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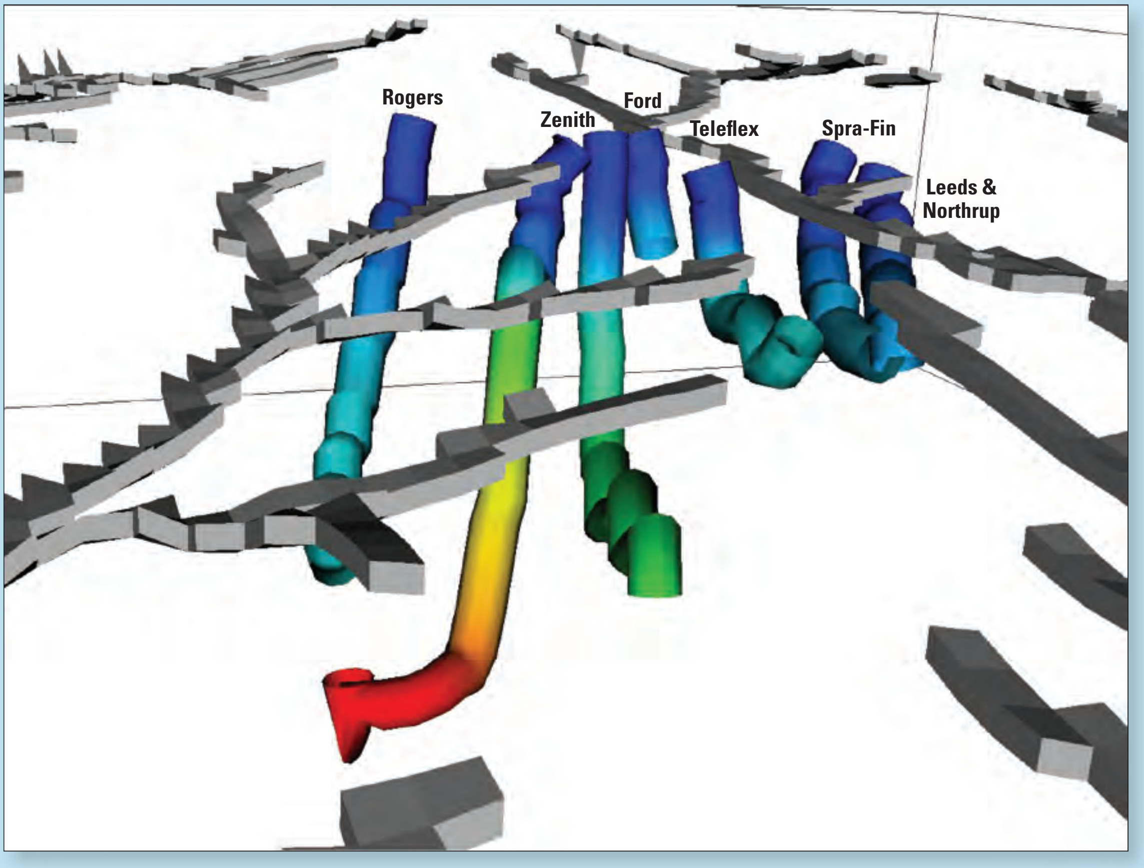
Effects of Changes in Pumping on Regional Groundwater-Flow Paths, 2005 and 2010, and Areas Contributing Recharge to Discharging Wells, 1990–2010, in the Vicinity of North Penn Area 7 Superfund Site, Montgomery County, Pennsylvania



Scientific Investigations Report 2017–5014

U.S. Department of the Interior
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Cover. Three-dimensional perspective view from the southwest of simulated groundwater-flow paths under 2010 conditions, North Penn Area 7 Superfund site and vicinity, Montgomery County, Pennsylvania. Portions of the flow paths are colored by the relative time of travel from the recharge source: short (blue) to long (red). Stream cells in the top layer of the model are also shown (gray), and each cell has dimensions of 100 × 100 × 6 meters. Refer to figures 14 and 15.

Effects of Changes in Pumping on Regional Groundwater-Flow Paths, 2005 and 2010, and Areas Contributing Recharge to Discharging Wells, 1990–2010, in the Vicinity of North Penn Area 7 Superfund Site, Montgomery County, Pennsylvania

By Lisa A. Senior and Daniel J. Goode

Prepared in cooperation with the U.S. Environmental Protection Agency

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

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Conversion Factors

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)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Flow rate	
gallon per minute (gal/min)	5.45099	cubic meter per day (m^3/d)
cubic meter per day (m^3/d)	35.31	cubic foot per day (ft^3/d)
cubic meter per day (m^3/d)	0.183453	gallon per minute (gal/min)
cubic meter per day (m^3/d)	264.2	gallon per day (gal/d)

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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

Supplemental Information

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

Concentrations of chemical constituents in water are given in micrograms per liter (µg/L).

Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Effects of Changes in Pumping on Regional Groundwater-Flow Paths, 2005 and 2010, and Areas Contributing Recharge to Discharging Wells, 1990–2010, in the Vicinity of North Penn Area 7 Superfund Site, Montgomery County, Pennsylvania

By Lisa A. Senior and Daniel J. Goode

Abstract

A previously developed regional groundwater flow model was used to simulate the effects of changes in pumping rates on groundwater-flow paths and extent of recharge discharging to wells for a contaminated fractured bedrock aquifer in southeastern Pennsylvania. Groundwater in the vicinity of the North Penn Area 7 Superfund site, Montgomery County, Pennsylvania, was found to be contaminated with organic compounds, such as trichloroethylene (TCE), in 1979. At the time contamination was discovered, groundwater from the underlying fractured bedrock (shale) aquifer was the main source of supply for public drinking water and industrial use. As part of technical support to the U.S. Environmental Protection Agency (EPA) during the Remedial Investigation of the North Penn Area 7 Superfund site from 2000 to 2005, the U.S. Geological Survey (USGS) developed a model of regional groundwater flow to describe changes in groundwater flow and contaminant directions as a result of changes in pumping. Subsequently, large decreases in TCE concentrations (as much as 400 micrograms per liter) were measured in groundwater samples collected by the EPA from selected wells in 2010 compared to 2005–06 concentrations.

To provide insight on the fate of potentially contaminated groundwater during the period of generally decreasing pumping rates from 1990 to 2010, steady-state simulations were run using the previously developed groundwater-flow model for two conditions prior to extensive remediation, 1990 and 2000, two conditions subsequent to some remediation 2005 and 2010, and a No Pumping case, representing pre-development or cessation of pumping conditions. The model was used to (1) quantify the amount of recharge, including potentially contaminated recharge from sources near the land surface, that discharged to wells or streams and (2) delineate the areas contributing recharge that discharged to wells or streams for the five conditions.

In all simulations, groundwater divides differed from surface-water divides, partly because of differences in stream elevations and because of geologic structure and pumping. In the 1990 and 2000 simulations, all recharge in and near the vicinity of North Penn Area 7 discharged to wells, but in the 2005 and 2010 simulations some recharge in this area discharged to streams, indicating possible discharge of contaminated groundwater from North Penn Area 7 sources to streams. As the amount of groundwater withdrawals by wells has declined since 1990, the area contributing recharge to wells in the vicinity of North Penn Area 7 has decreased.

To determine the effect of changes in pumping on flow paths and possible flow-path-related contributions to the observed changes in spatial distribution of contaminants in groundwater from 2005 to 2010, the USGS conducted simulations using the previously developed regional groundwater-flow model using reported pumping and estimated recharge rates for 2005 and 2010. Flow paths from recharge at known contaminant source areas to discharge locations at wells or streams were simulated under steady-state conditions for the two periods. Simulated groundwater-flow paths shifted only slightly from 2005 to 2010 as a result of changes in pumping rates. These slight changes in groundwater-flow paths from known sources of contamination are not coincident with the spatial distribution of observed changes in TCE concentrations from 2005 to 2010, indicating that the decreases of TCE concentrations may be a result of other processes, such as source removal or degradation. Results of the simulations and the absence of increases in TCE-degradation-product concentrations indicate that the decreases of TCE concentrations observed in 2010 may be at least partly related to contaminant-source removal by soil excavation completed in 2005, although additional data would be needed to confirm this preliminary explanation.

Introduction

Groundwater in and around Lansdale Borough and Upper Gwynedd Township, Montgomery County, Pennsylvania, was found to be contaminated with organic compounds, such as trichloroethylene (TCE) and tetrachloroethylene (PCE) in 1979. At the time contamination was discovered, groundwater was the main source of supply for public and private drinking water and industrial use in this region of the county. The U.S. Environmental Protection Agency (EPA) investigated sources of soil and groundwater contamination and designated five contaminated properties within an approximately 2 square-mile (mi^2) area in the vicinity of production well L-22 (also named well MG-202 by the U.S. Geological Survey) as North Penn Area 7 (fig. 1), placing the site on the National Priorities List (NPL) in March 1989 (CH2M Hill, 1992). The North Penn Area 7 Superfund site lies largely in Upper Gwynedd Township, southeast from, and nearly adjacent to, the NPL (Superfund) site North Penn Area 6 centered in Lansdale and northwest of North Wales Borough (fig. 1). Although some wells in and near North Penn Area 7 were abandoned after contamination was discovered, other wells, including industrial, production, and domestic supply wells, have remained active for various periods. Pumped wells at the West Point, Pa., facility of Merck & Co., Inc., (Merck; fig. 1) account for the largest groundwater withdrawals in the immediate vicinity of North Penn Area 7 as of 2013.

In 2000, the EPA began a Remedial Investigation (RI) with separate operable units for groundwater and soils at North Penn Area 7 (CDM Federal Programs Corporation, 2011a). Since 2000, EPA has installed numerous monitoring wells and conducted several rounds of groundwater sampling of these and other wells (2005, 2006, and 2010). Additionally, contaminated soils were removed at the former Ford property (2004) and at the former Spra-Fin property (2009). Other areas where soil contamination has been of concern include the former Zenith, former Leeds & Northrup, and former Teleflex properties (fig. 1).

The EPA requested technical assistance from the U.S. Geological Survey (USGS). Therefore the USGS, in cooperation with the EPA, conducted a study to provide hydrogeologic data and interpretation of the data to be used in the RI for the North Penn Area 7 Superfund site. From 2000 to 2005, USGS collected groundwater-level, geophysical, and aquifer-test data to describe the groundwater system and to provide a basis for the simulation of groundwater flow (Senior and Ruddy, 2004; Senior and others, 2005, 2008). Simulations of steady-state regional groundwater flow for periods of different pumping conditions (1990, 1996, 2000, 2005) showed that directions of groundwater flow changed in response to changes in pumping (Senior and Goode, 2013). Senior and Goode (2013) also showed that the observed spatial distribution of contaminants was generally consistent with advective transport by groundwater flow from known source areas.

