0.02	<0.02
April 27, 2010	14:27	April 29, 2010	14:26	622769	19	–	34 30 32.56	80 15 08.44	<0.02	<0.02	19.9	<0.02	<0.02	0.59
April 27, 2010	14:40	April 29, 2010	14:24	622770	20	–	34 30 31.44	80 15 10.23	<0.02	<0.02	1.29	<0.02	<0.02	<0.02
April 27, 2010	14:42	April 29, 2010	14:22	622771	21	–	34 30 30.11	80 15 12.36	<0.02	<0.02	1.59	<0.02	<0.02	<0.02
April 27, 2010	14:45	April 29, 2010	14:20	622772	22	–	34 30 28.87	80 15 14.32	<0.02	<0.02	0.87	<0.02	<0.02	<0.02
April 27, 2010	14:49	April 29, 2010	14:17	622773	23	–	34 30 27.47	80 15 16.66	<0.02	<0.02	2.76	<0.02	<0.02	<0.02
April 27, 2010	14:52	April 29, 2010	14:11	622774	24	–	34 30 26.57	80 15 17.92	<0.02	<0.02	0.92	0.07	<0.02	<0.02
April 29, 2010	13:32	April 29, 2010	15:21	622775	25	–	34 30 22.86	80 15 14.20	<0.02	<0.02	3.23	<0.02	<0.02	<0.02
April 27, 2010	14:55	April 29, 2010	14:07	622776	26	–	34 30 25.18	80 15 20.03	<0.02	<0.02	1.37	<0.02	<0.02	<0.02
April 27, 2010	14:57	April 29, 2010	14:01	622777	27	–	34 30 23.97	80 15 21.75	<0.02	<0.02	2.83	<0.02	<0.02	<0.02
April 27, 2010	15:00	April 29, 2010	14:15	622778	28	–	34 30 23.09	80 15 23.13	<0.02	<0.02	1.29	<0.02	<0.02	<0.02

Table 10. Mass of ethylene dibromide, dibromochloropropane, total petroleum hydrocarbons, perchloroethylene, trichloroethylene, and chloroform detected in soil-gas samplers deployed April 2010, and March, May, and August 2012, McBee, South Carolina.—Continued

[EDB, ethylene dibromide; DBCP, dibromochloropropane; TPH, total petroleum hydrocarbons; PCE, perchloroethylene; TCE, trichloroethylene; ID, identification; MRL, minimum reporting limit; µg, micrograms; <, less than; Field IDs are generic and related to local landmarks for reference only; missing, sampler was deployed but could not be located for retrieval; –, no data available; samples are in micrograms]

Deploy date	Deploy time	Retrieval date	Retrieval time	Soil-gas sampler ID	Deploy sampler count	Field ID	Longitude	Latitude	Ethylene dibromide (EDB)	Dibromo-chloropropane (DBCP)	Total petroleum hydro-carbons (TPH)	Per-chloro-ethylene (PCE)	Tri-chloro-ethylene (TCE)	Chloro-form
MRL									0.02	0.02	0.5	0.02	0.02	0.02
March 12, 2012	13:02	March 16, 2012	11:10	685073	29	MM–1	34 28 40.20	80 14 54.20	<0.02	<0.02	31.4	<0.02	<0.02	<0.02
March 12, 2012	13:20	March 16, 2012	11:50	685074	30	MM–2	34 28 39.35	80 14 52.31	<0.02	<0.02	3.74	<0.02	0.03	0.7
March 12, 2012	13:45	March 16, 2012	11:21	685075	31	MM–3	34 28 38.77	80 14 50.76	<0.02	<0.02	6.9	<0.02	0.05	0.03
March 12, 2012	14:08	March 16, 2012	11:23	685076	32	MM–4	34 28 37.48	80 14 48.17	<0.02	<0.02	3.01	<0.02	<0.02	<0.02
March 12, 2012	14:17	March 16, 2012	11:27	685077	33	MM–5	34 28 35.06	80 14 43.89	<0.02	<0.02	2.9	<0.02	<0.02	<0.02
March 12, 2012	14:39	March 16, 2012	11:18	685078	34	MM–6	34 28 38.81	80 14 51.20	<0.02	<0.02	50.7	<0.02	<0.02	0.19
March 12, 2012	14:47	March 16, 2012	11:12	685079	35	MM–7	34 28 39.35	80 14 53.14	<0.02	<0.02	10.1	<0.02	<0.02	1.59
March 12, 2012	15:11	March 16, 2012	11:39	685080	36	AOS–1	34 28 57.55	80 14 43.35	<0.02	<0.02	3.27	<0.02	<0.02	<0.02
March 12, 2012	15:20	March 16, 2012	11:43	685081	37	AOS–2	34 28 54.91	80 14 46.63	<0.02	<0.02	30.6	<0.02	<0.02	<0.02
March 12, 2012	15:34	March 16, 2012	11:51	685082	38	AOS–3	34 28 53.25	80 14 48.83	<0.02	<0.02	36.8	<0.02	<0.02	<0.02
				685083		Trip blank			<0.02	<0.02	<0.05	<0.02	<0.02	<0.02
				685084		Trip blank			<0.02	<0.02	<0.05	<0.02	<0.02	<0.02
May 4, 2012	10:40	May 8, 2012	10:17	687386	39	MM–8	34 28 39.91	80 14 53.38	<0.02	<0.02	1.78	<0.02	<0.02	0.45
May 4, 2012	10:46	May 8, 2012	10:18	687387	40	MM–9	34 28 39.64	80 14 53.00	<0.02	<0.02	11.7	<0.02	<0.02	0.49
May 4, 2012	10:52	May 8, 2012	10:19	687388	41	MM–10	34 28 39.65	80 14 53.07	<0.02	<0.02	8.04	<0.02	<0.02	0.2
May 4, 2012	10:53	May 8, 2012	10:21	687389	42	MM–11	34 28 39.35	80 14 52.62	<0.02	<0.02	1.71	<0.02	<0.02	0.25
May 4, 2012	10:56	May 8, 2012	10:22	687390	43	MM–12	34 28 39.32	80 14 52.48	<0.02	<0.02	11.5	<0.02	<0.02	0.11
May 4, 2012	11:00	May 8, 2012	10:27	687391	44	MM–13	34 28 39.07	80 14 52.21	<0.02	<0.02	5.61	<0.02	<0.02	0.39
May 4, 2012	11:04	May 8, 2012	10:26	687392	45	MM–14	34 28 39.67	80 14 52.29	<0.02	<0.02	1.62	<0.02	<0.02	<0.02
May 4, 2012	11:07	May 8, 2012	10:24	687393	46	MM–15	34 28 39.75	80 14 52.82	<0.02	<0.02	2.32	<0.02	<0.02	<0.02
May 4, 2012	11:12	May 8, 2012	10:31	687394	47	MM–16	34 28 41.07	80 14 56.76	<0.02	<0.02	0.98	<0.02	<0.02	<0.02
May 4, 2012	11:16	May 8, 2012	10:34	687395	48	MM–17	34 28 41.24	80 14 57.23	<0.02	<0.02	3.39	<0.02	<0.02	<0.02
May 4, 2012	11:20	May 8, 2012	10:32	687396	49	MM–18	34 28 41.56	80 14 56.86	<0.02	<0.02	1.68	<0.02	<0.02	<0.02
May 4, 2012	11:24	May 8, 2012	Missing	687397		MM–19								
May 4, 2012	11:28	May 8, 2012	10:43	687398	50	MM–20	34 28 42.42	80 15 0.00	<0.02	<0.02	1.35	<0.02	<0.02	<0.02
May 4, 2012	11:31	May 8, 2012	10:45	687399	51	MM–21	34 28 42.48	80 14 59.65	<0.02	<0.02	5.39	<0.02	<0.02	<0.02
May 4, 2012	11:35	May 8, 2012	10:47	687400	52	MM–22	34 28 43.24	80 15 2.30	<0.02	<0.02	1.59	<0.02	<0.02	<0.02
May 4, 2012	11:38	May 8, 2012	10:48	687401	53	MM–23	34 28 43.40	80 15 2.69	<0.02	<0.02	1.31	<0.02	<0.02	<0.02
May 4, 2012	11:42	May 8, 2012	10:50	687402	54	MM–24	34 28 43.67	80 15 2.32	<0.02	<0.02	1.11	<0.02	<0.02	<0.02

Table 10. Mass of ethylene dibromide, dibromochloropropane, total petroleum hydrocarbons, perchloroethylene, trichloroethylene, and chloroform detected in soil-gas samplers deployed April 2010, and March, May, and August 2012, McBee, South Carolina.—Continued

[EDB, ethylene dibromide; DBCP, dibromochloropropane; TPH, total petroleum hydrocarbons; PCE, perchloroethylene; TCE, trichloroethylene; ID, identification; MRL, minimum reporting limit; µg, micrograms; <, less than; Field IDs are generic and related to local landmarks for reference only; missing, sampler was deployed but could not be located for retrieval; –, no data available; samples are in micrograms]

Deploy date	Deploy time	Retrieval date	Retrieval time	Soil-gas sampler ID	Deploy sampler count	Field ID	Longitude	Latitude	Ethylene dibromide (EDB)	Dibromo-chloropropane (DBCP)	Total petroleum hydro-carbons (TPH)	Per-chloro-ethylene (PCE)	Tri-chloro-ethylene (TCE)	Chloro-form
MRL									0.02	0.02	0.5	0.02	0.02	0.02
May 4, 2012	13:03	May 8, 2012	10:58	687403	55	MM–25	34 28 56.32	80 14 58.32	<0.02	<0.02	15.0	0.02	<0.02	<0.02
May 4, 2012	13:09	May 8, 2012	11:01	687404	56	MM–26	34 28 55.49	80 14 58.91	<0.02	<0.02	0.91	<0.02	<0.02	<0.02
May 4, 2012	13:13	May 8, 2012	11:03	687405	57	MM–27	34 28 54.48	80 14 59.40	<0.02	<0.02	20.6	<0.02	<0.02	<0.02
May 4, 2012	13:17	May 8, 2012	11:04	687406	58	MM–28	34 28 53.64	80 14 59.65	<0.02	<0.02	35.2	<0.02	<0.02	<0.02
May 4, 2012	13:19	May 8, 2012	11:05	687407	59	MM–29	34 28 52.63	80 15 0.43	<0.02	<0.02	16.7	<0.02	<0.02	<0.02
May 4, 2012	13:22	May 8, 2012	11:10	687408	60	MM–30	34 28 51.77	80 15 0.86	<0.02	<0.02	1.19	<0.02	<0.02	<0.02
May 4, 2012	13:26	May 8, 2012	11:11	687409	61	MM–31	34 28 51.04	80 15 1.22	<0.02	<0.02	1.3	<0.02	<0.02	<0.02
May 4, 2012	13:29	May 8, 2012	11:13	687410	62	MM–32	34 28 50.47	80 15 1.47	<0.02	<0.02	39.4	<0.02	<0.02	<0.02
May 4, 2012	13:32	May 8, 2012	11:26	687411	63	MM–33	34 28 50.09	80 15 1.66	<0.02	<0.02	1.01	<0.02	<0.02	<0.02
May 4, 2012	13:35	May 8, 2012	11:30	687412	64	MM–34	34 28 48.77	80 15 2.08	<0.02	<0.02	1.36	<0.02	<0.02	<0.02
May 4, 2012	13:40	May 8, 2012	11:31	687413	65	MM–35	34 28 47.47	80 15 2.75	<0.02	<0.02	8.53	<0.02	<0.02	<0.02
May 4, 2012	13:45	May 8, 2012	11:36	687414	66	MM–36	34 28 46.02	80 15 3.52	<0.02	<0.02	0.83	<0.02	<0.02	<0.02
May 4, 2012	13:49	May 8, 2012	11:33	687415	67	MM–37	34 28 45.20	80 15 3.65	<0.02	<0.02	1.32	<0.02	<0.02	<0.02
				687416		Trip blank			<0.02	<0.02	<0.05	<0.02	<0.02	<0.02
August 24, 2012	10:39	August 30, 2012	11:25	697346	68	WT1	34 30 51.53	80 14 55.87	<0.02	<0.02	<0.5	<0.02	<0.02	<0.02
August 24, 2012	10:42	August 30, 2012	11:27	697347	69	WT2	34 30 51.64	80 14 55.00	<0.02	<0.02	<0.5	<0.02	<0.02	<0.02
August 24, 2012	10:46	August 30, 2012	11:29	697348	70	WT3	34 30 50.73	80 14 55.67	<0.02	<0.02	<0.5	<0.02	<0.02	<0.02
August 24, 2012	10:49	August 30, 2012	11:30	697349	71	WT4	34 30 51.07	80 14 54.65	<0.02	<0.02	<0.5	<0.02	<0.02	<0.02
August 24, 2012	11:24	August 30, 2012	11:35	697350	72	NWR1	34 30 37.18	80 16 00.91	<0.02	<0.02	<0.5	<0.02	<0.02	<0.02
August 24, 2012	11:30	August 30, 2012	11:33	697351	73	NWR2	34 30 36.37	80 15 99.68	<0.02	<0.02	1.36	<0.02	<0.02	0.14
August 24, 2012	11:34	August 30, 2012	12:29	697352	74	NWR3	34 30 34.80	80 15 55.19	<0.02	<0.02	0.79	<0.02	<0.02	<0.02
August 24, 2012	11:39	August 30, 2012	12:25	697353	75	NWR4	34 30 33.17	80 15 50.30	<0.02	<0.02	<0.5	<0.02	<0.02	0.5
August 24, 2012	11:45	August 30, 2012	12:19	697354	76	NWR5	34 30 33.08	80 15 43.09	<0.02	<0.02	14.4	<0.02	<0.02	<0.02
August 24, 2012	11:50	August 30, 2012	12:13	697355	77	NWR6	34 30 30.08	80 15 40.87	<0.02	<0.02	3.93	<0.02	<0.02	<0.02
August 24, 2012	11:57	August 30, 2012	12:03	697356	78	NWR7	34 30 27.05	80 15 31.34	<0.02	<0.02	0.6	<0.02	<0.02	<0.02
August 24, 2012	12:00	August 30, 2012	12:00	697357	79	NWR8	34 30 25.62	80 15 26.61	<0.02	<0.02	0.68	<0.02	<0.02	<0.02
August 24, 2012	12:05	August 30, 2012	12:01	697358	80	NWR9	34 30 26.43	80 15 28.73	<0.02	<0.02	0.66	<0.02	<0.02	<0.02
August 24, 2012	12:11	August 30, 2012	12:05	697359	81	NWR10	34 30 27.69	80 15 33.20	<0.02	<0.02	0.78	<0.02	<0.02	<0.02
August 24, 2012	12:16	August 30, 2012	12:08	697360	82	NWR11	34 30 28.90	80 15 37.14	<0.02	<0.02	<0.5	<0.02	<0.02	<0.02