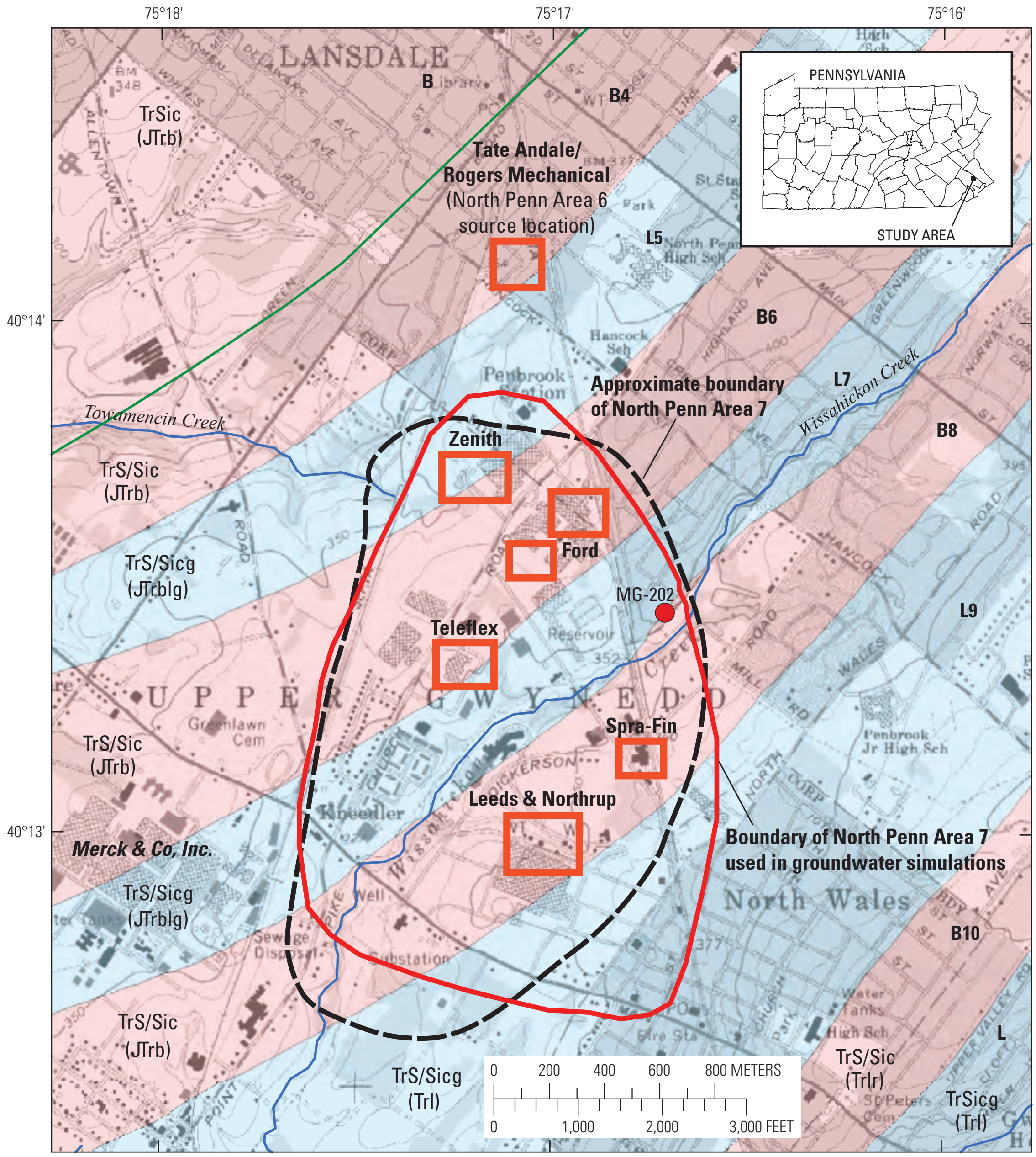
Results of groundwater sampling in 2005 and 2006 by EPA during the RI showed that TCE was the most wide-spread contaminant of concern, although other contaminants [primarily volatile organic compounds (VOCs)] are present in groundwater, including PCE and chlorofluorocarbons (CFC) CFC-11 and CFC-113 (CDM Federal Programs Corporation, 2011a). Simulated groundwater-flow paths under 2005 conditions (Senior and Goode, 2013) from known sources of soil contamination were consistent with the distribution of contaminants in groundwater determined from the autumn 2005 sampling, including apparent separate plumes of CFC-11 and CFC-113. In 2010, the EPA collected another round of groundwater samples in the western part of North Penn Area 7 that showed large decreases in contaminant concentrations compared to 2005–06 results (CDM Federal Programs Corporation, 2011a, b; David Turner, EPA, written commun., 2014).

Subsequently, to further assist the EPA in understanding how pumping may have affected groundwater-flow directions and, specifically, whether 2005 to 2010 decreases in TCE concentrations could be related to changes in pumping, the USGS conducted simulations using the previously developed regional groundwater-flow model (Senior and Goode, 2013). Changes in pumping may also result in changes in the amount of contaminated groundwater discharging to wells or to streams and (or) changes in plume configuration and control. The simulations were done to provide insight on the extent of recharge, including recharge potentially contaminated by sources within North Penn Area 7, that discharges to wells or stream under previous periods of 1990 and 2000, when pumping rates were relatively high, for recent periods of 2005 and 2010, and for a No Pumping case, representing natural background or cessation of pumping conditions.

Purpose and Scope

This report describes the results of simulations of groundwater flow using a previously developed calibrated groundwater-flow model for North Penn Area 7 (Senior and Goode, 2013). The model was used to simulate groundwater flow (1) under 1990, 2000, 2005, 2010, and No Pumping (representing natural background or cessation of pumping) conditions to quantify the amount of recharge discharging to wells and streams and delineate the areas contributing recharge to discharging wells and streams in and near North Penn Area 7, and (2) under 2005 and 2010 conditions to evaluate the effects of changes in pumping between those time periods on groundwater-flow directions and potential distribution of contaminants in groundwater. Water budgets for the five simulation periods and maps showing simulated areas contributing recharge to discharging wells or streams under No Pumping, 1990, 2000, 2005, and 2010 conditions are presented.

Pumping conditions and recharge rates used for the 2010 simulation are documented. Flow paths from known sources of soil contamination simulated under 2010 conditions are compared to observed concentrations of TCE in 2010 groundwater samples and with flow paths simulated under 2005 conditions. Reported concentrations of TCE from 1994 to 2013 in a set of pumped industrial wells that withdraw groundwater originating as recharge in North Penn Area 7 are presented to provide additional data on observed decreases in groundwater-contaminant concentrations.



Base from U.S. Geological Survey Lansdale 1983, 1:24,000
Universal Transverse Mercator projection, Zone 18
North American Datum of 1927

Geology from Berg and others (1980) with nomenclature from Lyttle and Epstein (1987) and additional mapping and lithologic classification from Joseph Smoot (Senior and Goode, 2013))

EXPLANATION

Geologic unit nomenclature			
Bed code, (Senior and Goode, 2013)	Lyttle and Epstein (1987)	Lithologic designation by Joseph Smoot (Senior and Goode, 2013)	Lithology
B	JTrb	TrSic	Brunswick Group (non-deltaic)
B4, B6, B8, B10	JTrb, Trlr	TrS/Sic	Red beds predominant (deltaic)
L5, L7, L9	JTrblg, Trl	TrS/Sicg	Gray beds predominant (deltaic)
L	Trl	TrSicg	Lockatong Formation (non-deltaic)

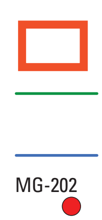


Figure 1. Location of, mapped geology and lithologic units for, and contaminant source areas in North Penn Area 7 Superfund site and vicinity, Montgomery County, Pennsylvania. Geologic nomenclature includes bed codes for geologic units used in the groundwater-flow model of Senior and Goode (2013) and lithologic designations by Joseph Smoot (Senior and Goode, 2013).

Hydrogeologic Setting

Mesozoic-age sedimentary rocks of the Newark Basin underlie North Penn Area 7 and vicinity. Mapped geologic units include the Brunswick Group and Lockatong Formation and consist primarily of shales and siltstones (fig. 1) underlain by siltstones and sandstones of the Stockton Formation to the southeast of the study area (fig. 2). In the vicinity of North Penn Area 7, lithologic units between the underlying predominantly gray beds of the Lockatong Formation and overlying predominantly red beds of Brunswick Group have been mapped as alternating predominant red and gray beds that are deltaic in origin (fig. 1; Senior and Goode, 2013). Bedding of the units generally strikes to the northeast and dips (about 10 degrees) to the northwest at and near North Penn Area 7. The formations form a leaky layered-fractured-rock aquifer recharged locally by precipitation. The North Penn Area 7 Superfund site lies on a surface-water (topographic) divide between the Towamencin Creek Basin to the west and Wissahickon Creek Basin to the east, with the eastern part of the North Penn Area 7 straddling Wissahickon Creek (figs. 1 and 2). The hydrogeologic characteristics of the study area are described in greater detail by Senior and Goode (2013).

Groundwater has been pumped for industrial and public supply since the area was developed more than 100 years ago (circa 1900). Changes in pumping patterns have occurred because of changes in water demand and, more recently, new sources of surface-water supply since the late 1990s.

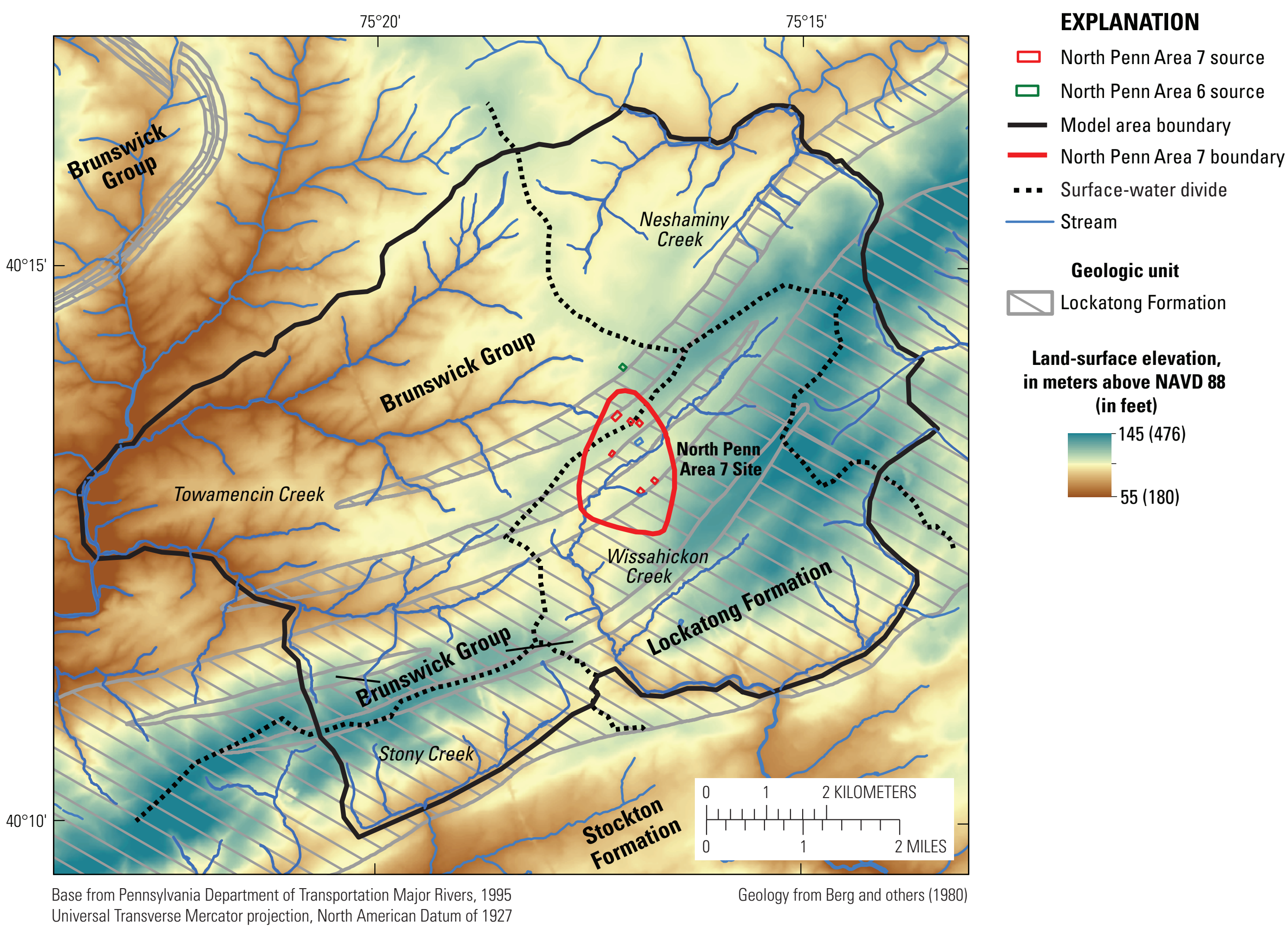


Figure 2. Topography, bedrock geology, streams, surface-water divides, contaminant-source locations, and groundwater-model boundary, North Penn Area 7 Superfund site and vicinity, Montgomery County, Pennsylvania. Geologic units shown are Brunswick Group (unshaded), Lockatong Formation (hachured), and Stockton Formation (unshaded) of the Newark Basin of Triassic age. Streams are shown in blue, with dashed black lines indicating surface-water divides that separate major stream drainages, labeled with the stream name, within the model area. Model and source locations from Senior and Goode (2013).

Changes in Contaminant Concentrations between 2005 and 2010

The EPA conducted three rounds of sampling since monitoring well installation was completed in 2005 as part of the RI. The first two rounds took place in autumn 2005 and spring 2006, and the third round was completed in autumn 2010 (table 1). The spatial distribution and magnitude of concentrations of VOCs in samples from the 2005 and 2006 sampling rounds are similar. TCE had the most wide-spread concentrations at greater than the drinking-water maximum contaminant level of 5 micrograms per liter (µg/L; CDM Federal Programs Corporation, 2011a). However, relatively large differences (decreases) in measured TCE concentrations were apparent between samples collected in 2005 and 2010 from some wells (CDM Federal Programs Corporation, 2011a, b), especially those located in the western part of North Penn Area 7 (fig. 3). A listing of TCE concentrations in wells sampled in 2005 in relation to TCE concentrations in the same wells sampled in 2006 and 2010 shows generally small concentration differences between 2005 and 2006 but a pattern of lower concentrations in 2010 (table 1). TCE concentrations decreased as much as 404 µg/L from 2005 to 2010 in samples from monitoring well MG-2128 (RI-13S). Decreases in concentrations from 2005 to 2010 were at least 100 µg/L in samples from 13 wells [MG-1149 (T10), MG-1148 (T12), MG-1557 (N22), MG-2091 (RI-5I), MG-2121 (RI-10S), MG-2120 (RI-10I), MG-2119 (RI-10D), MG-2128 (RI-13S), MG-2127 (RI-13I), MG-2134 (RI-15S), MG-2133 (RI-15I), and MG-125 (PW-2)] (table 1), all of which except one [MG-2099 (RI-8S)] are in the western part or west of North Penn Area 7 (fig. 3). Decreases in TCE concentrations ranging from 40 to 99 µg/L were apparent for samples from 5 other wells, 3 of which [MG-2089 (RI-4S), MG-2092 (RI-5S), and MG-1423 (PW-12)] are in the western part or west of North Penn Area 7 (fig. 3). The decreases in TCE concentrations between 2005 and 2010 were not associated with increases in concentrations of TCE degradation products such as *cis*-1,2-dichloroethylene (*cis*-1,2-DCE) or vinyl chloride (VC) in samples from wells in the western part of North Penn Area 7, as evidenced by reported data (CDM Federal Programs Corporation 2011a), indicating that degradation may not be a primary process controlling the apparent decreases in TCE concentrations in groundwater in those locations. However, data regarding possible degradation products and processes are limited to a few sampling periods (fall 2005, spring 2006, and fall 2010; CDM Federal Programs Corporation, 2011a), and the extent of possible TCE degradation is unknown.

Additional data on concentrations of TCE and other VOCs in groundwater at and near the Merck facility in West Point, Pa., to the southwest of North Penn Area 7 (fig. 1) were available for the period 1994 to 2013 (David Turner, EPA, written commun., 2014). TCE concentrations in water samples from Merck production and monitoring wells were relatively constant from 1995 to 2005 but generally decreased by as much as an order of magnitude from 2005 to 2013 (fig. 4). The TCE concentration data for samples from Merck wells (fig. 4) confirm and support the apparent decrease in TCE concentrations in samples from monitoring wells in the western part of North Penn Area 7 between two rounds of EPA sampling in 2005 and 2010 (fig. 3).

As with the 2005 and 2010 results of sampling in monitoring wells in the western part of North Penn Area 7 (fig. 3), the observed decreases in TCE concentrations in samples from pumped and monitoring wells at and near the Merck facility (fig. 4) were not accompanied by increases in TCE degradation products *cis*-1,2-DCE (fig. 5) and VC. Concentrations of *cis*-1,2-DCE were relatively constant or decreased from 2005 to 2013 in samples from all pumped and monitoring wells at and near the Merck facility (fig. 5), with the exception of monitoring well N3 (USGS well MG-1539), sited to the northeast of the Merck facility (figs. 3 and 5); concentrations of *cis*-1,2-DCE increased slightly in well N3 during that period.

Pumping Rates in 2010

Pumping rates in and near North Penn Area 7 have been decreasing since alternative sources of water supply became available in the mid to late 1990s and because of changes in industrial activity. In 2010, the annual mean pumping rate in the model area [6,845 cubic meters per day (m^3/d)] was about 40 percent of the annual mean pumping rate in 1990 (16,501 m^3/d) and about 70 percent of the pumping rate in June 2005 (9,705 m^3/d) (data from Russell A. Ludlow, USGS, written commun., 2013) (table 2). Although pumping rates have declined generally through time, the spatial distribution of pumping varied, with about one-third of the wells pumping at higher rates and two-thirds of the wells pumping at lower rates in 2010 than in 2005 (table 2). Within the boundary of North Penn Area 7, annual mean pumping rates in 2010 were similar to or lower than those in June 2005. In the immediate vicinity of North Penn Area 7 (within a distance of 1 mile from the approximate site boundary), pumping rates in 2010 were lower than in previous periods in most wells and higher in only two wells at Merck (table 2). The pumping rate for well MG-1052 in 2005 (table 2) has been corrected on the basis of improved information and differs from that used in the previously developed model (Senior and Goode, 2013). The pumping rates listed for 2010 in units of gal/min and m^3/d (table 2) are the annual mean rates reported for each well, except as noted for three wells near the model boundary, for which pumping rates used in the model are one-half of annual mean rates.

Table 1. Concentrations of selected contaminants in samples collected from monitoring and other wells at and near North Penn Area 7 Superfund site, Montgomery County, Pennsylvania, 2005, 2006, and 2010, and differences in concentrations between 2005 samples compared to 2006 and 2010 samples. Data from CDM Federal Programs Corporation (2011a) and U.S. Environmental Protection Agency (David Turner, written commun., 2014).

[USGS, U.S. Geological Survey; PCE, tetrachloroethylene; TCE, trichloroethylene; DCE, dichloroethylene; *cis*-12DCE, *cis*-1,2-dichloroethylene; µg/L, micrograms per liter; nd, not detected; --, no data or not applicable; <, less than; **Bold**, indicates wells with decreases in TCE concentrations of at least 25 micrograms per liter from 2005 to 2006 or from 2005 to 2010]

USGS local well name (Prefix is MG-)	Other well name	Concentrations of volatile organic compounds (µg/L)														
		2005			2006			2010			Difference between 2006 and 2005			Difference between 2010 and 2005		
		PCE 2005	TCE 2005	*cis*-12DCE05	PCE 2006	TCE 2006	*cis*-12DCE06	PCE 2010	TCE 2010	*cis*-12DCE10	PCEdif 06-05	TCEdif 06-05	DCEdif 06-05	PCEdif 10-05	TCEdif 10-05	DCEdif 10-05
174	Clearline 2	1.9	24	11	0.21	24	9.2	0.30	31	24.00	-1.69	0.00	-1.80	-1.60	7.00	13.00
175	Spra-Fin 1	0	0.52	0.23	0	0.86	0.15	0.00	0.86	0.00	0.00	0.34	-0.08	0.00	0.34	-0.23
1144	T-13	1.9	0.77	0	1.5	1	0.25	1.40	0	0.00	-0.40	0.23	0.25	-0.50	-0.77	0.00
1145	T-14	0.16	6.6	1.8	0.38	3.5	1.4	0.00	1.5	0.00	0.22	-3.10	-0.40	-0.16	-5.10	-1.80
1146	**T-4**	0.6	92	7	1.3	170	14	0.80	62	6.60	0.70	78.00	7.00	0.20	**-30.00**	-0.40
1147	**T-11**	3.1	220	14	9.1	340	17	4.00	190	9.20	6.00	120.00	3.00	0.90	**-30.00**	-4.80
1148	**T-12**	0.7	200	41	0	130	28	0.00	25	13.00	-0.70	**-70.00**	-13.00	-0.70	**-175.00**	-28.00
1149	**T-10**	6.1	130	17	4.5	130	24	3.30	13	9.10	-1.60	0.00	7.00	-2.80	**-117.00**	-7.90
1497		0	0.68	0	0	0.59	0	0.00	0.45	0.00	0.00	-0.09	0.00	0.00	-0.23	0.00
1505	R-18	0	80	250	0	100	290	1.80	250	9.00	0.00	20.00	40.00	1.80	170.00	-241.00
1537	N1	0	15.8	5.73	0	13.2	4.37	0.00	13.1	4.17	0.00	-2.60	-1.36	0.00	-2.70	-1.56
1539	N3	3.78	35.5	5.6	6.19	36.4	6.2	13.80	26.2	7.15	2.41	0.90	0.60	10.02	-9.30	1.55
1540	N4	1	1.43	0	1.35	1.35	0	1.84	0.9	0.00	0.35	-0.08	0.00	0.84	-0.53	0.00
1557	**N22**	0.56	158	16.5	1.77	140	16.8	0.63	13.6	4.15	1.21	-18.00	0.30	0.07	**-144.40**	-12.35
1841	Spra-Fin 2	0	4	0.53	0	4.5	0.14	0.00	4.8	0.39	0.00	0.50	-0.39	0.00	0.80	-0.14
1842	**T-15**	12	260	24	13	370	33	8.10	170	22.00	1.00	110.00	9.00	-3.90	**-90.00**	-2.00
1843	T-6	0.38	20	5.2	0.45	12	3	0.29	12	2.60	0.07	-8.00	-2.20	-0.09	-8.00	-2.60
1844		0	0	0	0	0	0	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1845		0	0	0	0	0	0	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1846		0	0.16	0	0	0	0	0.00	0	0.00	0.00	-0.16	0.00	0.00	-0.16	0.00
1847		4.4	9.2	0	4.2	43	0.33	--	--	--	-0.20	33.80	0.33	--	--	--
1848		0.3	0	0	0.42	0	0	--	--	--	0.12	0.00	0.00	--	--	--
1849			0	0	0.31	0	0	--	--	--	0.31	0.00	0.00	--	--	--
1897	Clearline 3	0	20	0.93	0.94	4.4	0.47	0.00	0.94	0.20	0.94	-15.60	-0.46	0.00	-19.06	-0.73
2080	RI-1D	0	0	0	0	0.22	0	0.00	0	0.00	0.00	0.22	0.00	0.00	0.00	0.00
2081	RI-2D	0	7.4	3.9	0	9.9	5.7	0.00	3.5	3.80	0.00	2.50	1.80	0.00	-3.90	-0.10
2082	RI-2I	0	0.61	0.18	0	0.83	0.33	0.00	0.58	0.85	0.00	0.22	0.15	0.00	-0.03	0.67

Table 1. Concentrations of selected contaminants in samples collected from monitoring and other wells at and near North Penn Area 7 Superfund site, Montgomery County, Pennsylvania, 2005, 2006, and 2010, and differences in concentrations between 2005 samples compared to 2006 and 2010 samples. Data from CDM Federal Programs Corporation (2011a) and U.S. Environmental Protection Agency (David Turner, written commun., 2014).—Continued

[USGS, U.S. Geological Survey; PCE, tetrachloroethylene; TCE, trichloroethylene; DCE, dichloroethylene; *cis*-12DCE, *cis*-1,2-dichloroethylene; µg/L, micrograms per liter; nd, not detected; --, no data or not applicable; <, less than; **Bold**, indicates wells with decreases in TCE concentrations of at least 25 micrograms per liter from 2005 to 2006 or from 2005 to 2010]