Table 10. Mass of ethylene dibromide, dibromochloropropane, total petroleum hydrocarbons, perchloroethylene, trichloroethylene, and chloroform detected in soil-gas samplers deployed April 2010, and March, May, and August 2012, McBee, South Carolina.—Continued

[EDB, ethylene dibromide; DBCP, dibromochloropropane; TPH, total petroleum hydrocarbons; PCE, perchloroethylene; TCE, trichloroethylene; ID, identification; MRL, minimum reporting limit; µg, micrograms; <, less than; Field IDs are generic and related to local landmarks for reference only; missing, sampler was deployed but could not be located for retrieval; –, no data available; samples are in micrograms]

Deploy date	Deploy time	Retrieval date	Retrieval time	Soil-gas sampler ID	Deploy sampler count	Field ID	Longitude	Latitude	Ethylene dibromide (EDB)	Dibromo-chloropropane (DBCP)	Total petroleum hydro-carbons (TPH)	Per-chloro-ethylene (PCE)	Tri-chloro-ethylene (TCE)	Chloro-form
MRL									0.02	0.02	0.5	0.02	0.02	0.02
August 24, 2012	12:20	August 30, 2012	12:15	697361	83	NWR12	34 30 30.40	80 15 42.22	<0.02	<0.02	7.34	<0.02	<0.02	<0.02
August 24, 2012	12:26	August 30, 2012	15:56	697362	84	NWR13	34 30 31.37	80 15 45.38	<0.02	<0.02	1.29	<0.02	<0.02	<0.02
August 24, 2012	12:30	August 30, 2012	12:17	697363	85	NWR14	34 30 30.47	80 15 42.73	<0.02	<0.02	0.89	<0.02	<0.02	<0.02
August 24, 2012	12:41	August 30, 2012	11:55	697364	86	NWR15	34 30 25.15	80 15 24.39	<0.02	<0.02	<0.5	<0.02	<0.02	<0.02
August 24, 2012	13:51	August 30, 2012	15:35	697365	87	SF1	34 30 23.81	80 15 20.44	<0.02	<0.02	0.7	<0.02	<0.02	<0.02
August 24, 2012	13:58	August 30, 2012	13:51	697366	88	SF2	34 30 22.21	80 15 16.37	<0.02	<0.02	<0.5	<0.02	<0.02	<0.02
August 24, 2012	14:05	August 30, 2012	15:31	697367	89	SF3	34 30 21.15	80 15 14.08	<0.02	<0.02	<0.5	<0.02	<0.02	<0.02
August 24, 2012	14:15	August 30, 2012	14:05	697368	90	SF4	34 30 19.36	80 15 16.35	<0.02	<0.02	<0.5	<0.02	<0.02	<0.02
August 24, 2012	14:20	August 30, 2012	14:07	697369	91	SF5	34 30 17.32	80 15 17.83	<0.02	<0.02	8.36	<0.02	<0.02	<0.02
August 24, 2012	14:27	August 30, 2012	14:12	697370	92	SF6	34 30 13.38	80 15 20.84	<0.02	<0.02	1.58	<0.02	<0.02	0.23
August 24, 2012	14:35	August 30, 2012	14:15	697371	93	SF7	34 30 10.10	80 15 23.62	<0.02	<0.02	1.29	<0.02	<0.02	<0.02
August 24, 2012	14:40	August 30, 2012	14:19	697372	94	SF8	34 30 05.02	80 15 27.70	<0.02	<0.02	0.68	<0.02	<0.02	<0.02
August 24, 2012	14:50	August 30, 2012	Missing	697373										
August 24, 2012	15:05	August 30, 2012	14:20	697374	95	SF10	34 29 45.17	80 15 32.44	<0.02	<0.02	2.32	<0.02	<0.02	<0.02
August 24, 2012	15:10	August 30, 2012	14:38	697375	96	SF11	34 29 46.00	80 15 28.68	<0.02	<0.02	8.79	<0.02	<0.02	0.11
August 24, 2012	15:15	August 30, 2012	Missing	697376										
August 24, 2012	15:20	August 30, 2012	14:45	697377	97	SF13	34 29 47.84	80 15 19.25	<0.02	<0.02	0.95	<0.02	<0.02	<0.02
August 24, 2012	15:24	August 30, 2012	14:49	697378	98	SF14	34 29 48.65	80 15 14.57	<0.02	<0.02	0.64	<0.02	<0.02	<0.02
August 24, 2012	15:28	August 30, 2012	14:51	697379	99	SF15	34 29 49.59	80 15 10.42	<0.02	<0.02	1.66	<0.02	<0.02	0.53
August 24, 2012	15:32	August 30, 2012	14:55	697380	100	SF16	34 29 50.55	80 15 06.55	<0.02	<0.02	6.1	<0.02	<0.02	<0.02
August 24, 2012	15:55	August 30, 2012	15:09	697381	101	SF17	34 29 48.66	80 15 32.45	<0.02	<0.02	0.84	<0.02	<0.02	<0.02
August 24, 2012	16:30	August 30, 2012	14:00	697382	102	SF18	34 30 21.23	80 15 14.07	<0.02	<0.02	<0.5	<0.02	<0.02	<0.02
August 24, 2012	14:35	August 30, 2012	14:03	697383	103	SF19	34 30 20.63	80 15 14.46	<0.02	<0.02	<0.5	<0.02	<0.02	<0.02
				697384		Trip blank			<0.02	<0.02	<0.05	<0.02	<0.02	<0.02
				697385		Trip blank			<0.02	<0.02	<0.05	<0.02	<0.02	<0.02
				697386		Trip blank			<0.02	<0.02	<0.05	<0.02	<0.02	<0.02
				697387		Trip blank			<0.02	<0.02	<0.05	<0.02	<0.02	<0.02

area between 2010 and 2012 (table 10). Concentrations of TPH were detected above the MRL of 0.50 µg in 90 soil-gas samplers deployed (87 percent of soil-gas samplers). The average TPH mass detected was 6.99 µg. The highest mass of TPH detected during the April 2010 survey (50.4 and 35.1 µg) was found in soil-gas samplers located along the railroad tracks (fig. 34). It is not clear if the detection of TPH vapors in these samplers is related to petroleum hydrocarbons near the railroad tracks or from upgradient adjacent areas that include agricultural land uses, because vapors from compounds included in the TPH classification include a variety of sources that use petroleum hydrocarbons, such as gasoline, heating oil, diesel fuel, or paint. The next highest TPH mass detected in soil-gas samplers installed during April 2010 along Wire Road was in soil-gas sampler 19, which had 19.9 µg TPH; this sampler was located downgradient from a residence. The highest mass of TPH for a soil-gas sampler installed during March 2012 along the utility right-of-way to the east of U.S. Highway 1 North was in soil-gas sampler 34, which had a concentration of 50.7 µg. A nearby sampler (29) had a concentration of 31.4 µg. The TPH mass above 30 µg also was detected in soil-gas samplers 37 and 38, located in a wooded low-altitude area, near where a pipe outfall of unknown origin was located to the south of soil-gas sampler 36. During the August 2012 soil-gas survey, the highest mass of TPH (14.4 µg) was detected in soil-gas sampler 76, located along the eastern boundary of the Carolina Sandhills NWR.

Perchloroethylene was detected above the MRLs in one soil-gas sampler deployed in the McBee area between 2010 and 2012 (sampler 24, table 10). Vapors of PCE were detected above the MRL of 0.02 µg in this soil-gas sampler deployed April 27, 2010, near a residence along Wire Road. The detection of PCE vapors in that soil-gas sampler may be related to the common use of PCE as a solvent to degrease metals, rather than the use of PCE as a dry-cleaning fluid. Although agricultural-supply well CTF–209 is located near this soil-gas sampler location and contained various organic compounds, including some chlorinated compounds (table 6), PCE was not detected in groundwater from well CTF–209 during sampling in 2011.