USGS local well name (Prefix is MG-)	Other well name	Concentrations of volatile organic compounds (µg/L)														
		2005			2006			2010			Difference between 2006 and 2005			Difference between 2010 and 2005		
		PCE 2005	TCE 2005	*cis*-12DCE05	PCE 2006	TCE 2006	*cis*-12DCE06	PCE 2010	TCE 2010	*cis*-12DCE10	PCEdif 06-05	TCEdif 06-05	DCEdif 06-05	PCEdif 10-05	TCEdif 10-05	DCEdif 10-05
2083	RI-2S	0	0	0	0	0.38	0.13	0.00	0	0.00	0.00	0.38	0.13	0.00	0.00	0.00
2084	RI-3D	16	1.3	0	20	0.76	0.1	25.00	0.75	0.00	4.00	-0.54	0.10	9.00	-0.55	0.00
2085	RI-3I	51	0.6	0.46	54	0.89	0.65	79.00	1.5	1.10	3.00	0.29	0.19	28.00	0.90	0.64
2086	RI-3S	1.4	130	21	0	180	21	1.90	490	86.00	-1.40	50.00	0.00	0.50	360.00	65.00
2087	RI-4D	3.9	9.1	0.63	4.6	9.4	0.69	3.90	9.1	0.63	0.70	0.30	0.06	0.00	0.00	0.00
2088	RI-4I	28	62	6.8	67	99	7.5	59.00	60	4.70	39.00	37.00	0.70	31.00	-2.00	-2.10
2089	**RI-4S**	7.6	140	8.5	17	190	11	6.00	85	5.20	9.40	50.00	2.50	-1.60	**-55.00**	-3.30
2090	**RI-5D**	0.63	51	18	0.49	57	14	0.13	22	5.40	-0.14	6.00	-4.00	-0.50	**-29.00**	-12.60
2091	**RI-5I**	2.5	210	47	2.9	350	65	1.60	5.8	15.00	0.40	140.00	18.00	-0.90	**-204.20**	-32.00
2092	**RI-5S**	3.1	210	49	3.1	340	63	2.10	170	33.00	0.00	130.00	14.00	-1.00	**-40.00**	-16.00
2093	RI-6D	0	0	0	0	0	0	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2094	RI-6S	0	0	0	0	0	0	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2095	RI-7D	0	0	0	0	0	0	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2096	RI-7S	0.3	20	5.1	0.44	25	3.6	0.30	15	1.50	0.14	5.00	-1.50	0.00	-5.00	-3.60
2097	RI-8D	0	0	0	0	0	0	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2098	**RI-8I**	3.7	52	0.7	2.1	49	0.82	0.98	25	0.35	-1.60	-3.00	0.12	-2.72	**-27.00**	-0.35
2099	**RI-8S**	23	200	0.37	25	280	0.45	13.00	100	0.16	2.00	80.00	0.08	-10.00	**-100.00**	-0.21
2100	RI-9D	0	0	0	0	0	0	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2101	RI-9I	0	0	0	0	0	0	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2102	RI-9S	0	9.3	2.6	0	4.7	0.9	0.00	1.9	0.90	0.00	-4.60	-1.70	0.00	-7.40	-1.70
2119	**RI-10D**	1.3	140	12	1.3	210	13	0.64	6.8	3.60	0.00	70.00	1.00	-0.66	**-133.20**	-8.40
2120	**RI-10I**	2.1	200	31	4.3	350	41	2.00	4.6	3.90	2.20	150.00	10.00	-0.10	**-195.40**	-27.10
2121	**RI-10S**	4.8	400	56	5.7	400	34	3.20	3.5	6.40	0.90	0.00	-22.00	-1.60	**-396.50**	-49.60
2122	RI-11D	0	0	0	0	0	0	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2123	RI-11I	0.4	31	35	140	200	270	1.80	140	120.00	139.60	169.00	235.00	1.40	109.00	85.00
2124	RI-11S	4.1	280	110	7.7	650	200	11.00	750	190.00	3.60	370.00	90.00	6.90	470.00	80.00
2125	RI-12D	0	1.4	0.2	0	2	0.25	0.00	1.4	0.20	0.00	0.60	0.05	0.00	0.00	0.00

Table 1. Concentrations of selected contaminants in samples collected from monitoring and other wells at and near North Penn Area 7 Superfund site, Montgomery County, Pennsylvania, 2005, 2006, and 2010, and differences in concentrations between 2005 samples compared to 2006 and 2010 samples. Data from CDM Federal Programs Corporation (2011a) and U.S. Environmental Protection Agency (David Turner, written commun., 2014).—Continued

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USGS local well name (Prefix is MG-)	Other well name	Concentrations of volatile organic compounds (µg/L)														
		2005			2006			2010			Difference between 2006 and 2005			Difference between 2010 and 2005		
		PCE 2005	TCE 2005	*cis*-12DCE05	PCE 2006	TCE 2006	*cis*-12DCE06	PCE 2010	TCE 2010	*cis*-12DCE10	PCEdif 06-05	TCEdif 06-05	DCEdif 06-05	PCEdif 10-05	TCEdif 10-05	DCEdif 10-05
2126	RI-13D	0	6.3	1.3	0	6.8	1.3	0.00	6.3	1.30	0.00	0.50	0.00	0.00	0.00	0.00
2127	**RI-13I**	1.9	160	26	2.3	270	44	1.30	8.1	9.50	0.40	110.00	18.00	-0.60	**-151.90**	-16.50
2128	**RI-13S**	3.6	410	310	2	55	37	1.30	5.8	16.00	-1.60	**-355.00**	-273.00	-2.30	**-404.20**	-294.00
2129	RI-14I	16	0.58	0.17	27	0.55	0.18	32.00	0.68	0.33	11.00	-0.03	0.01	16.00	0.10	0.16
2130	RI-14S	1.2	0	0	1.7	0	0	1.80	0	0.00	0.50	0.00	0.00	0.60	0.00	0.00
2131	RI-15DD	--	--	--	0.21	46	2	0.00	29	1.70	--	--	--	--	--	--
2132	RI-15D	0	59	2.5	--	--	--	0.00	52	3.50	--	--	--	--	-7.00	1.00
2133	**RI-15I**	0.42	410	4.7	0.44	390	4.4	0.25	230	2.70	0.02	-20.00	-0.30	-0.17	**-180.00**	-2.00
2134	**RI-15S**	0.49	220	4.3	0.86	290	6.3	0.40	68	2.10	0.37	70.00	2.00	-0.09	**-152.00**	-2.20
124	PW1	nd	1.8	nd	nd	2.1	nd	<0.5	0.8	<0.5	--	0.33	--	--	-1.00	--
125	**PW2**	0.91	182.0	9.6	1.6	85.2	6.4	0.67	17.2	3.0	0.69	**-96.80**	-3.25	-0.24	**-164.80**	-6.61
126	PW3	nd	8.7	0.7	nd	2.5	0.7	nd	2.4	1.1	--	-6.21	0.04	--	-6.36	0.48
128	PW5	nd	2.0	0.6	nd	1.5	0.6	<0.5	1.2	<0.5	--	-0.59	0.02	--	-0.88	--
130	PW7	nd	24.2	0.9	0.94	19.5	1.6	1.65	7.9	1.7	--	-4.70	0.61	--	-16.27	0.73
991	PW8	nd	13.8	0.8	nd	12.8	1.0	<0.5	2.9	0.7	--	-1.00	0.22	--	-10.90	-0.10
1198	PW9	nd	23.0	0.6	nd	10.1	0.9	<0.5	3.1	<0.5	--	-12.90	0.38	--	-19.91	--
1199	PW11	nd	1.3	nd	nd	2.0	nd	<0.5	<0.05	<0.5	--	0.72	--	--	--	--
1423	**PW12**	0.76	54.4	12.5	1	61.3	11.2	<0.5	9.8	6.5	0.24	6.90	-1.30	--	**-44.59**	-6.01
1424	PW13	nd	5.8	nd	nd	7.5	0.8	<0.5	4.5	<0.5	--	1.65	--	--	-1.30	--
1701	PW14	0.81	28.6	2.2	1.13	26.0	2.0	1.00	6.7	1.0	0.32	-2.60	-0.17	0.19	-21.86	-1.22
1702	PW15	nd	3.6	nd		9.2	2.74	<0.5	2.2	2.35	--	5.67	--	--	-1.31	--
Minimum		0	0	0	0	0	0	0	0	0	-1.69	-355	-273	-10	-404.2	-294
Maximum		51	410	310	140	650	290	79	750	190	139.6	370	235	31	470	85
Mean		3.51	75.81	18.68	7.03	96.65	20.91	4.75	51.86	10.52	3.63	21.39	2.28	1.30	-27.26	-8.95
Median		0.49	12.55	1.55	0.445	10.95	1.1	0.3	5.8	1.4	0	0.22	0	0	-0.77	-0.1

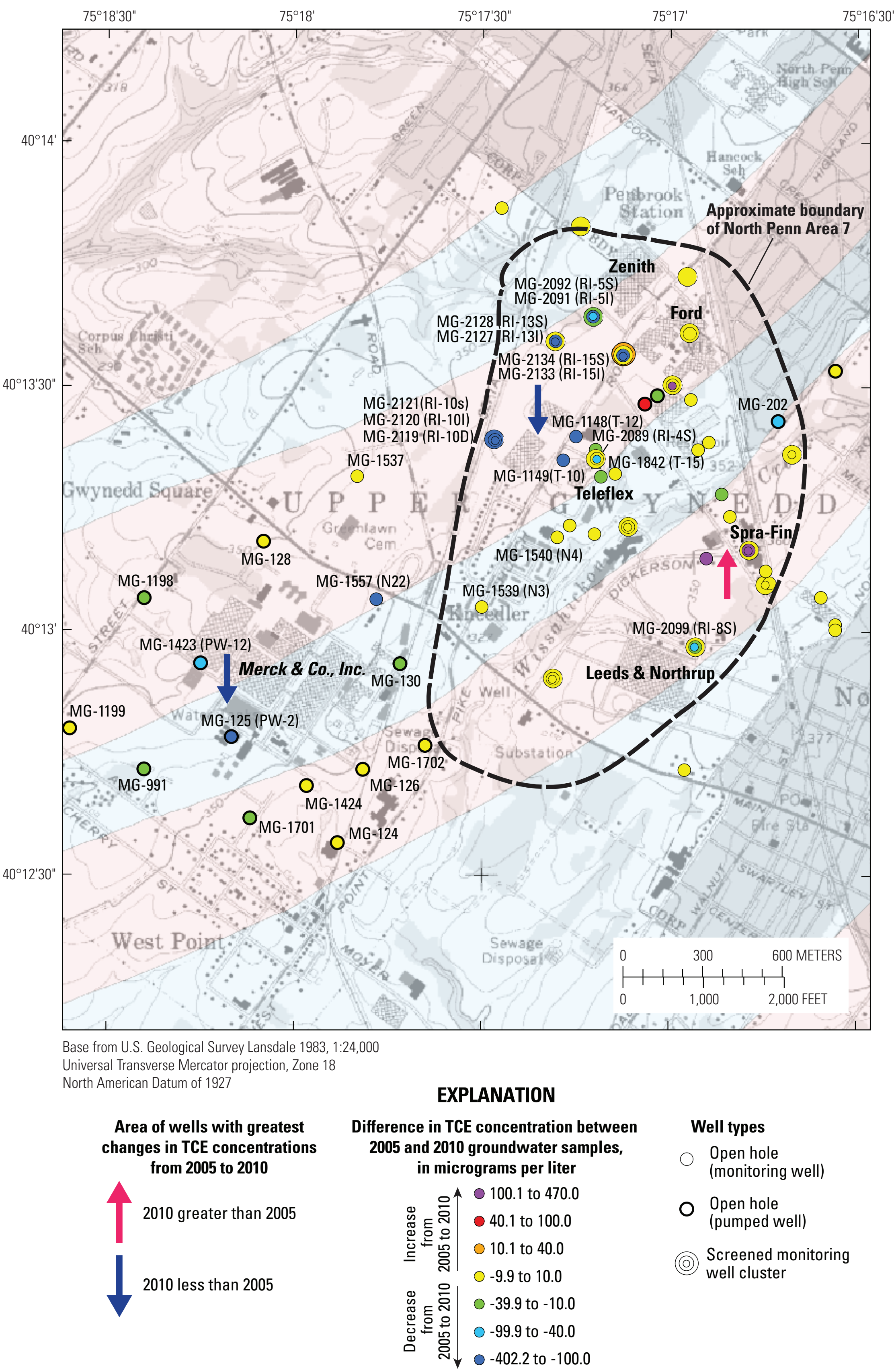

Figure 3. Differences in trichloroethylene (TCE) concentrations between groundwater samples collected in 2005 and 2010 from wells in the North Penn Area 7 Superfund site and vicinity, Montgomery County, Pennsylvania. (Data from CDM Federal Programs Corporation, 2011a and 2011b and David Turner, U.S. Environmental Protection Agency, written commun., 2014)

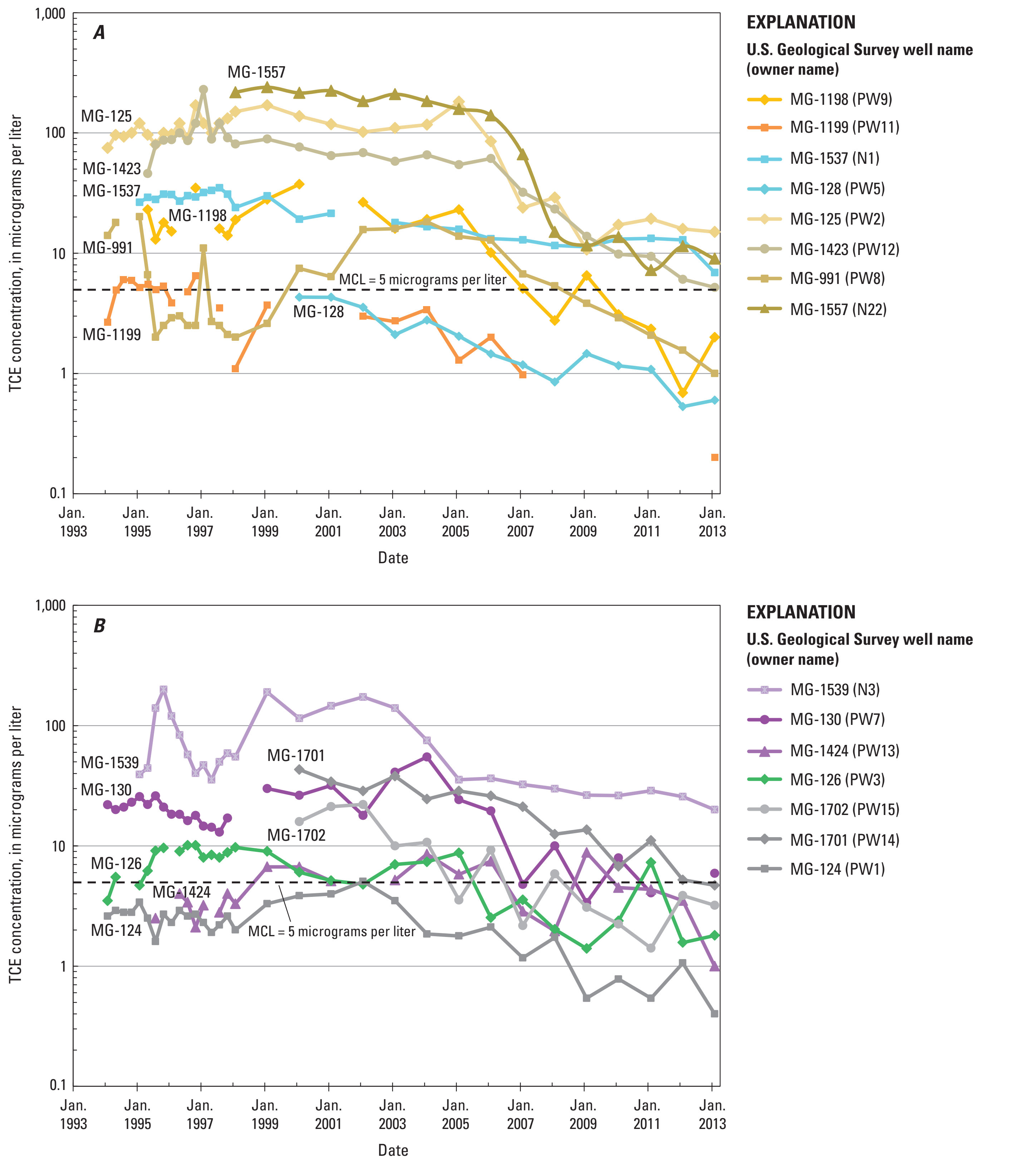

Figure 4. Concentrations of trichloroethylene (TCE) in production (prefix PW) and monitoring wells (prefix N) at Merck West Point facility near North Penn Area 7 Superfund site, Montgomery County, Pennsylvania, 1993–2013: *A*, wells in or close to area of simulated groundwater-flow paths from sources at Zenith, Ford 1, and Ford 2, and *B*, wells in or close to area of simulated groundwater-flow paths from sources at Teleflex, Spra-Fin, and Leeds & Northrup. [Data are from Merck & Co., Inc. (David Turner, EPA, written commun., 2014). See figure 12 for locations of wells and groundwater-flow paths from contaminant sources simulated under 2010 conditions. MCL, maximum contaminant level; PW, prefix for production well; N, prefix for monitoring well]

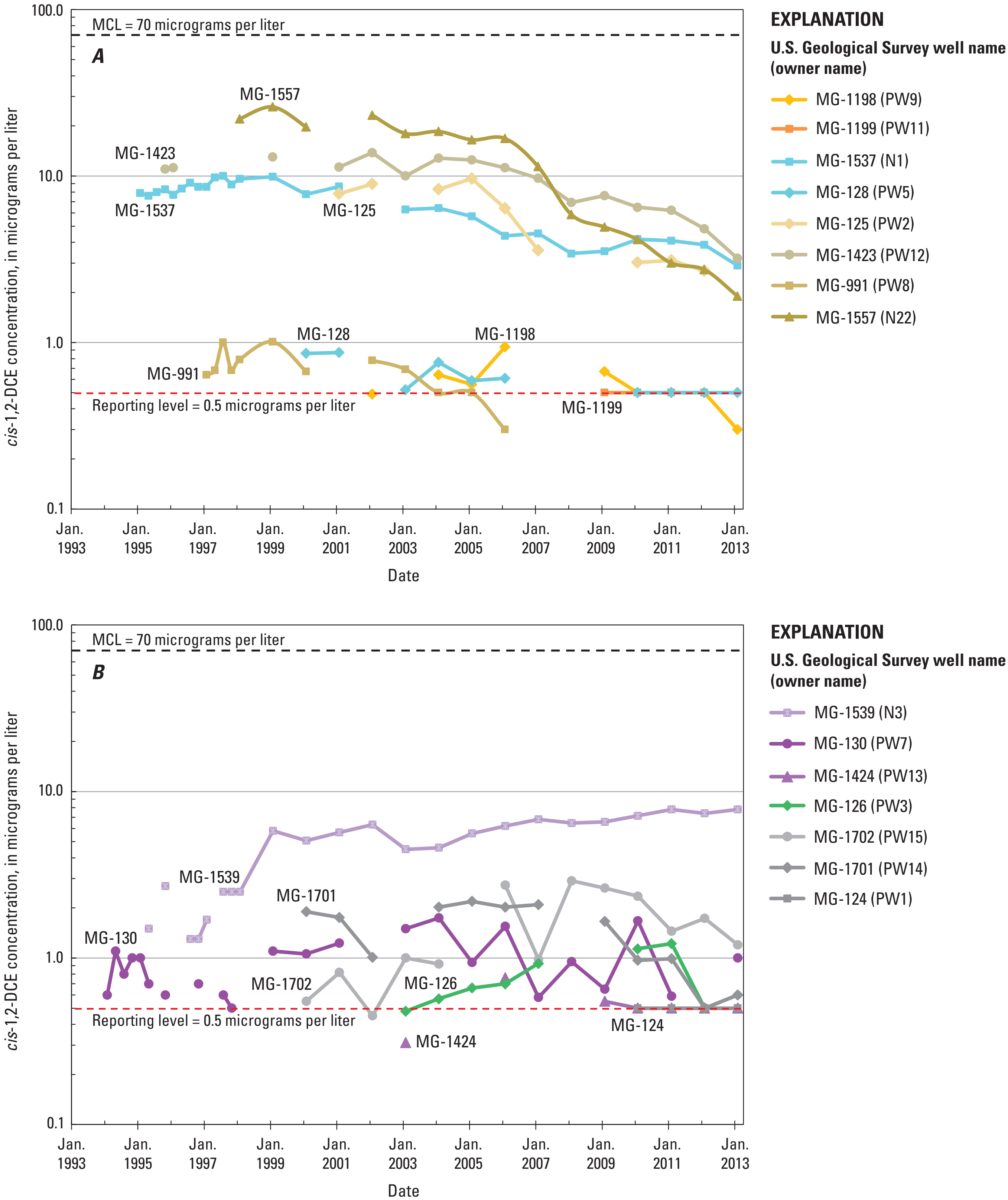

Figure 5. Concentrations of *cis*-1,2-dichloroethylene (*cis*-1,2-DCE) in production (prefix PW) and monitoring wells (prefix N) at Merck West Point facility near North Penn Area 7 Superfund site, Montgomery County, Pennsylvania, 1993–2013 : *A*, wells in or close to area of simulated groundwater-flow paths from sources at Zenith, Ford 1, and Ford 2, and *B*, wells in or close to area of simulated groundwater-flow paths from sources at Teleflex, Spra-Fin, and Leeds & Northrup. [Data from Merck & Co., Inc. (David Turner, EPA, written commun., 2014). See figure 12 for location of wells and groundwater-flow paths from contaminant sources simulated under 2010 conditions. MCL, maximum contaminant level; PW, prefix for production well; N, prefix for monitoring well]

Table 2. Pumping well identification and pumping rates in 1990, 2000, 2005, and 2010 used in regional groundwater-flow model for North Penn Area 7 Superfund site and vicinity, Montgomery County, Pennsylvania. Locations of wells in model area shown on maps in Senior and Goode (1999; plate 1) and Senior and Goode (2013; fig. 40). Shaded rows indicate wells within (dark gray) or at a distance of about 1 mile or less from (light gray) the North Penn Area 7 Superfund site boundary.