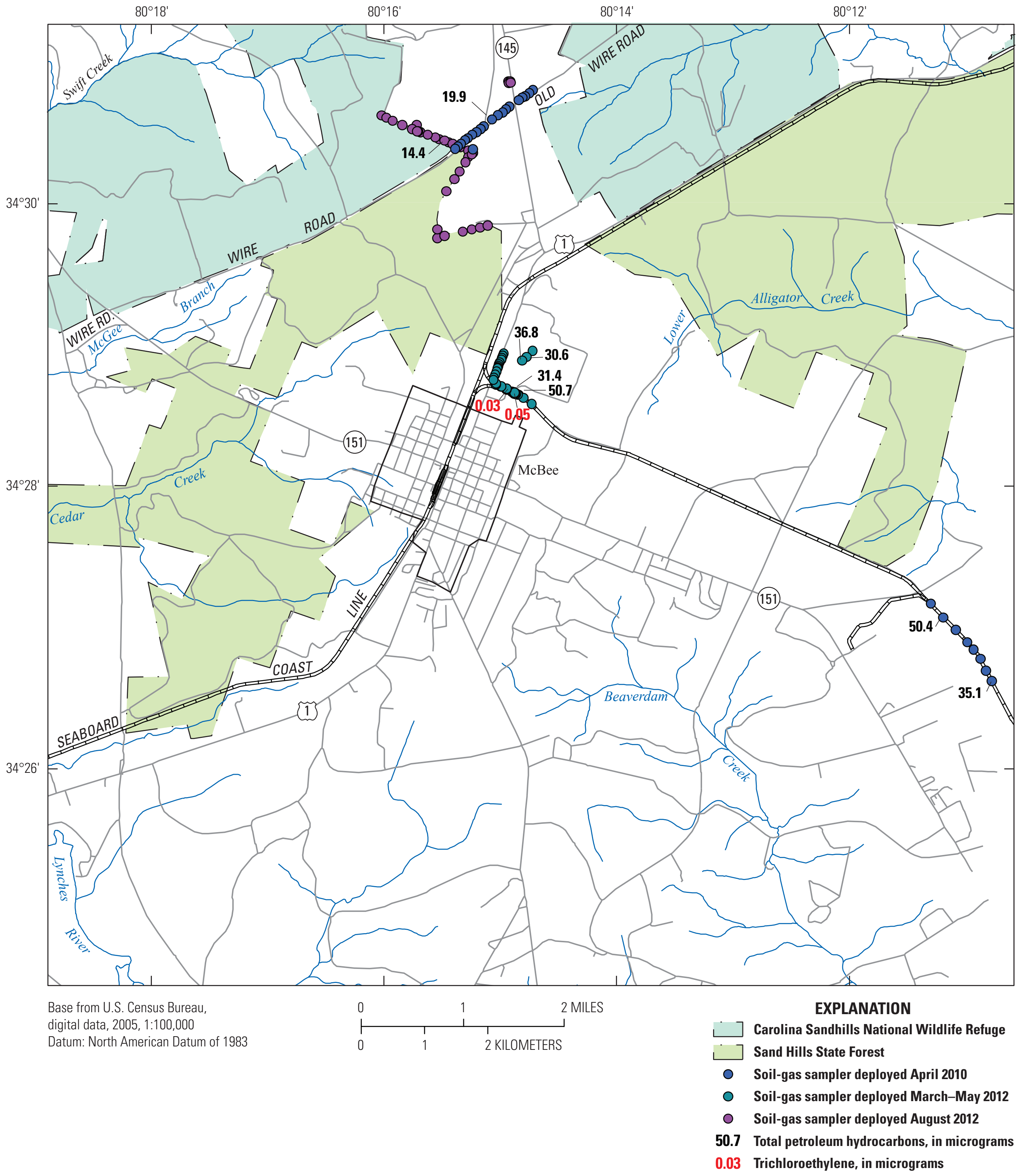
Trichloroethylene vapors were detected above the MRL of 0.02 µg in two soil-gas samplers located along a water utility right-of-way to the east of U.S. Highway 1 North and just north of a railroad track (table 10; fig. 34). The two soil-gas samplers that had TCE detections were located in an area where, during soil-gas sampler installation on March 12, 2012, water was observed discharging from a pipe located to the south of the railroad track, adjacent to a local industrial building (fig. 34). It is not clear how this discharge may have affected the soil-gas sampler results, because measurement of the water quality of the discharged water was beyond the scope of the soil-gas survey. Public-supply Well 10 is located to the east of the soil-gas samplers that contained TCE detections, and TCE was detected in groundwater from Well 10 each time the well was sampled between 2010 and 2012; Well 10 contained TCE at low concentrations of 0.032, 0.019, and 0.101 µg/L during August 2010, August 2011, and August 2012, respectively. These concentrations of TCE are lower than the MCL of 5 µg/L. Well 10 also had consistent detections of other chlorinated solvents, such as 1,1–DCA and 1,1–DCE, between 2010 and 2012. The detection of 0.016 µg/L TCE in monitoring well MW3 (table 6) was not an estimated value but was below the MRL.

Chloroform was detected above the MRL of 0.02 µg at multiple locations near McBee (table 10). As described previously, chloroform is used to disinfect water and, less commonly, as a solvent; its detection in soil gas is likely a result of the release of treated water through septic drain fields (Ivahnenko and Zogorski, 2006). All soil-gas samplers used as trip blanks indicated that the results reported above are considered environmental samples, rather than artifacts of sample collection, as TPH was below the detection level in all seven trip blanks, and PCE, TCE, and chloroform were found to be non-detections in all seven trip blanks.

Groundwater-Age Dates

Concentrations of trichlorofluoromethane (CFC–11), dichlorodifluoromethane (CFC–12), and 1,1,2-trichloro-1,2,2-trifluoroethane (CFC–113) were detected above the MRL in all groundwater samples collected in the McBee area in 2010 (table 11). The piston-type flow model-derived, apparent ages of groundwater calculated from these concentrations range from the mid 1940s to the mid 1980s (table 11). Only a few groundwater samples showed elevated concentrations of one CFC (CFC–12), indicating that CFC–12 concentrations were in excess of air-water equilibrium and could indicate that non-atmospheric sources (perhaps sewage effluent or other contamination) have added CFCs to groundwater in excess of air-water equilibrium. The elevated concentration of CFC–12 in the McBee Well(R) may be related to the co-detection of PCE in groundwater from that well; however, sample results from all wells could be used to assign apparent recharge ages.

The apparent age dates of groundwater and their relative distribution throughout the public-supply wellfield are depicted in terms of the prevailing groundwater-flow system as determined by the simulated potentiometric contour distribution for 2010 using the model described in Campbell and Landmeyer (2014). Flow pathway 1 (fig. 35*A* and *B*) comprises groundwater samples from the McBee Well(R) at higher water-table altitudes to lower altitudes and groundwater levels in public-supply Wells 7, 5 and 9; groundwater from this flow pathway ultimately discharges to the Lynches River. Groundwater ages in the McBee Well(R) were the youngest, in the 1980s. As groundwater flows toward the Lynches River, the ages get older, in the 1970s in Wells 5, 7, and monitoring well CTF–222, and are the oldest (in the 1960s) in groundwater from Well 9. The groundwater sample from Well 9 contained a low (<20 percent) fraction of shallow (young) water using CFC ratios (table 11) and the lower fraction of young water may indicate that the deeper screened intervals that produce older groundwater are responsible for most of the



Base from U.S. Census Bureau,
digital data, 2005, 1:100,000
Datum: North American Datum of 1983

Figure 34. Locations of all soil-gas samplers deployed April 2010, and March, May, and August 2012, with those samplers identified that had mass of total petroleum hydrocarbons and trichloroethylene above the method detection level, near McBee, South Carolina.

Table 11. Concentrations of chlorofluorocarbons in groundwater samples and apparent groundwater age dates, McBee, South Carolina, 2010.

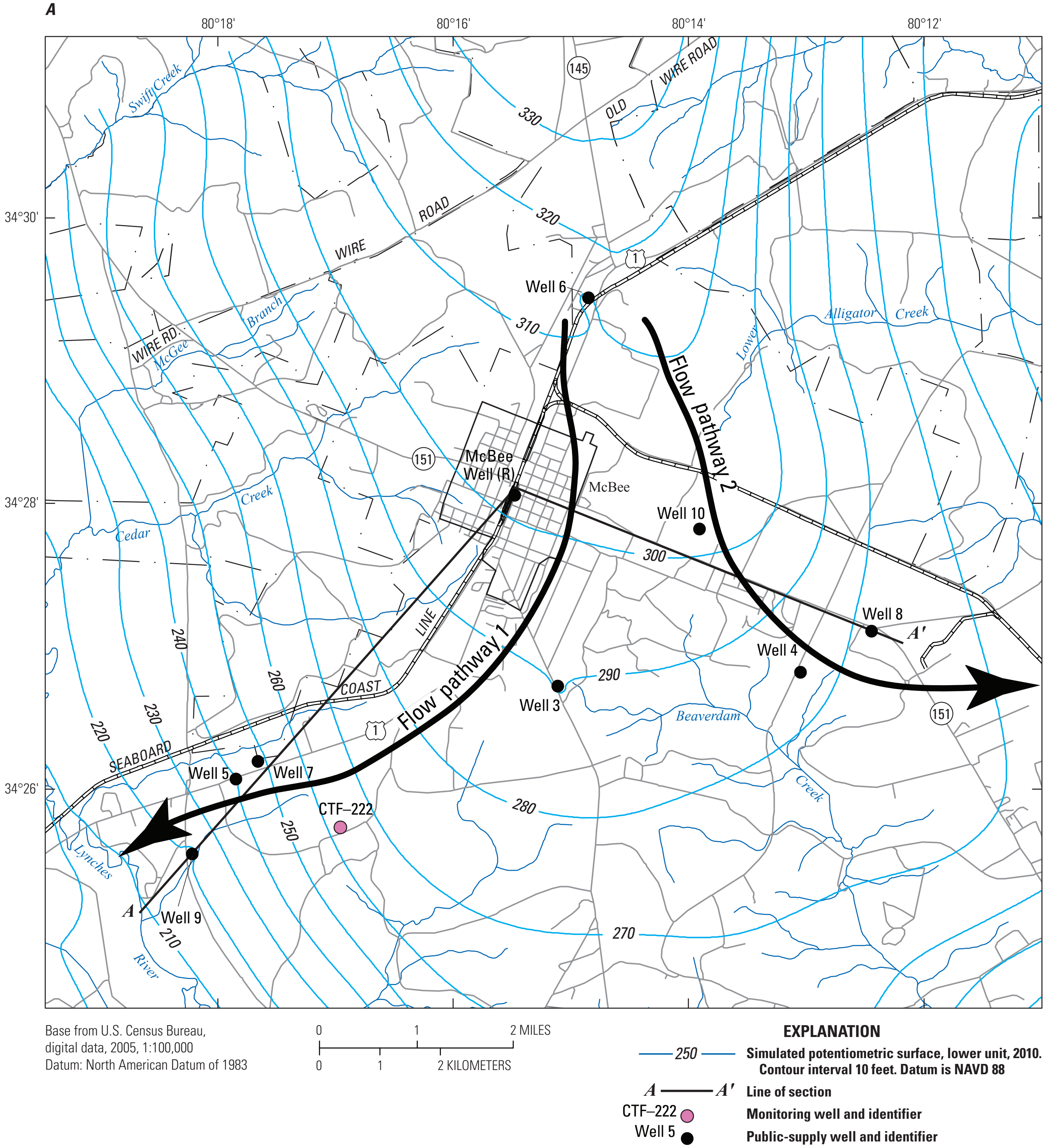
[ID, identification; n, unique county-well number; (R), replacement well; Location of wells are shown in figure 8; CFC, chlorofluorocarbon; pk/kg, picogram per kilogram; triplicate samples were analyzed for concentrations of CFCs and are reported here—the three CFC analyses were used to assign a CFC recharge time; CFC–11, trichlorofluoromethane; CFC–12, dichlorodifluoromethane; CFC–113, trichlorotrifluoroethane; contam., CFC concentrations are in excess of air-water equilibrium and can indicate that non-atmospheric sources (perhaps sewage effluent) have added CFCs to groundwater; —, no data available]

Well ID	County number, CTF–n	USGS site ID	Sample date	Sample time	Concentration in solution (pg/kg)			Piston-type flow recharge dates			CFCs used for ages	Assigned CFC apparent ground-water age date	Years recharge occurred prior to sampling in 2010, based on CFC–11	Percent young water in mixture		
					CFC–11	CFC–12	CFC–113	CFC–11	CFC–12	CFC–113				From CFC11/12	From CFC113/12	From CFC113/11
Monitoring wells																
CTF–189	CTF–189	343105080172100	August 30, 2010	13:18	289.44	143.40	31.29	1978.0	1980.0	1984.5	CFC–11,12	Early to mid 1980s	32.7	—	73.4	61.4
CTF–189	CTF–189	343105080172100	August 30, 2010	13:18	281.47	139.53	31.67	1977.0	1979.5	1984.5	—	—	33.7	—	69.8	56.3
CTF–222	CTF–222	342543080165800	August 18, 2010	11:50	178.31	66.74	40.66	1973.0	1971.0	1986.5	CFC–11,12	Early 1970s	37.6	—	—	—
CTF–222	CTF–222	342543080165800	August 18, 2010	11:50	177.62	64.69	44.41	1973.0	1970.5	1987.0	—	—	37.6	—	—	—
Public-supply wells																
McBee Well(R)	CTF–179	342803080152900	August 3, 2010	15:25	60.72	281.48	22.49	1966.0	Contam.	1981.5	CFC–113	Early 1980s	44.6	—	—	—
McBee Well(R)	CTF–179	342803080152900	August 3, 2010	15:25	62.37	286.92	23.24	1966.0	Contam.	1982.0	—	—	44.6	—	—	—
Well 3	CTF–83	342642080150709	August 4, 2010	15:20	23.63	1.33	0.00	1960.0	1946.5	1953.0	CFC–12, 113	Mid 1940s or older	50.6	—	—	—
Well 3	CTF–83	342642080150709	August 4, 2010	15:20	14.56	1.21	0.00	1957.0	1946.0	1953.0	—	—	53.6	—	—	—
Well 3	CTF–83	342642080150709	August 4, 2010	15:20	23.35	1.57	0.00	1960.0	1946.5	1953.0	—	—	50.6	—	—	—
Well 4	CTF–88	342652080130109	August 4, 2010	12:40	256.47	111.24	11.80	1976.0	1975.5	1976.5	All	Mid 1970s	34.6	89.3	84.8	90.6
Well 4	CTF–88	342652080130109	August 4, 2010	12:40	243.69	109.54	11.80	1975.5	1975.0	1976.5	—	—	35.1	91.1	84.8	84.8
Well 5	CTF–89	342559080180509	July 29, 2010	16:10	489.59	344.71	10.87	1987.5	Contam.	1975.5	CFC–113	Mid 1970s	23.1	—	—	—
Well 5	CTF–89	342559080180509	July 29, 2010	16:15	469.39	341.45	10.68	1986.5	Contam.	1975.5	—	—	24.1	—	—	—
Well 5	CTF–89	342559080180509	July 29, 2010	16:19	469.81	341.57	17.99	1986.5	Contam.	1979.5	—	—	24.1	—	—	—
Well 6	CTF–106	342929080145009	July 29, 2010	13:29	60.17	30.95	3.37	1965.5	1964.0	1967.0	All	Mid 1960s	45.1	42.3	22.5	18.3
Well 6	CTF–106	342929080145009	July 29, 2010	13:34	56.60	31.07	2.25	1965.0	1964.0	1964.0	—	—	45.6	54.0	—	—