[USGS, U.S. Geological Survey; gal/min, gallons per minute; m³/d, cubic meters per day; NP7, North Penn Area 7; **Bold**, indicates wells at the Merck & Co., Inc., facility]

USGS local well name (Prefix is MG-)	Owner's well name or number	Pumping rate (gal/min)				Pumping rate (m³/d)					
		Mean in 1990	December 2000	June 2005	Mean in 2010	Mean in 1990	December 2000	June 2005	Mean in 2010	Difference between 2010 and 1990	Difference between 2010 and 2005
Wells inside NP7 boundary											
89	Ford-1	0	0	0	0	0	0	0	0	0	0
90	Ford-2	0	0	0	0	0	0	0	0	0	0
135	Ford-3	48.2	0	0	0	263	0	0	0	-263	0
147	Ford-4	74.4	0	0	0	406	0	0	0	-406	0
151	Ford-5	86.3	0	0	0	470	0	0	0	-470	0
167	PW1 L&N	14.6	0	0	0	80	0	0	0	-80	0
171	PW1	4.6	4.6	4.6	5.1	25	25	25	28	3	3
202	L-22	81.8	72.1	107.1	88.7	446	393	584	483	38	-100
204	PW2	4.6	4.6	4.6	5.1	25	25	25	28	3	3
223	PW2 L&N	15.8	0	0	0	86	0	0	0	-86	0
1841	Spra-Fin	4.5	4.5	4.5	0	25	25	25	0	-25	-25
TOTAL for wells inside NP7 boundary		334.8	85.8	120.8	98.9	1,825	468	659	539	-1,286	-119
Wells outside of but within 1 mile of NP7 boundary											
52	NW-4	35	0	0	0	191	0	0	0	-191	0
55	NW-5	60	0	0	0	327	0	0	0	-327	0
56	NW-6	0	0	0	0	0	0	0	0	0	0
59	PW3	37.9	30.5	21.4	15.1	207	166	117	82	-124	-34
66	L-7	39.8	0	0	0	217	0	0	0	-217	0
71	L-12	41.3	0	0	0	225	0	0	0	-225	0
73	L-14	71.1	70.4	0	0	388	384	0	0	-388	0
75	L-16	34.8	0	0	0	190	0	0	0	-190	0
76	L-17	87.2	75	66.7	34.6	475	409	364	189	-287	-175
77	L-18	125.6	133.9	0	0	685	730	0	0	-685	0
78	L-19	68.1	50	138.2	54.3	371	273	753	296	-75	-457
124	**PW1**	94.1	74	99.2	89.6	513	403	541	488	-25	-52
125	**PW2**	42.5	45	35.4	44.7	232	245	193	244	12	51
126	**PW3**	94.1	69	80.6	85.6	513	376	439	467	-46	27
128	**PW5**	0	53	72.5	39	0	289	395	213	213	-183
130	**PW7**	88.7	66	29.9	51.8	483	360	163	282	-201	119
140	PW4	78.9	59.3	47.1	41.2	430	323	257	225	-205	-32
203	NW-7	46.2	0	0	0	252	0	0	0	-252	0
566	PW-5	55	60.6	79	54.4	300	330	431	297	-3	-134
991	**PW8**	98.2	48	108.6	76.8	535	262	592	419	-117	-173
1198	**PW9**	50.6	7	23.1	21	276	38	126	114	-161	-11
1199	**PW11**	41.7	68	101.7	68.3	227	371	554	372	145	-182
1336	Allied Conc.	4.4	4.4	4.4	4.4	24	24	24	24	0	0
1423	**PW12**	0	11	35.3	31.2	0	60	192	170	170	-22
1424	**PW13**	0	51	88.1	55.7	0	278	480	304	304	-177
1701	**PW14**	0	15	13.6	12.9	0	82	74	70	70	-4
1702	**PW15**	0	75	113.1	109.4	0	409	616	596	596	-20
TOTAL for wells within 1 mile of NP7 boundary		1,295.2	1,066.1	1,157.9	890.0	7,059	5,811	6,311	4,851	-2,209	-1,460

Table 2. Pumping well identification and pumping rates in 1990, 2000, 2005, and 2010 used in regional groundwater-flow model for North Penn Area 7 Superfund site and vicinity, Montgomery County, Pennsylvania. Locations of wells in model area shown on maps in Senior and Goode (1999; plate 1) and Senior and Goode (2013; fig. 40). Shaded rows indicate wells within (dark gray) or at a distance of about 1 mile or less from (light gray) the North Penn Area 7 Superfund site boundary.—Continued

[USGS, U.S. Geological Survey; gal/min, gallons per minute; m^3/d, cubic meters per day; NP7, North Penn Area 7; **Bold**, indicates wells at the Merck & Co., Inc., facility]

USGS local well name (Prefix is MG-)	Owner's well name or number	Pumping rate (gal/min)				Pumping rate (m^3/d)					
		Mean in 1990	December 2000	June 2005	Mean in 2010	Mean in 1990	December 2000	June 2005	Mean in 2010	Difference between 2010 and 1990	Difference between 2010 and 2005
Other wells in model area											
67	L-8	60	0	0	0	327	0	0	0	-327	0
68	L-9	2.3	0	0	0	13	0	0	0	-13	0
69	L-10	68.8	0	0	0	375	0	0	0	-375	0
70	L-11	0	0	0	0	0	0	0	0	0	0
122		0	0	0	0	0	0	0	0	0	0
134	Kendick Rubber	2.4	2.4	2.4	2.4	13	13	13	13	0	0
143	L-21	72.5	0	0	0	395	0	0	0	-395	0
150			0	0	0	0	0	0	0	0	0
152	PW1	0	0	0	0	0	0	0	0	0	0
153	PW-2	19.6	0	0	0	107	0	0	0	-107	0
168			0	0	0	0	0	0	0	0	0
169	well 3	0	0	0	0	0	0	0	0	0	0
187			0	0	0	0	0	0	0	0	0
188			0	0	0	0	0	0	0	0	0
192			0	0	0	0	0	0	0	0	0
193			0	0	0	0	0	0	0	0	0
198			0	0	0	0	0	0	0	0	0
200	H-1		0	0	0	0	0	0	0	0	0
205			0	0	0	0	0	0	0	0	0
454			0	0	0	0	0	0	0	0	0
498	L-23	27.5	24.5	20.8	13.5	150	134	113	74	-76	-40
592			0	0	0	0	0	0	0	0	0
593	L-25	64.9	0	0	0	354	0	0	0	-354	0
594			0	0	0	0	0	0	0	0	0
617			0	0	0	0	0	0	0	0	0
620	PW-3	10.6	0	0	0	58	0	0	0	-58	0
621	PW-4	10	0	0	0	55	0	0	0	-55	0
622			0	0	0	0	0	0	0	0	0
625	Rex-1	35.4	35.4	35.4	31.6	193	193	193	172	-21	-21
626	PW3		0	0	0	0	0	0	0	0	0
629			0	0	0	0	0	0	0	0	0
630			0	0	0	0	0	0	0	0	0
644	H-5	0	0	0	0	0	0	0	0	0	0
685			0	0	0	0	0	0	0	0	0
704	L-26	39.7	0	0	0	216	0	0	0	-216	0
853	NP-46	0	0	0	0	0	0	0	0	0	0
875	NW-17	69.3	5.2	5.15	11	378	28	28	60	-318	32
876			0	0	0	0	0	0	0	0	0
909	NP-8	0	0	0	0	0	0	0	0	0	0
914	NP-12	99.6	0	0	0	543	0	0	0	-543	0
919	NP-17	258.4	118.9	172.1	9	1,409	648	938	49	-1,359	-889
1028	NP34	80	76.4	71.5	0	436	416	390	0	-436	-390

Table 2. Pumping well identification and pumping rates in 1990, 2000, 2005, and 2010 used in regional groundwater-flow model for North Penn Area 7 Superfund site and vicinity, Montgomery County, Pennsylvania. Locations of wells in model area shown on maps in Senior and Goode (1999; plate 1) and Senior and Goode (2013; fig. 40). Shaded rows indicate wells within (dark gray) or at a distance of about 1 mile or less from (light gray) the North Penn Area 7 Superfund site boundary.—Continued

[USGS, U.S. Geological Survey; gal/min, gallons per minute; m^3/d, cubic meters per day; NP7, North Penn Area 7; **Bold**, indicates wells at the Merck & Co., Inc., facility]

USGS local well name (Prefix is MG-)	Owner's well name or number	Pumping rate (gal/min)				Pumping rate (m^3/d)					
		Mean in 1990	December 2000	June 2005	Mean in 2010	Mean in 1990	December 2000	June 2005	Mean in 2010	Difference between 2010 and 1990	Difference between 2010 and 2005
1045	PW5	13.4	0	0	0	73	0	0	0	-73	0
1048	NW-16		0	0	0	0	0	0	0	0	0
1049	NW-20		0	0	0	0	0	0	0	0	0
1050	NW-21	139.8	65.5	65.5	72.7	762	357	357	396	-366	39
1051	NW-22	121.9	9.7	9.74	11.6	664	53	53	63	-601	10
1052	NW-23b	52.2	0	0	0	285	0	0	0	-285	0
1053	NW-25		0	0	0	0	0	0	0	0	0
1122	L-29		0	0	0	0	0	0	0	0	0
1124	NP-58		0	0	0	0	0	0	0	0	0
1125	NP-61	40.4	72.8	79.4	14.6	220	397	433	80	-141	-353
1126	NP-62		0	0	0	0	0	0	0	0	0
1127	NP-66		0	0	0	0	0	0	0	0	0
1128	NP-70		0	0	0	0	0	0	0	0	0
1130	NP-72		0	0	0	0	0	0	0	0	0
1141	NW-15		0	0	0	0	0	0	0	0	0
1151	H-9		0	0	0	0	0	0	0	0	0
1152	H-11		0	0	0	0	0	0	0	0	0
1407	Hatfield M #10		0	0	0	0	0	0	0	0	0
1416			0	0	0	0	0	0	0	0	0
1417			0	0	0	0	0	0	0	0	0
1418	Ziegler	2.5	2.5	0	0	14	14	0	0	-14	0
1484	Trotter Pretzel	0.32	0	0	0	2	0	0	0	-2	0
1534			0	0	0	0	0	0	0	0	0
1625	Electra ELEEX	0	0	0	21	0	0	0	114	114	114
1641	Rex-2S	0	5	5	5	0	27	27	27	27	0
1653	Trotter Pretzel 1	0.06	0	0	0	0.3	0	0	0	-0.3	0
1667	Royal Cleaners	2	2	0	0	11	11	0	0	-11	0
1899	Westside	0	0	0	22.3	0	0	0	122	122	122
1946	Keystone 7	0	0	20	15.3	0	0	109	83	83	-26
1938	Royal 2	0	0	15	37	0	0	82	202	202	120
Three wells close to model border are simulated using pumping rates listed below, which are one-half of reported rates.											
924	NP-21	28.7	0	0	0	156	0	0	0	-156	0
1014	H-10	74	64.7	0	0	404	352	0	0	-404	0
1486	Baum Meat	1.15	0	0	0	6	0	0	0	-6	0
TOTAL for other wells		1,397.4	484.9	502.0	267.0	7,617	2,643	2,736	1,455	-6,161	-1,281
TOTAL for all wells in model area		*3,027.4*	*1,636.8*	*1,780.7*	*1,255.9*	*16,503*	*8,923*	*9,707*	*6,847*	*-9,656*	*-2,860*

Groundwater-Flow Simulations

For this investigation, a previously developed model of regional groundwater flow in and near North Penn Area 7 (Senior and Goode, 2013) was used to evaluate (1) groundwater flow under No Pumping (representing natural background conditions or cessation of pumping in the area), 1990, 2000, 2005, and 2010 conditions and to delineate areas contributing recharge to discharging wells and streams, and (2) the effect of changes in pumping between 2005 and 2010 on directions of groundwater flow and potential distribution of contaminants in groundwater. The model construction, parameters, and calibration are described by Senior and Goode (2013), and only modifications to that model are discussed in detail in this report. Model input files and other information needed to run the model for simulations presented in this report are provided in a USGS data release (Goode and Senior, 2017).

The model area encompasses approximately 67 square kilometers (km^2) (26 mi^2). As described by Senior and Goode (2013), the model grid is aligned parallel to the regional strike of the dipping sedimentary beds (45 degrees NE) and corresponds to the assumed major axis of anisotropy of horizontal hydraulic conductivity. Cell dimensions of the horizontal model grid are 100 meters (m) × 100 m (328 ft × 328 ft). The top two hydrogeologic units are conceptualized as a soil or colluvium unit and a highly weathered rock unit with uniform thicknesses of 6 m (19.7 ft) each. Beneath the subhorizontal soil and highly weathered rock units, the regional-scale model has a vertical structure that mimics the dipping stratigraphy of the geologic units, which vary in thickness from 47 to 233 m (154 to 764 ft), as defined by geologic mapping in the area and by correlations between borehole logs (Senior and others, 2008).

The groundwater-flow model software and optional packages used for all simulations were the same as those used by Senior and Goode (2013). In summary, the software and optional packages include Graphical user interface version 4.35 of Winston (2000) and Argus Interware, Inc. (1997), MODFLOW-2000 version 1.19 (Harbaugh and others, 2000), GMG solver (Wilson and Naff, 2004), Hydrogeologic-Unit Flow package (Anderman and Hill, 2000), Multi-Node Well package (Halford and Hanson, 2002), and STReam package (Prudic, 1989; Harbaugh and others, 2000). Flow paths were delineated and areas contributing recharge to discharging wells and streams were mapped by use of MODPATH (version 5 update of Pollock, 1994). Flow paths were delineated from areas of known soil contamination to final discharge locations in well or stream cells of the model. Flow paths were visualized in three dimensions using Model Viewer version 1.6 (Hsieh and Winston, 2002). Model water budgets were computed using ZONEBUDGET version 3.01 (Harbaugh, 1990).