Table 11. Concentrations of chlorofluorocarbons in groundwater samples and apparent groundwater age dates, McBee, South Carolina, 2010.—Continued

[ID, identification; n, unique county-well number; (R), replacement well; Location of wells are shown in figure 8; CFC, chlorofluorocarbon; pk/kg, picogram per kilogram; triplicate samples were analyzed for concentrations of CFCs and are reported here—the three CFC analyses were used to assign a CFC recharge time; CFC–11, trichlorofluoromethane; CFC–12, dichlorodifluoromethane; CFC–113, trichlorotrifluoroethane; contam., CFC concentrations are in excess of air-water equilibrium and can indicate that non-atmospheric sources (perhaps sewage effluent) have added CFCs to groundwater; —, no data available]

Well ID	County number, CTF–n	USGS site ID	Sample date	Sample time	Concentration in solution (pg/kg)			Piston-type flow recharge dates			CFCs used for ages	Assigned CFC apparent ground-water age date	Years recharge occurred prior to sampling in 2010, based on CFC–11	Percent young water in mixture		
					CFC–11	CFC–12	CFC–113	CFC–11	CFC–12	CFC–113				From CFC11/12	From CFC113/12	From CFC113/11
Public-supply wells—Continued																
Well 7	CTF–107	342711080174909	August 3, 2010	13:10	114.84	62.99	5.06	1970.0	1970.0	1970.5	All	1970	40.6	—	83.4	41.9
Well 7	CTF–107	342711080174909	August 3, 2010	13:10	114.84	62.27	4.31	1970.0	1970.0	1969.5	—	—	40.6	—	—	—
Well 8	CTF–108	342707080122909	August 4, 2010	14:05	116.35	35.91	4.50	1970.0	1965.5	1969.5	All	Mid to late 1960s	40.6	—	24.7	—
Well 8	CTF–108	342707080122909	August 4, 2010	14:05	115.39	36.64	4.12	1970.0	1966.0	1969.0	—	—	40.6	—	27.7	—
Well 9	CTF–198	342532080181309	August 3, 2010	10:36	60.85	22.25	3.56	1965.5	1961.5	1967.5	All	Early 1960s	45.1	—	12.7	17.1
Well 9	CTF–198	342532080181309	August 3, 2010	10:36	60.72	24.06	3.19	1965.5	1962.5	1966.5	—	—	45.1	—	15.3	18.8
Well 10	CTF–219	342749080125500	August 4, 2010	11:35	1,684.43	103.98	16.11	Contam.	1974.5	1978.5	CFC–12, 113	Mid 1970s	Contam.	—	59.2	—
Well 10	CTF–219	342749080135500	August 4, 2010	11:35	57.42	94.43	11.99	1965.5	1973.5	1976.5	—	—	45.1	—	63.5	—
Well 10	CTF–219	342749080125500	August 4, 2010	11:35	88.60	92.86	8.06	1968.0	1973.0	1973.5	—	—	42.6	—	90.4	20.1



Base from U.S. Census Bureau,
digital data, 2005, 1:100,000
Datum: North American Datum of 1983

Figure 35. Idealized groundwater flow pathways (*A*) 1 and 2 depicted on the 2010 potentiometric surface for the lower unit, and (*B*) on a generalized hydrogeologic cross section, McBee, South Carolina. The potentiometric surfaces were simulated using the model described in Campbell and Landmeyer (2014).

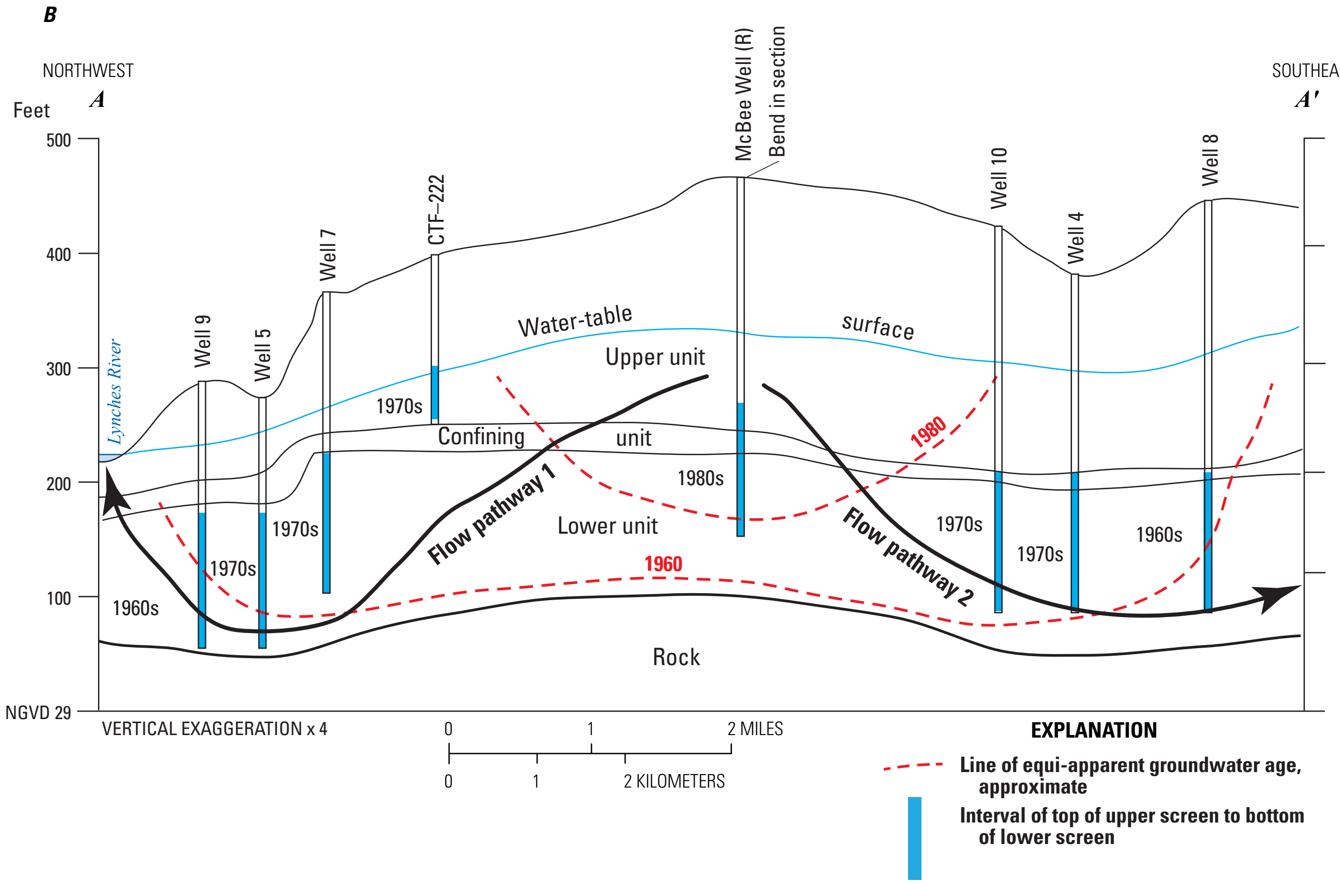


Figure 35. Idealized groundwater flow pathways (*A*) 1 and 2 depicted on the 2010 potentiometric surface for the lower unit, and (*B*) on a generalized hydrogeologic cross section, McBee, South Carolina. The potentiometric surfaces were simulated using the model described in Campbell and Landmeyer (2014).–Continued

water produced during pumping. The presence of old water from the deep parts of the aquifers relative to younger water in the shallower parts of the same aquifers has been observed in other groundwater systems (Tesoriero and others, 2007).

Flow pathway 2 (fig. 35*A* and *B*) comprises groundwater samples from the McBee Well(R) at higher water-table altitudes to lower altitudes and groundwater levels in Wells 10, 4, and 8; groundwater from this flow pathway ultimately discharges to Lake Robinson. Apparent groundwater ages in the McBee Well(R) were the youngest, in the 1980s. As groundwater flows toward the Lake, the ages become older, in the 1970s in Wells 10 and 4, and the oldest (in the 1960s) in Well 8. Groundwater sampled from public-supply Well 8 is represented by the low (<20 percent) fraction of shallow (young) water in the mixture sampled as determined from CFC ratios (table 11). As was the case for groundwater from Well 9, the lower fraction of young water indicates that the deeper screened intervals that produce older groundwater are responsible for most of the water produced during pumping.

There are some exceptions to the analysis of the distribution of ages using the piston-type flow model. For example, the age of groundwater samples reported for Well 6 are older than would be expected from the location of this well near the highest land-surface altitudes, groundwater altitudes, and proximity of recharge and flow pathways (fig. 35*A*). The 1960s value can be explained, however, by the fact that this well is located in an area where multiple wells have been used since at least the 1980s to irrigate crops in the vicinity of all wells. The groundwater pumping by irrigation wells would necessarily remove recently recharged water and then re-recharge the water in the same area. If spray irrigation was used during some time since irrigation began in the area, the concentration of CFCs in the water would decrease due to volatilization. Hence, the irrigation water recharged would tend to have lower concentrations of CFCs, which would bias the water pumped by the local public-supply well toward older ages.

In contrast, the groundwater pumped from public-supply Well 3, located at a much lower land-surface and water-table altitude than Well 6, was characterized by the oldest groundwater age date measured—1940s or older (table 11). The location of this well in the context of the groundwater-flow system near McBee helps explain this older age (fig. 35*A*). The well is located between, and is essentially equidistant from, the two regional groundwater discharge locations of the Lynches River and Lake Robinson. As such, the hydraulic gradients in the area of Well 3 are lower than any other part of the flow system, groundwater-flow rates are slower, and groundwater apparent ages are, therefore, the oldest.

As described previously, groundwater samples collected from the McBee Well(R) and Well 5 were characterized by CFC–12 in excess of air-water equilibrium and can indicate that non-atmospheric sources have added CFCs to groundwater. These values were not used to assign an age date to groundwater sampled from these wells; rather, CFC–113 was used. One groundwater sample from Well 10 had concentrations of CFC–11 in excess of air-water equilibrium; concentrations of CFC–12 and CFC–113 were used to assign an age date.

Concentrations of methane, carbon dioxide, nitrogen, oxygen, and argon in groundwater samples collected from wells sampled for CFC concentrations are given in table 12. The absence of dissolved methane confirms the high concentrations of dissolved-oxygen concentrations from 7.66 to 9.86 mg/L measured during groundwater sample collection. Moreover, the presence of dissolved oxygen and absence of methane supports the use of CFCs to age date groundwater in the McBee area, because CFC concentrations attendant to past recharge events are preserved in oxic groundwater (table 12). The presence of dissolved oxygen also indicates that nitrate from natural or anthropogenic sources would not undergo dentrification in groundwater and would tend to accumulate; high concentrations of nitrate were not observed, however, in the McBee public-supply wells (Newcome, 2004). The average concentration of dissolved carbon dioxide was 16.07 mg/L; the source of the carbon dioxide most likely is the aerobic respiration of dissolved or sedimentary organic carbon in groundwater or aquifer material, respectively, or the interaction of carbonic acid in rainwater with the aquifer material. The average nitrogen concentration was 17.13 mg/L, reflective of ambient nitrogen-fixation processes. The average dissolved argon concentration was 0.611 mg/L.

Calculated recharge temperatures from dissolved-gas concentrations are listed in table 12 and shown in fig. 36. Recharge temperatures appear to be inversely correlated with groundwater age (fig. 36*A* and *B*). Groundwater recharge temperatures cooler than 15.5 °C were observed for groundwater recharged 50 years ago, and recharge temperatures warmer than 17.5 °C were observed in groundwater recharged 35 years and younger. Moreover, when the calculated recharge temperatures are compared to the long-term record of air temperature for nearby Cheraw, S.C. (as the average of a maximum and minimum daily measured value from 1950 to 2013, data not shown), the calculated recharge temperatures appear to confirm that groundwater recharge tends to occur during the cool winter months, when evapotranspiration rates in the area are low, rather than during the warmer summer months, even though summer rainfalls are higher, and removal is by evapotranspiration.

Particle-Tracking Analysis

A representative groundwater flow pathway to each of the public-supply wells was simulated using particle-tracking analysis, calibrated to CFC-age dates (fig. 37), and analyzed with respect to groundwater contamination. Representative groundwater flow pathways to some domestic-supply, agricultural, and monitoring wells were also simulated but were not calibrated by CFC-age dates.

The potential source(s) of the EDB-contaminated groundwater detected in wells located in a recharge area for the Crouch Branch aquifer north of McBee was analyzed using the distribution of EDB concentrations in groundwater (fig. 15), simulated groundwater flow pathways (fig. 37), and historical aerial photographs from 1961, 1964, 1978, and 1983 (figs. 38–41). A potential source of the long-term detection of EDB in groundwater from Well 6 (fig. 14) located north of McBee would likely be from the legacy-use of EDB as a soil fumigant, as described previously. Public-supply Well 6 is located hydrologically downgradient from land used for agricultural purposes since the early 1900s (light-gray to white, open area to the west of agricultural-supply well CTF–207, both north and south of Wire Road, fig. 38). The simulated groundwater flow pathway to Well 6 originates in this agricultural area (fig. 38), and the apparent age of groundwater pumped from Well 6 indicates recharge occurred during the mid-1960s (table 11), prior to the ban on use of EDB as a soil fumigant (fig. 21). The simulated groundwater flow pathway to Well 6 originates in these agricultural areas during the 1960s, when recharge occurred (1961 and 1964, fig. 38 and 39, respectively). The soil-fumigant origin of the EDB detected in groundwater from Well 6 is supported by the fact that no evidence of a gasoline station in that area appears to exist on the aerial photographs from 1961 and 1964. Similarly, simulated groundwater flow pathways to EDB-contaminated agricultural-supply wells CTF–209 and CTF–316 (fig. 15), although not calibrated by a CFC-derived apparent-age date, indicate that groundwater in these wells originated as recharge in the agricultural area north of McBee (light-colored open areas, north and south of Wire Road, fig. 38). The simulated groundwater flow pathway for CTF–316 is similar to pathways for Well 6 due to the proximity of these wells to each other. Multiple passive soil-gas samplers, however, did not reveal the presence of EDB or DBCP near this area (table 10; fig. 34).

Public-supply Well 3 is located hydrologically downgradient from land used for agricultural purposes since the early 1900s (light gray areas to the east of U.S. Highway 1, south of McBee (fig. 38) as well as more urban land uses within the town limits (grid pattern of McBee, fig. 38). The simulated groundwater flow pathway to Well 3 (fig. 38), which had groundwater characterized by an estimated detection of EDB (table 5), originates within the McBee town limit, as well as agricultural areas south of McBee. The apparent age of groundwater pumped from Well 6 indicates recharge occurred during the mid-1940s (table 11), prior to the ban on

Table 12. Concentrations of methane, carbon dioxide, nitrogen, oxygen, and argon in groundwater samples, McBee, South Carolina, 2010.

[ID, identification; n, unique county-well number; (R), replacement well; °C, degrees Celsius; g/kg, grams per kilogram; ft, feet; mg/L, milligrams per liter; CTF, Chesterfield; NGVD 29, National Geodetic Vertical Datum of 1929]

Well ID	County number, CTF-n	USGS site ID	Sample date	Sample time	Sample temperature (°C)	Sample salinity (g/kg)	Recharge altitude, feet NGVD 29	Sample bottle ID	Methane (CH_4) (mg/L)	Carbon dioxide (CO_2) (mg/L)	Nitrogen (N_2) (mg/L)	Oxygen (O_2) (mg/L)	Argon (Ar) (mg/L)	Calculated recharge temp (°C)
Monitoring wells														
CTF–189	CTF–189	343105080172100	August 30, 2010	13:18	21.72	0.010	304	10Y1541	0.000	21.04	15.26	7.69	0.58	17.4
CTF–189	CTF–189	343105080172100	August 30, 2010	13:18	21.72	0.010	304	10Y1570	0.000	20.67	14.97	7.66	0.57	17.5
CTF–222	CTF–222	342543080165800	August 18, 2010	11:50	21.24	0.010	395	10Y1544	0.000	19.47	15.49	8.43	0.58	17.8
CTF–222	CTF–222	342543080165800	August 18, 2010	11:50	21.24	0.010	395	10Y1546	0.000	19.44	15.56	8.52	0.57	18.1
Public-supply wells														
McBee well(R)	CTF–179	342803080152900	August 3, 2010	15:25	19.67	0.010	465	10Y1553	0.000	20.00	16.86	9.13	0.60	17.4
McBee well(R)	CTF–179	342803080152900	August 3, 2010	15:25	19.67	0.010	465	10Y1560	0.000	20.07	16.69	9.06	0.60	16.9
Well 3	CTF–83	342642080150709	August 4, 2010	15:20	21.17	0.010	420	10Y1542	0.000	15.94	18.49	9.36	0.65	15.1
Well 3	CTF–83	342642080150709	August 4, 2010	15:20	21.17	0.010	420	10Y1549	0.000	15.87	18.55	9.59	0.64	15.5
Well 4	CTF–88	342652080130109	August 4, 2010	12:40	19.26	0.010	395	10Y1552	0.000	12.88	17.14	9.14	0.61	17.1
Well 4	CTF–88	342652080130109	August 4, 2010	12:40	19.26	0.010	395	10Y1554	0.000	12.61	17.06	9.44	0.61	16.9
Well 5	CTF–89	342559080180509	July 29, 2010	16:10	19.36	0.010	278	10Y1559	0.000	18.49	16.94	7.90	0.61	16.4
Well 5	CTF–89	342559080180509	July 29, 2010	16:15	19.36	0.010	278	10Y1566	0.000	16.93	17.13	9.34	0.61	16.4
Well 6	CTF–106	342929080145009	July 29, 2010	13:29	18.38	0.010	475	10Y1551	0.000	15.65	18.26	9.41	0.64	15.8
Well 6	CTF–106	342929080145009	July 29, 2010	13:34	18.38	0.010	475	10Y1568	0.000	15.57	18.21	9.64	0.64	15.3
Well 7	CTF–107	34271108017409	August 3, 2010	13:10	19.51	0.010	299	10Y1557	0.000	15.60	17.15	9.23	0.61	17.3
Well 7	CTF–107	34271108017409	August 3, 2010	13:10	19.51	0.010	299	10Y1569	0.000	15.79	17.07	9.05	0.61	17.2
Well 8	CTF–108	342707080122909	August 4, 2010	14:05	19.42	0.010	430	10Y1543	0.000	14.03	17.25	9.55	0.61	17.2
Well 8	CTF–108	342707080122909	August 4, 2010	14:05	19.42	0.010	430	10Y1547	0.000	13.95	17.28	9.49	0.61	17.1
Well 9	CTF–198	342532080181309	August 3, 2010	10:36	18.66	0.010	289	10Y1556	0.000	17.64	17.81	9.42	0.63	16.1
Well 9	CTF–198	342532080181309	August 3, 2010	10:36	18.66	0.010	289	10Y1558	0.000	17.86	17.77	9.14	0.63	16.2
Well 10	CTF–219	342749080135500	August 4, 2010	11:35	18.68	0.010	415	10Y1555	0.000	11.49	17.66	9.73	0.62	16.6
Well 10	CTF–219	342749080135500	August 4, 2010	11:35	18.68	0.010	415	10Y1567	0.000	11.44	17.88	9.86	0.62	16.7

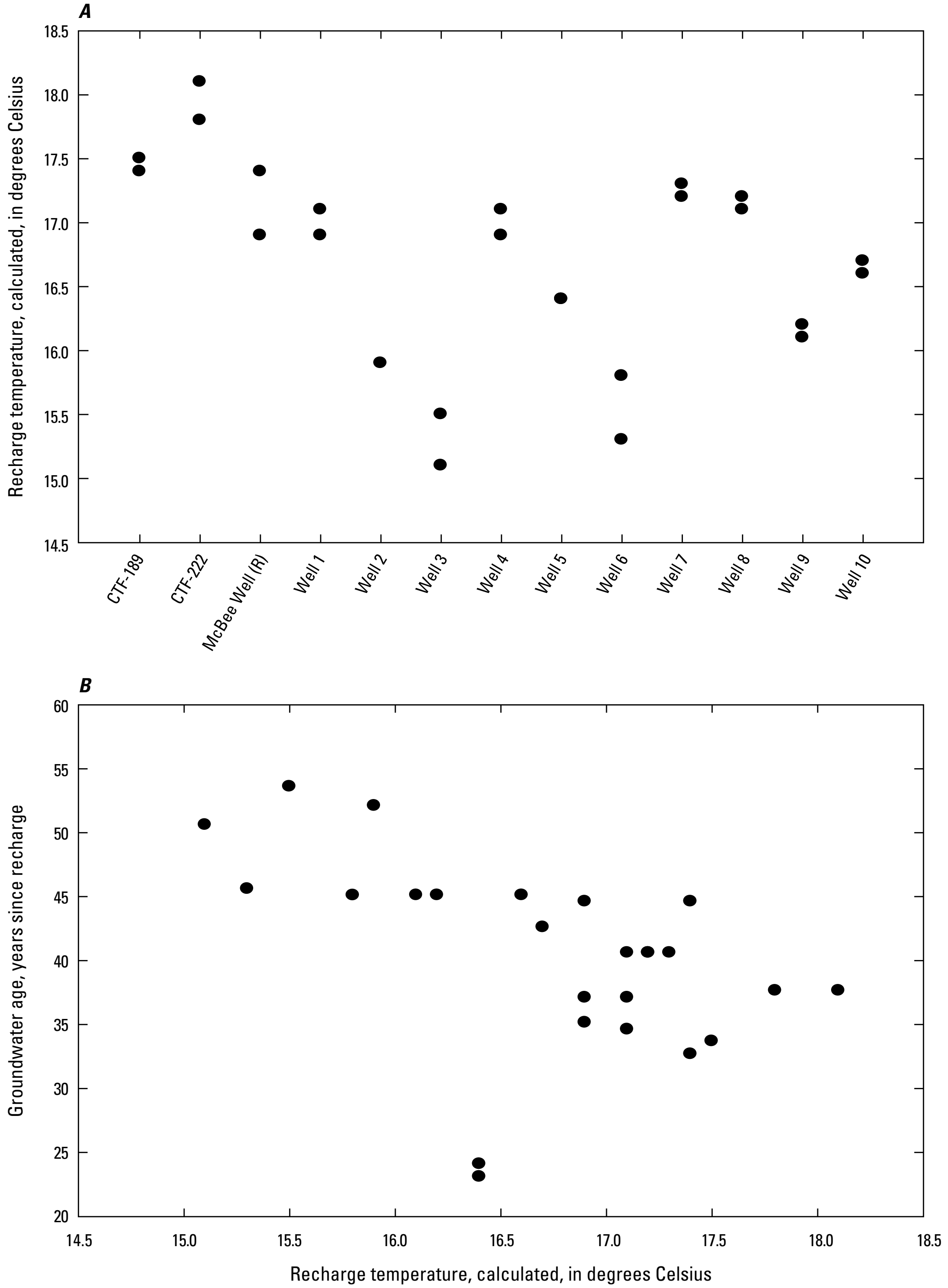


Figure 36. The (*A*) calculated recharge temperature for wells sampled, and (*B*) the relation between calculated recharge temperature and apparent groundwater age, McBee, South Carolina.