Steady-state water levels and groundwater fluxes were simulated for five conditions—No Pumping, 1990, 2000, 2005, and 2010. Of these, three conditions—1990, 2000, and 2005—were simulated by Senior and Goode (2013). Recharge rates in 2000 and 2005 [109 and 124 millimeters (mm)/year, respectively] were estimated by model calibration (Senior and Goode, 2013) and assumed to be spatially uniform, as was recharge for 1996, a relatively wetter year, as indicated by precipitation records (National Oceanic and Atmospheric Administration, 2015) (see table 1-1 in Appendix 1). Senior and Goode (2013) used the calibration results for 1996, 2000, and 2005 periods to estimate the recharge rate for use in simulating conditions in 1990 (127 mm/year), a near-normal year. For the two new conditions, No Pumping and 2010, the uniform recharge rate was assumed to be the same as that for 2005, intermediate between the calibrated rates in 1996 (wet year) and 2000 (dry year). The recharge rates used for the model (table 3) are similar in magnitude to the base flow calculated from the record for the USGS gaging station (01472810) on a nearby stream (East Branch Perkiomen Creek) (table 1-1 in Appendix 1) that drains the geologic units (Brunswick Group and Lockatong Formation) underlying the model area (fig. 1-1 in Appendix 1). Pumping rates for 2010 were estimated on the basis of information from USGS water-use data for 2010 (Russell A. Ludlow, USGS, written commun., 2013; table 2). In addition, the model of Senior and Goode (2013) was revised for 2000 and 2005 conditions by reducing the pumping rate of well MG-1052 to zero on the basis of revised historical pumping information (table 2).

A basic application of groundwater models is the quantification and delineation of areas of recharge that contribute groundwater discharge to wells or to streams as part of the overall water budget. In the vicinity of North Penn Area 7 or other locations with groundwater contamination, the role of pumped wells in controlling or capturing groundwater contamination may be important. For steady-state conditions, the budget describes the overall inflows to the aquifer system, including prescribed inflows, such as specified recharge, and simulated inflows, such as stream loss that enters the water table. Likewise, the outflows include prescribed pumping rates at wells and simulated base flow to streams. There are no groundwater inflows or outflows through the assumed no-flow lateral and bottom boundaries of the model domain. For the water budgets for the North Penn Area 7 Superfund site, the simulation included groundwater inflow and outflow within the site area and at the site boundary. Groundwater withdrawals were a large fraction of total outflow in the area for the study periods, and there were large changes in withdrawals between those periods. The area of the model used to calculate water budgets within the North Penn Area 7 boundary is shown in Appendix 1 figure 1-2.

The water budgets are different for each simulation period (table 3). The only differences in model-input parameters among the five simulations are the recharge rates and the pumping rates. Recharge to the entire modeled area and to the North Penn Area 7 varied from highest rates in 1990 to lowest rates in 2000. Of the simulations with pumping, withdrawal rates in the entire model area were lowest in 2010 but in the local North Penn 7 area were lowest in 2000 (table 3). Under the conditions in 1990, with the highest pumping rates, about 47 percent of the recharge for the entire model area ultimately discharged to pumped wells, and only 53 percent was net stream base flow. Because pumping rates have declined, pumping in 2010 accounted for a much smaller part of total recharge with about 20 percent of recharge discharging to wells.

Table 3. Simulated water budgets for No Pumping, 1990, 2000, 2005, and 2010 conditions for the model area and the North Penn Area 7 Superfund site, Montgomery County, Pennsylvania. Area for water-budget calculation delineated by North Penn Area 7 Superfund site boundary as shown in figure 1-2 in Appendix 1.

[m^3/d, cubic meters per day; mm, millimeters; area for site water-budget calculation delineated by North Penn Area 7 boundary as shown in figure 1]

	Unit	Conditions				
		No Pumping	1990	2000	2005	2010
Entire model						
Inflows						
Recharge	m^3/d	34,411	35,269	30,307	34,411	34,411
Stream loss	m^3/d	1,187	3,451	2,850	2,834	2,620
Outflows						
Withdrawal by wells	m^3/d	0	16,503	8,923	9,707	6,847
Stream gain	m^3/d	35,598	22,217	24,234	27,538	30,184
Net stream gain	m^3/d	*34,411*	*18,766*	*21,384*	*24,704*	*27,564*
North Penn Area 7 Superfund site						
Inflows						
Recharge	m^3/d	974	998	858	974	974
Stream loss	m^3/d	0	44	46	83	16
Groundwater inflow	m^3/d	1,511	2,012	1,294	1,902	1,958
Outflows						
Withdrawal by wells	m^3/d	0	1,825	468	659	539
Stream gain	m^3/d	870	0	2	39	159
Net stream gain	m^3/d	*870*	*-44*	*-44*	*-44*	*143*
Groundwater outflow	m^3/d	1,615	1,228	1,728	2,261	2,250
Entire model						
Inflows						
Recharge	mm	124	127	109	124	124
Stream loss	mm	4	12	10	10	9
Outflows						
Withdrawal by wells	mm	0	59	32	35	25
Stream gain	mm	128	80	87	99	109
Net stream gain	mm	*124*	*68*	*77*	*89*	*99*
North Penn Area 7 Superfund site						
Inflows						
Recharge	mm	124	127	109	124	124
Stream loss	mm	0	6	6	11	2
Groundwater inflow	mm	192	256	165	242	249
Outflows						
Withdrawal by wells	mm	0	232	60	84	69
Stream gain	mm	111	0	0	5	20
Net stream gain	mm	*111*	*-6*	*-6*	*-6*	*18*

Table 3. Simulated water budgets for No Pumping, 1990, 2000, 2005, and 2010 conditions for the model area and the North Penn Area 7 Superfund site, Montgomery County, Pennsylvania. Area for water-budget calculation delineated by North Penn Area 7 Superfund site boundary as shown in figure 1-2 in Appendix 1.—Continued

[m^3/d, cubic meters per day; mm, millimeters; area for site water-budget calculation delineated by North Penn Area 7 boundary as shown in figure 1]

	Unit	Conditions				
		No Pumping	1990	2000	2005	2010
Groundwater outflow	mm	205	156	220	288	286
Entire model						
Inflows						
Recharge	Inch	4.9	5.0	4.3	4.9	4.9
Stream loss	Inch	0.2	0.5	0.4	0.4	0.4
Outflows						
Withdrawal by wells	Inch	0.0	2.3	1.3	1.4	1.0
Stream gain	Inch	5.0	3.2	3.4	3.9	4.3
Net stream gain	Inch	*4.9*	*2.7*	*3.0*	*3.5*	*3.9*
North Penn Area 7 Superfund site						
Inflows						
Recharge	Inch	4.9	5.0	4.3	4.9	4.9
Stream loss	Inch	0.0	0.2	0.2	0.4	0.1
Groundwater inflow	Inch	7.6	10.1	6.5	9.6	9.8
Outflows						
Withdrawal by wells	Inch	0.0	9.1	2.3	3.3	2.7
Stream gain	Inch	4.4	0.0	0.0	0.2	0.8
Net stream gain	Inch	*4.4*	*-0.2*	*-0.2*	*-0.2*	*0.7*
Groundwater outflow	Inch	8.1	6.2	8.7	11.4	11.3

Areas Contributing Recharge to Discharging Wells and Streams

The spatial distribution and amount of recharge that discharged to wells or to streams in the vicinity of North Penn Area 7 has changed through time as a result of changes in pumping and recharge rates. The boundaries between areas contributing recharge to groundwater that discharges to streams are often similar to watershed boundaries (topographic divides) but are not necessarily aligned. Thus, groundwater basins and divides may differ spatially from the overlying surface-water basins and divides.

Areas contributing recharge to discharging wells and to streams (base flow) were simulated for No Pumping, 1990, 2000, 2005, and 2010 conditions by use of the model of Senior and Goode (2013). MODPATH (Pollock, 1994) was used to track a single particle from every model cell where recharge entered the model at the water table to its ultimate discharge point at a model cell containing either a stream or a well. The starting locations (model cells) of the particles were coded by the discharge locations, either 1 of the 4 major stream networks or pumped wells. Maps illustrate the area contributing recharge to the discharging wells and streams; the maps are similar to a watershed boundary, surface drainage, or topographic divide map that shows the area that provides overland runoff to different streams or stream networks.

No Pumping Conditions

The simulation for No Pumping conditions uses the model of Senior and Goode (2013) but without any active pumped wells. Such simulations are often used to approximate pre-development conditions and can represent cessation of all pumping. In many settings, the areas that contribute groundwater recharge to base flow to the regional stream networks (fig. 6) are similar to topographic watersheds; thus, groundwater divides are near the surface-water (topographic) divides (fig. 2). The North Penn Area 7 Superfund site is located along the topographic divide between the Towamencin Creek surface-water (drainage) basin and the Wissahickon Creek drainage basin. Under No Pumping conditions, some of the recharge that entered the water table within the Wissahickon Creek drainage area discharged to Towamencin Creek, or was “captured” by the adjacent stream network. This effect, caused in part by the relatively lower elevations of the Towamencin Creek than the adjacent streams (fig. 2) and in part by the regional hydrogeologic structure, was even more pronounced along the drainage divide between the Towamencin and Neshaminy Creeks in the north (fig. 6). Thus, the upper, headwater reaches of the Neshaminy Creek tributaries were not sustained by base flow under the assumed hydrologic conditions and recharge rate (equal to the 2005 rate).

1990 Conditions

Conditions for the 1990 simulation included the highest recharge rate and the highest overall rate of withdrawals by wells (tables 2 and 3). The area contributing recharge to discharging wells was the largest among the simulation periods. All recharge in the upper Wissahickon Creek area, including North Penn Area 7, discharged to wells (fig. 7). Additionally, some recharge in the adjacent Towamencin Creek surface-water (drainage) basin discharged to wells within the Wissahickon Creek drainage basin.

2000 Conditions

Conditions for the 2000 simulation included the lowest rate of recharge and lowest rate of withdrawals by wells in the vicinity of North Penn Area 7 (but not the lowest overall withdrawal rate for the modeled area) among simulation periods (tables 2 and 3). Although the area contributing recharge to discharging wells was smaller under 2000 conditions than under 1990 conditions, all recharge in the upper Wissahickon Creek area, including North Penn Area 7, discharged to wells in the 2000 simulation (fig. 8).

2005 Conditions

Conditions for the 2005 simulation included an intermediate rate of recharge and an intermediate rate of withdrawals by wells in the vicinity of North Penn Area 7 among the five simulation periods (tables 2 and 3). The area contributing recharge to discharging wells was smaller under 2005 conditions than under 1990 and 2000 conditions. A small area of recharge in the upper Wissahickon Creek Basin, including thin bands along the creek in North Penn Area 7, was simulated as discharging to Wissahickon Creek in the 2005 simulation (fig. 9).

2010 Conditions

Conditions for the 2010 simulation include an intermediate rate of recharge but the lowest rate of withdrawals by pumped wells overall among the five simulation periods (tables 2 and 3). The area contributing recharge to discharging wells was smaller under 2010 conditions than under 1990, 2000, and 2005 conditions. In contrast to the simulations for 1990 and 2000 conditions but similar to simulation the for 2005 conditions, some recharge in the upper Wissahickon Creek area, including parts of North Penn Area 7, discharged to Wissahickon Creek in the 2010 simulation; the balance discharged to pumped wells (fig. 10). The areas where recharge discharges to Wissahickon Creek are larger in the 2010 simulation than in the 2005 simulation. The 2010 simulation indicates that there is potential for groundwater that has acquired contaminants from recharge in source areas in North Penn Area 7 to discharge to streams (Wissahickon and Towamencin Creeks).