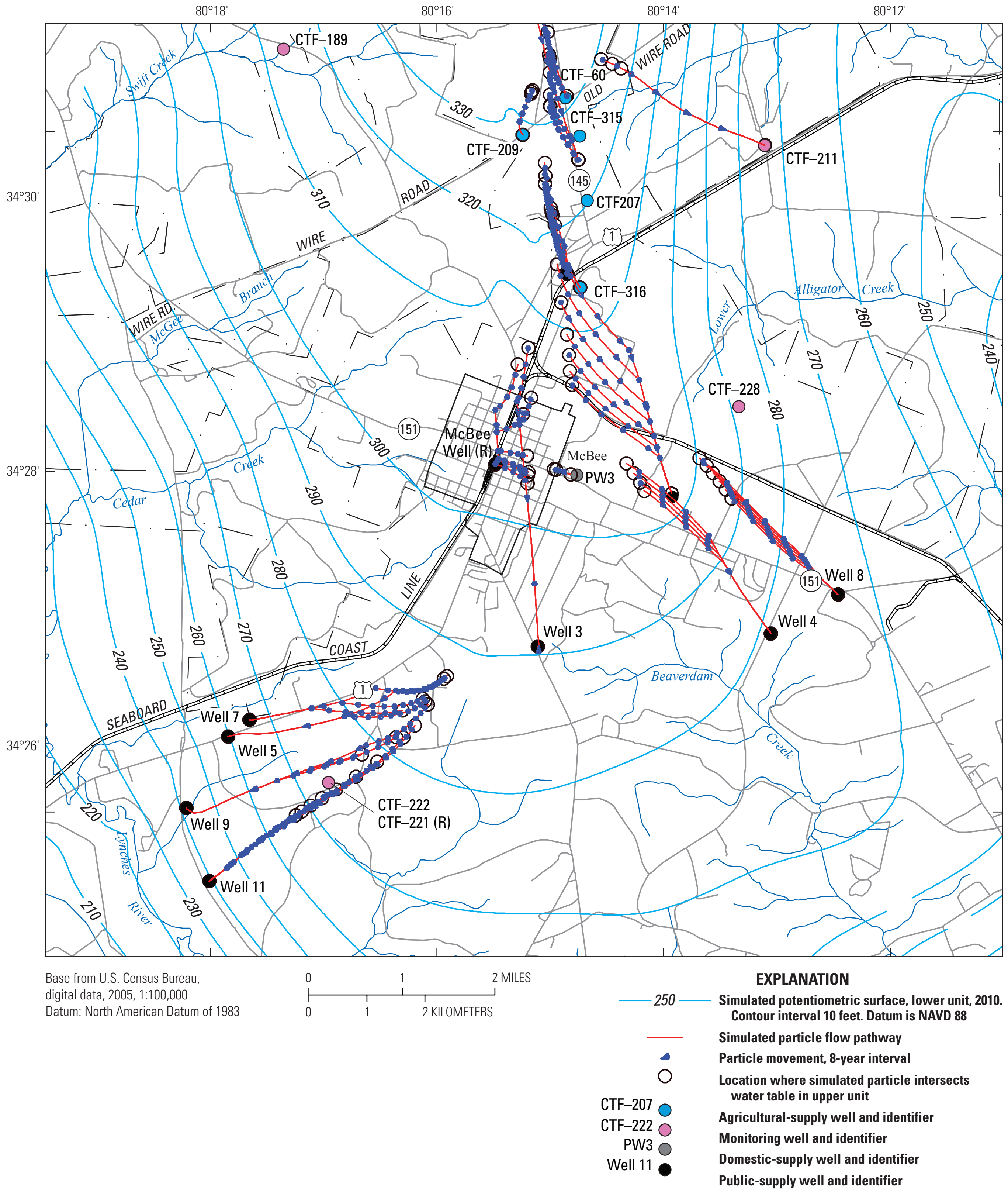
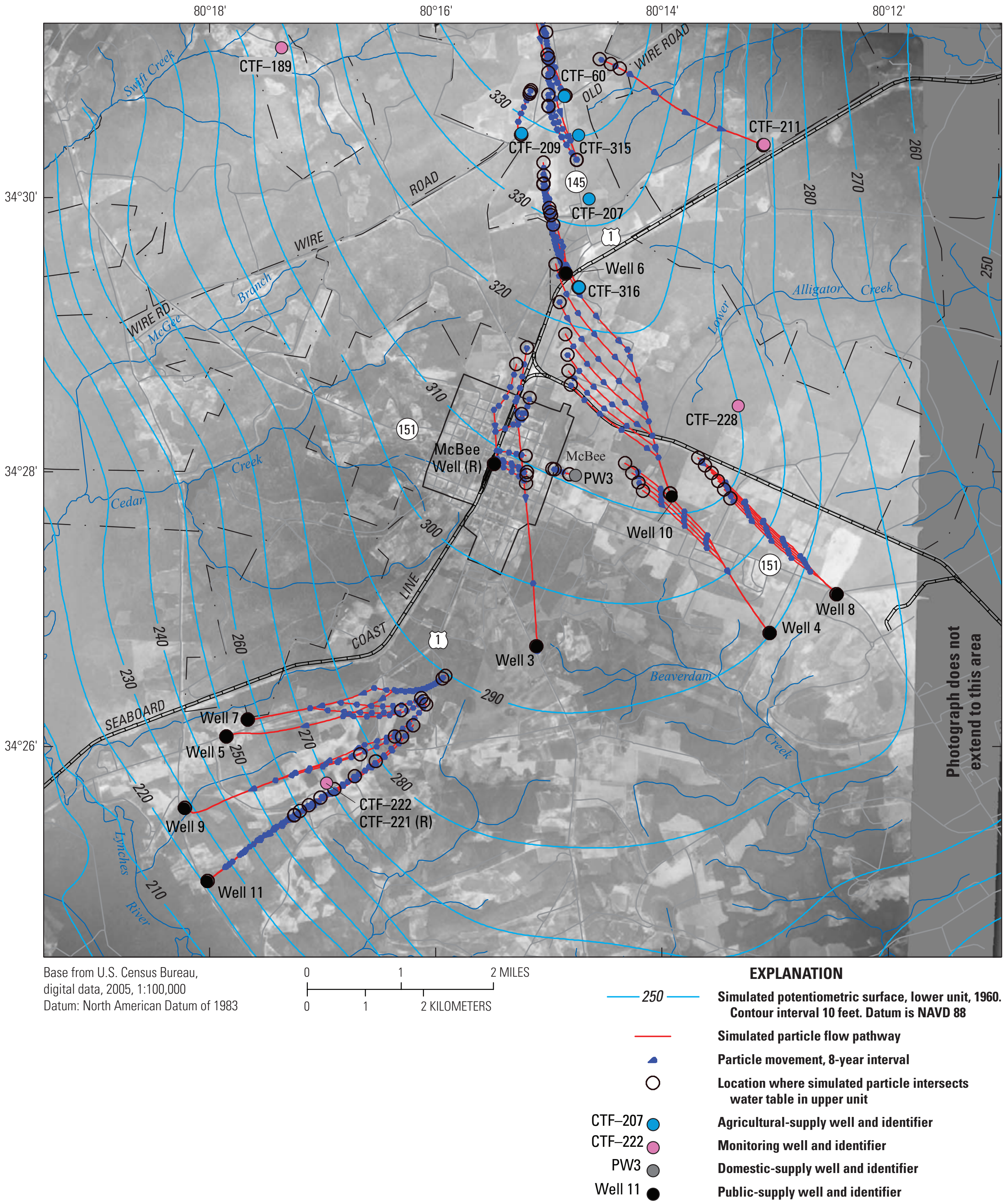
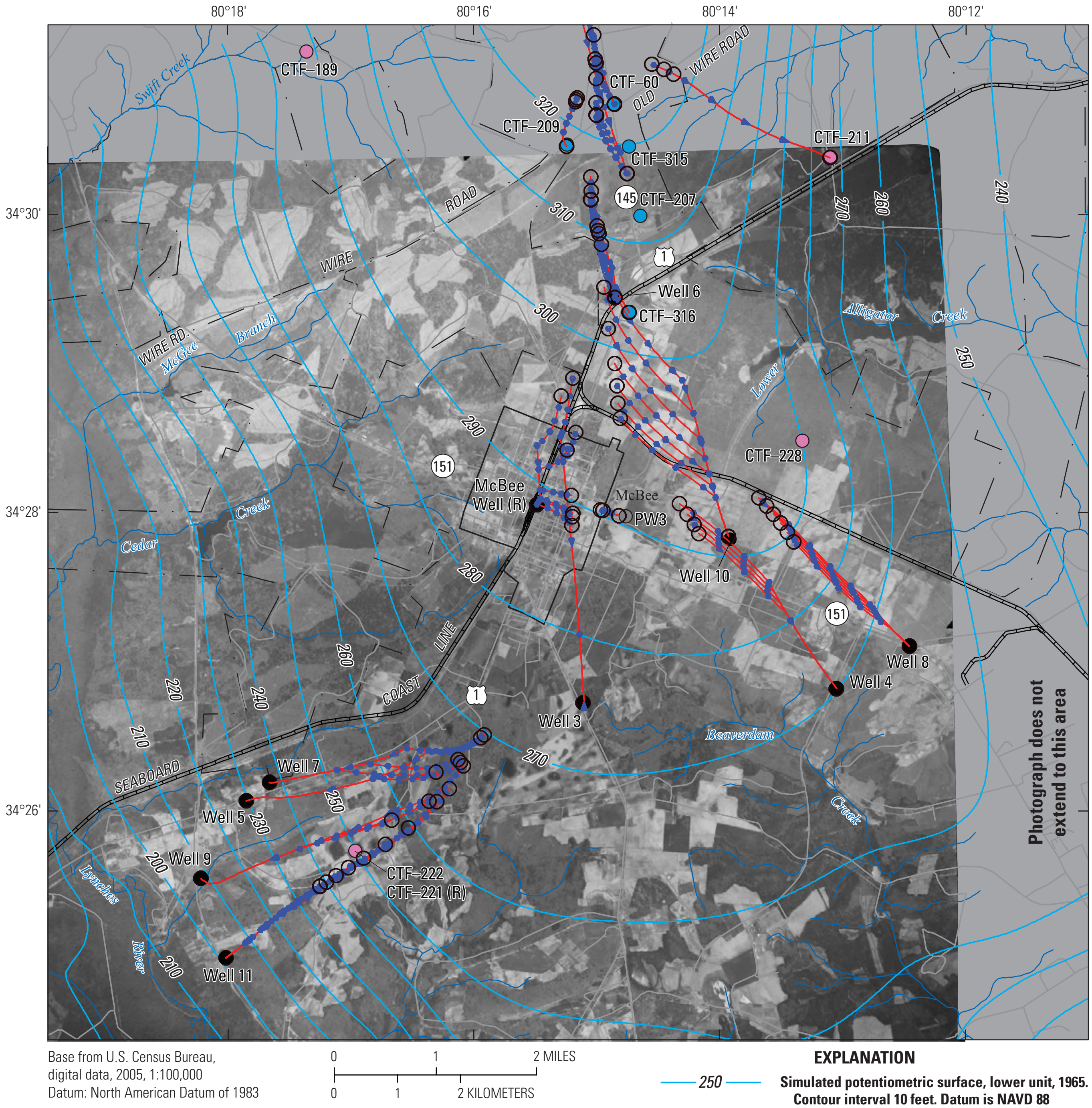


Figure 37. Simulated groundwater flow pathways to public-supply wells calibrated using apparent-age dates estimated by chlorofluorocarbon concentrations detected in groundwater in 2010, McBee, South Carolina. Simulated groundwater flow pathways to some agricultural-supply, domestic-supply, and monitoring wells are shown, but are not calibrated by apparent-age dates. The potentiometric surfaces were simulated using the model described in Campbell and Landmeyer (2014).



Base from U.S. Census Bureau,
digital data, 2005, 1:100,000
Datum: North American Datum of 1983

Figure 38. Simulated groundwater flow pathways to public-supply wells calibrated using apparent-age dates estimated by chlorofluorocarbon concentrations detected in groundwater in 2010, McBee, South Carolina. Land use data are from a 1961 aerial photograph. Simulated groundwater flow pathways to some agricultural-supply, domestic-supply, and monitoring wells are shown, but are not calibrated by apparent-age dates. The 1960 potentiometric surface was simulated using the model described in Campbell and Landmeyer (2014).

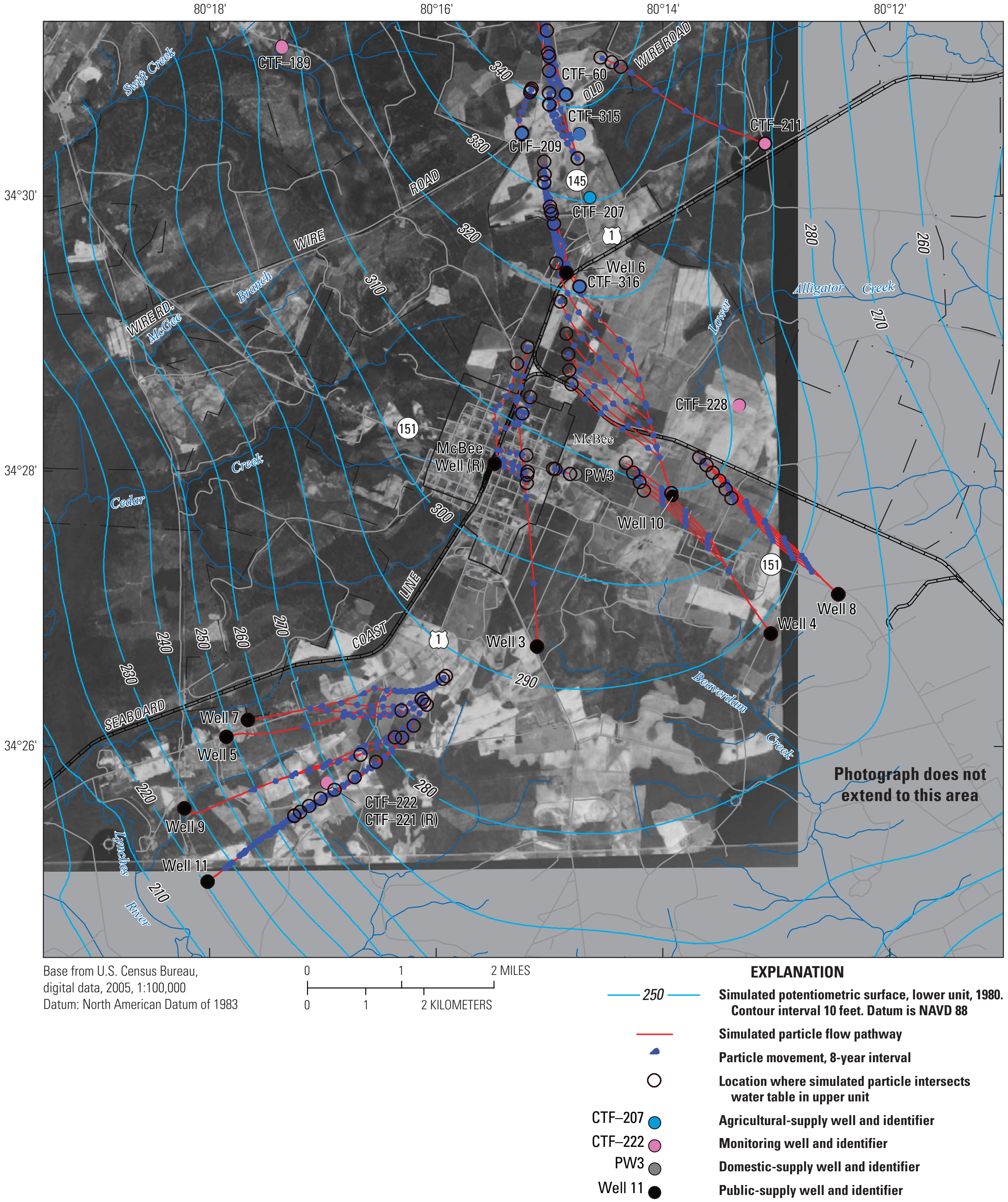


Base from U.S. Census Bureau,
digital data, 2005, 1:100,000
Datum: North American Datum of 1983

EXPLANATION

250	**Simulated potentiometric surface, lower unit, 1965. Contour interval 10 feet. Datum is NAVD 88**
	Simulated particle flow pathway
	Particle movement, 8-year interval
○	**Location where simulated particle intersects water table in upper unit**
CTF–207 ●	**Agricultural-supply well and identifier**
CTF–222 ●	**Monitoring well and identifier**
PW3 ●	**Domestic-supply well and identifier**
Well 11 ●	**Public-supply well and identifier**

Figure 39. Simulated groundwater flow pathways to public-supply wells calibrated using apparent-age dates estimated by chlorofluorocarbon concentrations detected in groundwater in 2010, McBee, South Carolina. Land use data are from a 1964 aerial photograph. Simulated groundwater flow pathways to some agricultural-supply, domestic-supply, and monitoring wells are shown, but are not calibrated by apparent-age dates. The 1965 potentiometric surface was simulated using the model described in Campbell and Landmeyer (2014).



Base from U.S. Census Bureau,
digital data, 2005, 1:100,000
Datum: North American Datum of 1983

Figure 40. Simulated groundwater flow pathways to public-supply wells calibrated using apparent-age dates estimated by chlorofluorocarbon concentrations detected in groundwater in 2010, McBee, South Carolina. Land use data are from a 1978 aerial photograph. Simulated groundwater flow pathways to some agricultural-supply, domestic-supply, and monitoring wells are shown, but are not calibrated by apparent-age dates. The 1980 potentiometric surface was simulated using the model described in Campbell and Landmeyer (2014).

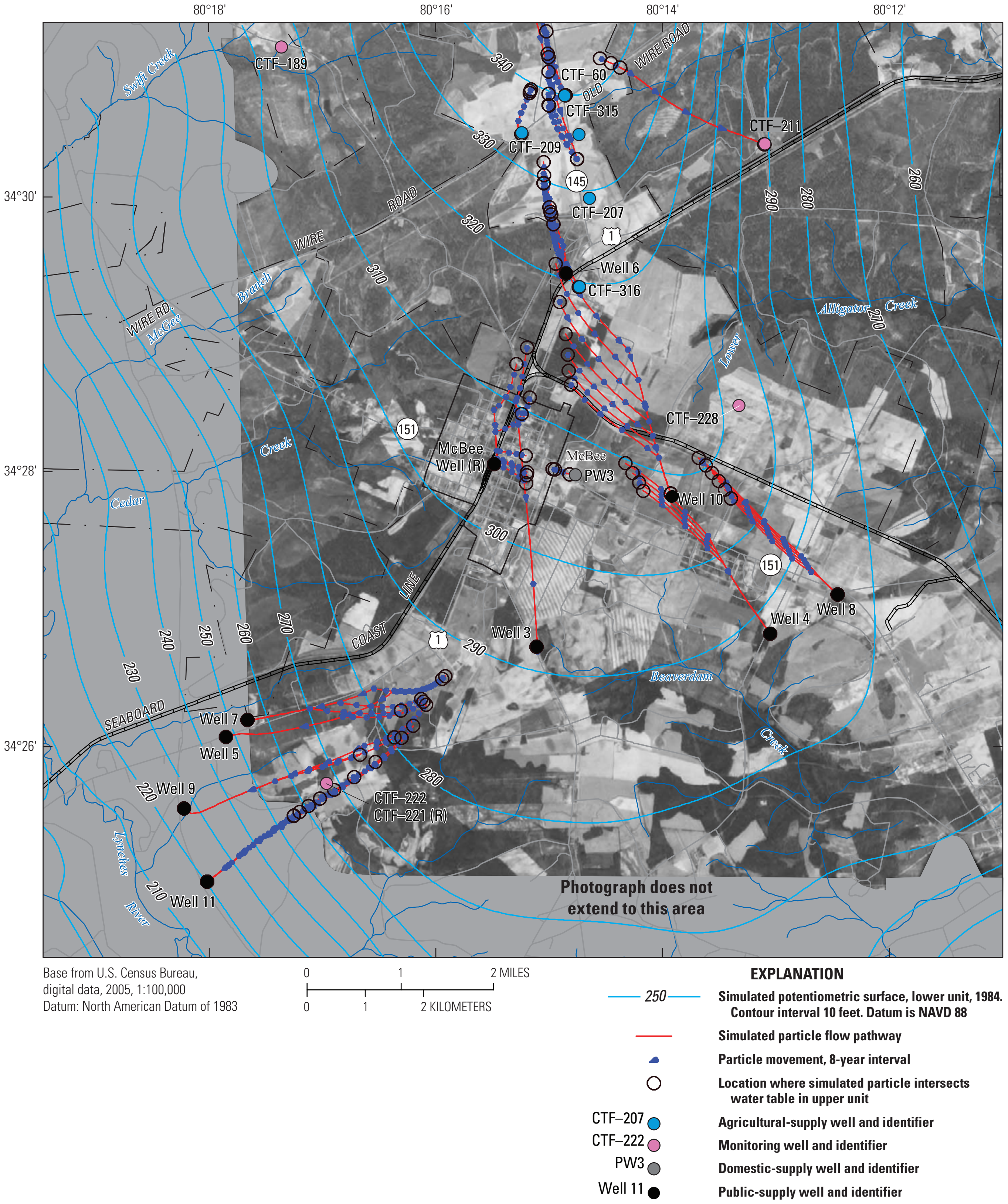


Figure 41. Simulated groundwater flow pathways to public-supply wells calibrated using apparent-age dates estimated by chlorofluorocarbon concentrations detected in groundwater in 2010, McBee, South Carolina. Land use data are from a 1983 aerial photograph. Simulated groundwater flow pathways to some agricultural-supply, domestic-supply, and monitoring wells are shown, but are not calibrated by apparent-age dates. The 1984 potentiometric surface was simulated using the model described in Campbell and Landmeyer (2014).

the widespread use of EDB as a soil fumigant but when EDB was used as a fuel additive (fig. 21). A gasoline source of EDB in groundwater is supported by the co-detection of 1,2–DCA in groundwater from Well 3 (table 6).

The potential source of the DBCP detected in groundwater from public-supply Well 6 and agricultural-supply wells CTF–209 and CTF–60 located north of McBee was assessed (fig. 17). As was the case for the source of EDB detected in these wells, simulated groundwater flow pathways to each well originate in the agricultural area north and south of Wire Road (fig. 38). The apparent age of groundwater pumped from Well 6 is from the mid-1960s and prior to the ban on use of DBCP as a soil fumigant (fig. 21). The potential source of the DBCP detected in groundwater from public-supply Well 3 in the Crouch Branch and McQueen Branch aquifers south of McBee was assessed (fig. 18). Although the EDB detected in groundwater from Well 3 appears to be related to the past use of EDB as a fuel additive, the DBCP detected in groundwater from Well 3 indicates the past application of DBCP as a soil fumigant in agricultural areas south of McBee along the simulated groundwater flow pathway to Well 3 (figs. 38–40). The DBCP detected in groundwater from Well 7 contained lower concentrations of DBCP than groundwater from Well 3 and is located southwest of McBee (fig. 18). The simulated groundwater flow pathway to Well 7 originates in agricultural areas south of McBee (fig. 38–40). The apparent age of groundwater pumped from Well 7 indicates recharge occurred during the mid-1970s (table 11), prior to the ban on the widespread use of DBCP as a soil fumigant (fig. 21).

The potential source(s) of the chlorinated compounds detected in Well 10, the McBee Well(R), and domestic-supply well PW3 was assessed. Well 10 was characterized by low concentrations of 1,1–DCA, TCE, and 1,1–DCE (fig. 19). The simulated groundwater flow pathway to Well 10 originates in an area north of McBee and east of Highway 1 originally used for agriculture (figs. 38–39) but later used for industry (figs. 40–41; building shown on fig. 41). Soil-gas samples collected in this area, where groundwater would have recharged the Crouch Branch aquifer during the 1970s (table 11), were characterized by TCE detections (table 10; fig. 34). The McBee Well(R), was characterized by low concentrations of PCE, TCE, and MTBE (table 6; fig. 19). The simulated groundwater flow pathway to the McBee Well(R) originates almost entirely within the McBee town limits (figs. 38–40). Groundwater would have recharged the Crouch Branch and McQueen Branch aquifers during the 1980s (table 11), a decade when MTBE was beginning to be used as a gasoline additive following the ban on tetraethyl lead. Other potential sources of the PCE and TCE include gasoline stations, auto-repair facilities, and dry cleaners. The domestic-supply well PW3, located between McBee and the McBee Well(R), had groundwater that contained low concentrations of 1,1–DCA, and 1,1–DCE when sampled in 2012 (fig. 19). Domestic-supply well PW3 most likely taps the shallower Crouch Branch aquifer. The simulated, but not age-date calibrated, groundwater flow pathway to PW3 originates near the eastern town limit (figs. 38–40). At the time of the writing of this report, the source of the chlorinated compounds detected in PW3 was not clear.

The relation between more recent land uses in the McBee area, as well as the simulated groundwater flow pathways to wells, is shown in fig. 42. This information may be useful in assessing where additional wells in the McBee area could be located with a lower probability of tapping contaminated groundwater.

Assumptions and Limitations of Methods Used

The assumptions and limitations of the methods used to determine the potential source(s) of observed groundwater contamination in the McBee area primarily revolve around those associated with the use of particle-tracking analyses to simulate groundwater flow pathways using the groundwater-flow model for Chesterfield County (Campbell and Landmeyer, 2014). For example, the groundwater-flow model was constructed using MODPATH, which has a number of limitations that are fully discussed in Pollock (2012). The simulated particle tracking of groundwater flow pathways to a particular well using MODPATH depicts a scenario, but slight changes in the simulated equipotential surface will alter the simulated flow pathways and, therefore, the final particle track pathway will differ slightly. Moreover, particle tracking is tracking the movement of imaginary particles of water, not contaminants dissolved in water. This scenario, however, is realistic for compounds such as EDB, DBCP, and TCE in groundwater in the McBee area where they appear to behave conservatively. Lateral and vertical head gradients and hydraulic properties are important factors that control simulated particle tracks using MODPATH. Hydraulic properties data for the Crouch and McQueen Branch aquifers in the McBee area are sparse, and there are no published measurements of the porosity or vertical hydraulic conductivity for either aquifer. The groundwater-flow model cell size affects the times of travel of the particles and can cause the times to be over- or underestimated depending on the location of production wells within the cells. The calibrated groundwater-flow model of Campbell and Landmeyer (2014) used to perform the MODPATH simulations is one representation of the study area over the time period simulated, and similar results could be achieved through different grid discretization's, model boundary types or locations, and interpolation of model layering or hydraulic properties. However, the calibrated model is considered a reasonable solution and can be used for the purpose of particle tracking described in this report. Because MODPATH particles cannot be placed exactly at the location of each well due to model cell-size limitations, particle-tracking results may over- or underestimate the extent of the simulated flow pathway depending on the locations of these wells within the model cells.

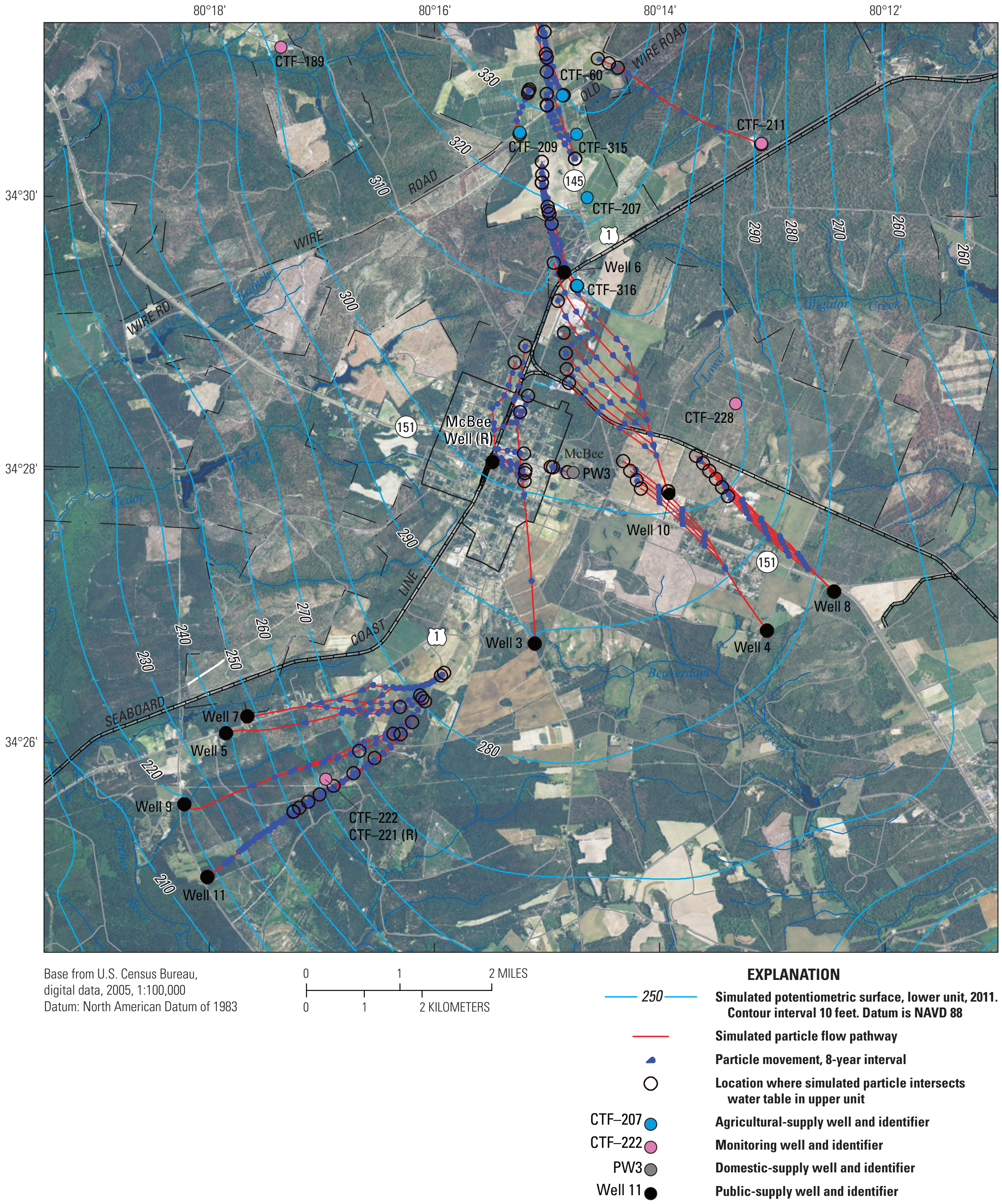


Figure 42. Simulated particle tracking of groundwater flow pathways for public-supply wells calibrated using apparent-age dates, McBee, South Carolina, showing land uses on an aerial photograph from 2011. Simulated particle tracks also shown for wells that are not used for public supply. The 2011 potentiometric surface was simulated using the model described in Campbell and Landmeyer (2014).

The distribution of the groundwater flow pathways delineated by the particles is affected by the conceptual groundwater-flow model and the number of particles simulated (Pollock, 2012). For example, particles placed in the deeper part of a screened interval will have to travel a farther distance (and, therefore, a longer groundwater flow pathway) to a recharge area than particles placed in the shallower part of the screen of the same well (shorter groundwater flow pathway). The simulated groundwater flow pathway of the particles also is affected by the presence of lower permeability confining layers. Groundwater flow and particle flow are primarily horizontal in the aquifer, but when the particles pass through a confining layer, the simulated particle flow pathways exhibit a slower groundwater-flow rate, steeper vertical gradient, and less horizontal flow. The numerical model of Campbell and Landmeyer (2014) consisted of three layers (the two aquifer units separated by a confining unit of lower permeability), groundwater flow occurs between units, and the particles are permitted to move from the well screen to the water table.

Summary and Conclusions

The results of groundwater, spring-water, and soil-gas samples collected and analyzed between 2010 and 2012, and particle-tracking analyses performed using the data collected as part of this investigation (in combination with some data collected by DHEC officials prior to 2010), support the following conclusions:

Ethylene Dibromide, Dibromochloropropane, and other Volatile Organic Compounds in Groundwater

1. The detection of EDB in public-supply Well 6 most likely is related to the past use of EDB as a fumigant in soils located along the groundwater flow pathway to the well, specifically in the recharge area north of McBee. The soil-fumigant source is supported by the co-detection in groundwater from Well 6 of the soil fumigant DBCP, the groundwater flow pathway from the agricultural land uses in the recharge area to the well, and the apparent age of groundwater from the well of the 1960s coincides with when EDB was used as a soil fumigant in the Southeastern United States.

2. The detection of EDB in agricultural-supply well CTF–209 most likely is related to the past use of EDB as a fumigant in soils located along the groundwater flow pathway to the well, specifically in the recharge area north of McBee. The soil-fumigant source is supported by the co-detection of the soil fumigants DBCP and 1,3–DCP in groundwater samples from this well, and the groundwater flow pathway from the agricultural land uses in the recharge area to the well. The detection of DCM and 1,1,2–TCA indicates a source of non-agricultural compounds located along the groundwater flow pathway to the well. The co-detection of tetrahydrofuran may be related to well construction methods.

3. The detection of EDB in groundwater from agricultural-supply well CTF–316 most likely is related to the past use of EDB as a fumigant in soils located along the groundwater flow pathway to the well, specifically in the recharge area north of McBee, and is supported by the groundwater flow pathway from the agricultural land uses in the recharge area to the well.

4. The detection of EDB in groundwater from monitoring wells W1, W2, W3, MW1, MW3, and MW4 most likely is related to the past use of EDB as a fumigant in soils located along the groundwater flow pathway to these wells and the location of the wells downgradient from the wells (described in bullets 1–3 above) that contain EDB. The soil-fumigant source is supported by the co-detection in groundwater from wells W1 and MW3 of the soil fumigant carbon disulfide and of 1,2–DCP in groundwater from wells MW1, MW3, and MW4.

5. The detection of EDB in groundwater from public-supply Well 3 is most likely related to the past use of EDB as an additive to leaded gasoline. The leaded-gasoline source is supported by the co-detection of the lead scavenger 1,2–DCA, and the apparent age of groundwater from the well (1940s) coincides with the time when EDB was used solely as a gasoline additive; this scenario is supported by the groundwater flow pathway from within the McBee town limit to the well.

6. The detection of DBCP in groundwater from agricultural-supply well CTF–60 most likely is related to the past use of DBCP as a fumigant in soils located along the groundwater flow pathway to the well, recharged north of McBee in agricultural areas. The soil-fumigant source is supported by the co-detection of the soil fumigant 1,2–DCP and detection of 1,2–DCP in groundwater from nearby agricultural-supply well CTF–315, and the groundwater flow pathway from the recharge area to the well.

7. Other VOCs such as 1,1–DCA, TCE, and 1,1–DCE detected in groundwater from public-supply Well 10 most likely are related to the past, non-agricultural use of these compounds during the 1970s in areas located along the groundwater flow pathway to the well, including industrial areas east of U.S. Highway 1, north of McBee.

8. Other VOCs such as PCE, TCE, and MTBE detected in groundwater from the public-supply well McBee Well(R) most likely are related to the past, non-agricultural use of these compounds during the 1980s in areas located along the groundwater flow pathway to the well located within the town limits; this scenario is supported by the groundwater flow pathway from within the McBee town limit to the well.

9. Other VOCs such as 1,1–DCA and 1,1–DCE detected in groundwater from domestic-supply well PW3 most likely are related to the past, non-agricultural use of these compounds in areas located along the groundwater flow pathway to the well; this scenario is supported by the groundwater flow pathway from within the McBee town limit to the well.

10. The detection of carbon disulfide in water samples from springs MG–015 and MG–001 most likely is related to the past use of carbon disulfide as one of the original soil fumigants in areas located along the groundwater flow pathway to the springs located downgradient from land historically used for agriculture north of McBee.

Radium Isotopes and Radon in Groundwater

1. Groundwater from public-supply Wells 8 and 10, domestic-supply well PW3, agricultural-supply wells CTF–60 and CTF–315, and monitoring well CTF–222(S), is characterized by concentrations of radium isotopes that exceed the MCL of 5 pCi/L.

2. Wells located north of McBee characterized by groundwater with high radium isotope concentrations all have predominately agricultural land uses along each groundwater flow pathway.

3. Wells located east of McBee and characterized by groundwater with high concentrations of radium isotopes have predominately urban/suburban land uses along each groundwater flow pathway.

4. Wells characterized by groundwater with high radium isotope concentrations are characterized by high specific conductance values. In agricultural areas north of McBee, the high specific conductance in groundwater appears to be related to fertilization. In urban/suburban areas near McBee, the high specific conductance in groundwater appears to be related to domestic and/or industrial septic system drain fields. These potential sources of increased specific conductance to groundwater are supported by groundwater flow pathways determined for these wells.

5. The source of the radium isotopes, at this time, appears to be uranium- and thorium-bearing minerals in aquifer sediments near well screens. It is likely that increases in specific conductance are causing the increased concentrations of radium isotopes in groundwater.

Inorganics in Groundwater

1. The average uranium concentration in ambient groundwater for the McBee area is 0.055 µg/L. The source of elevated uranium concentrations in some deep wells may be due to interaction of groundwater with uranium minerals in pre-Paleozoic to Middle Cambrian bedrock beneath the McQueen Branch aquifer.

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