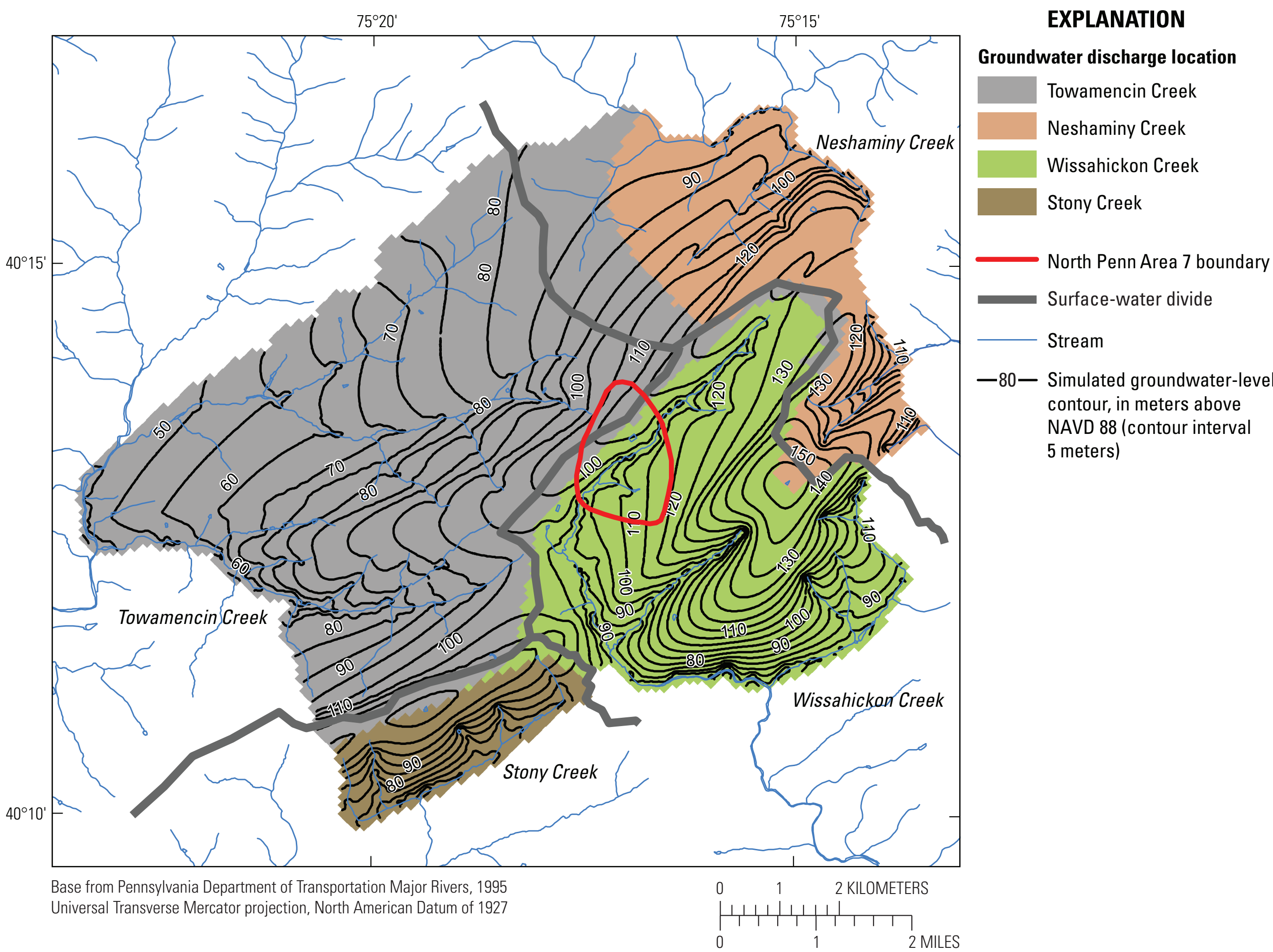

Figure 6. Location of simulated areas contributing recharge to stream base flow for No Pumping conditions, North Penn Area 7 Superfund site and vicinity, Montgomery County, Pennsylvania.

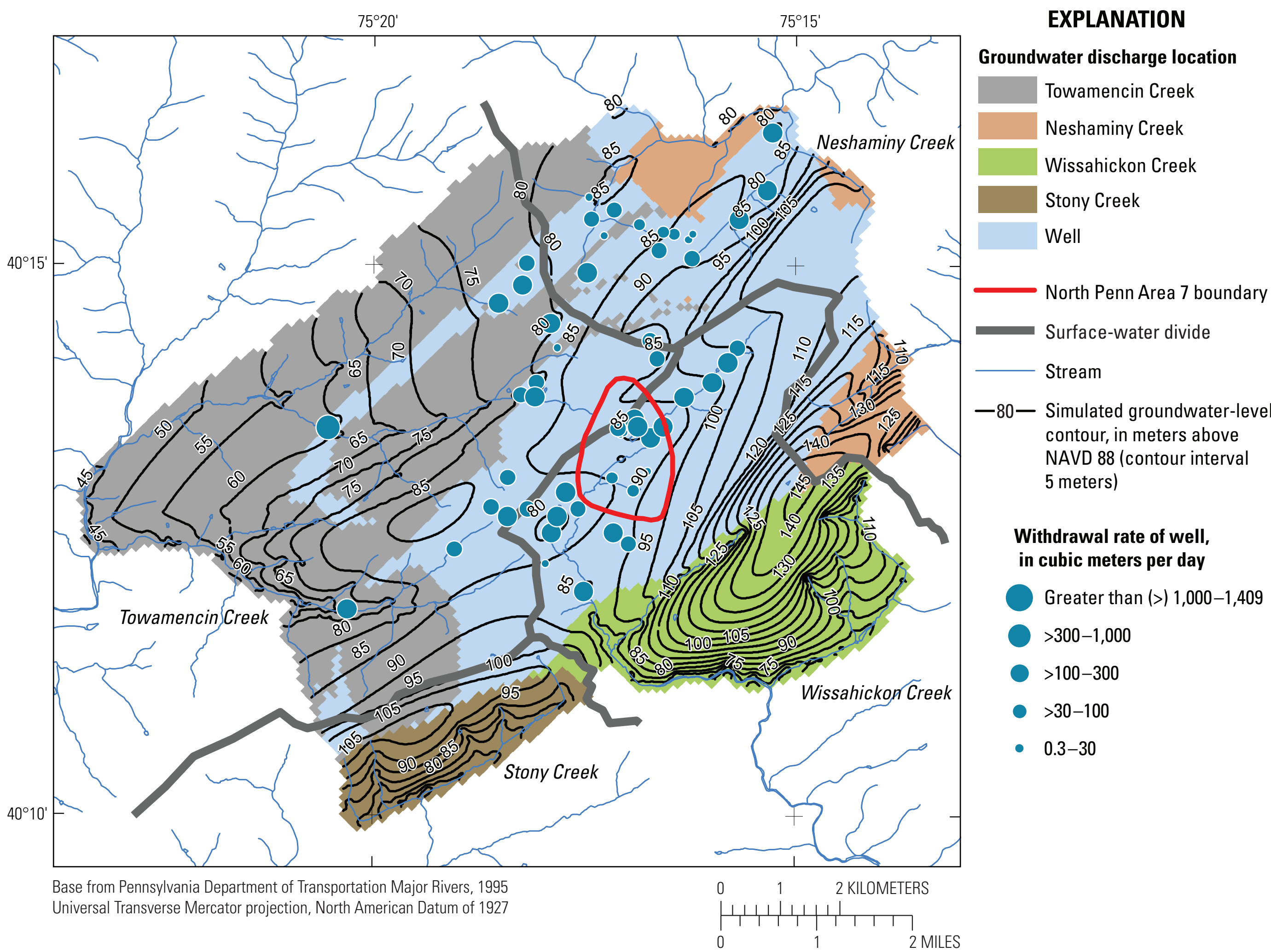

Figure 7. Location of simulated areas contributing recharge to discharging wells and streams, and well withdrawal rates for 1990 conditions, North Penn Area 7 Superfund site and vicinity, Montgomery County, Pennsylvania.

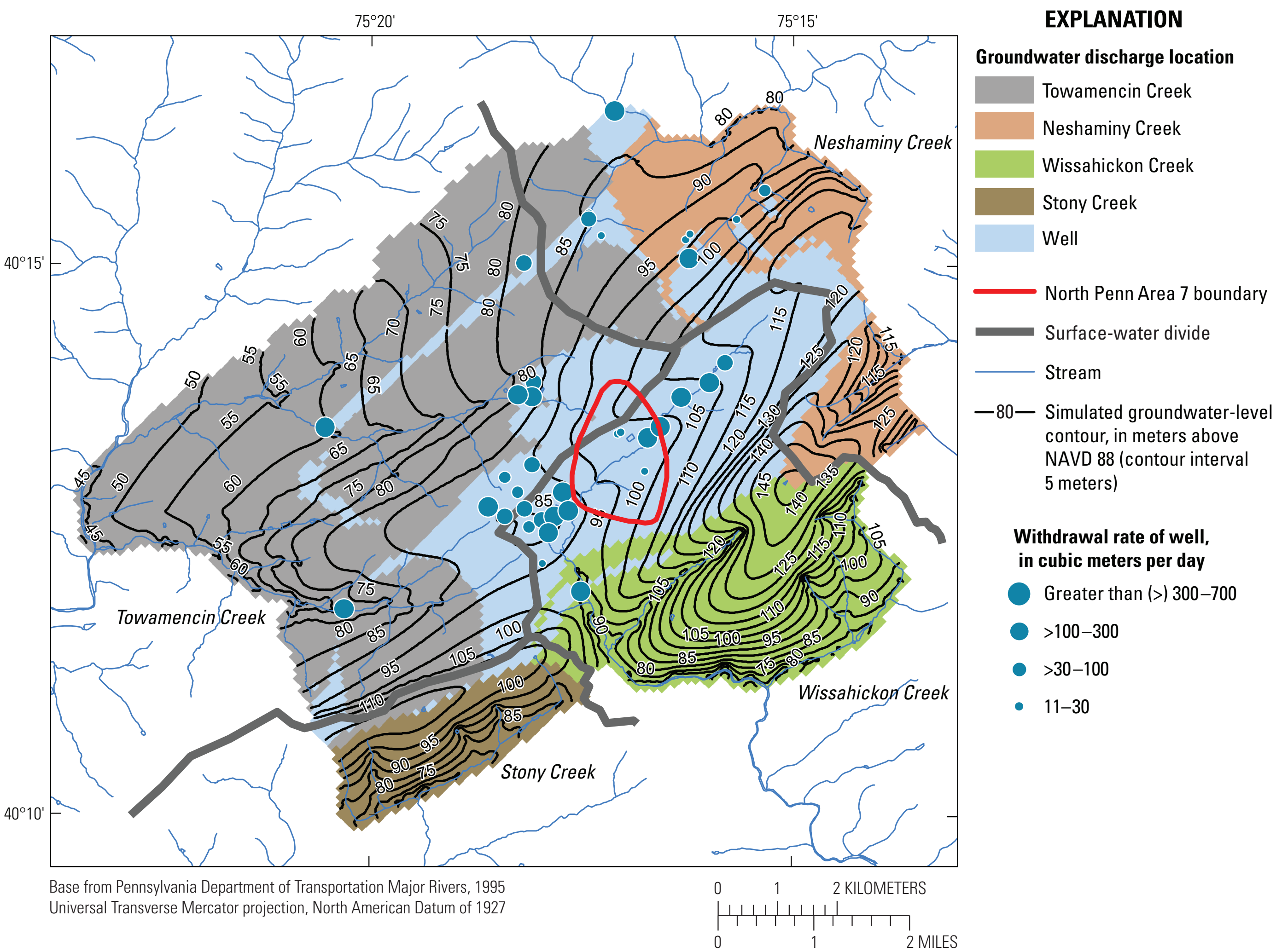

Figure 8. Location of simulated areas contributing recharge to discharging wells and streams, and well withdrawal rates for 2000 conditions, North Penn Area 7 Superfund site and vicinity, Montgomery County, Pennsylvania.

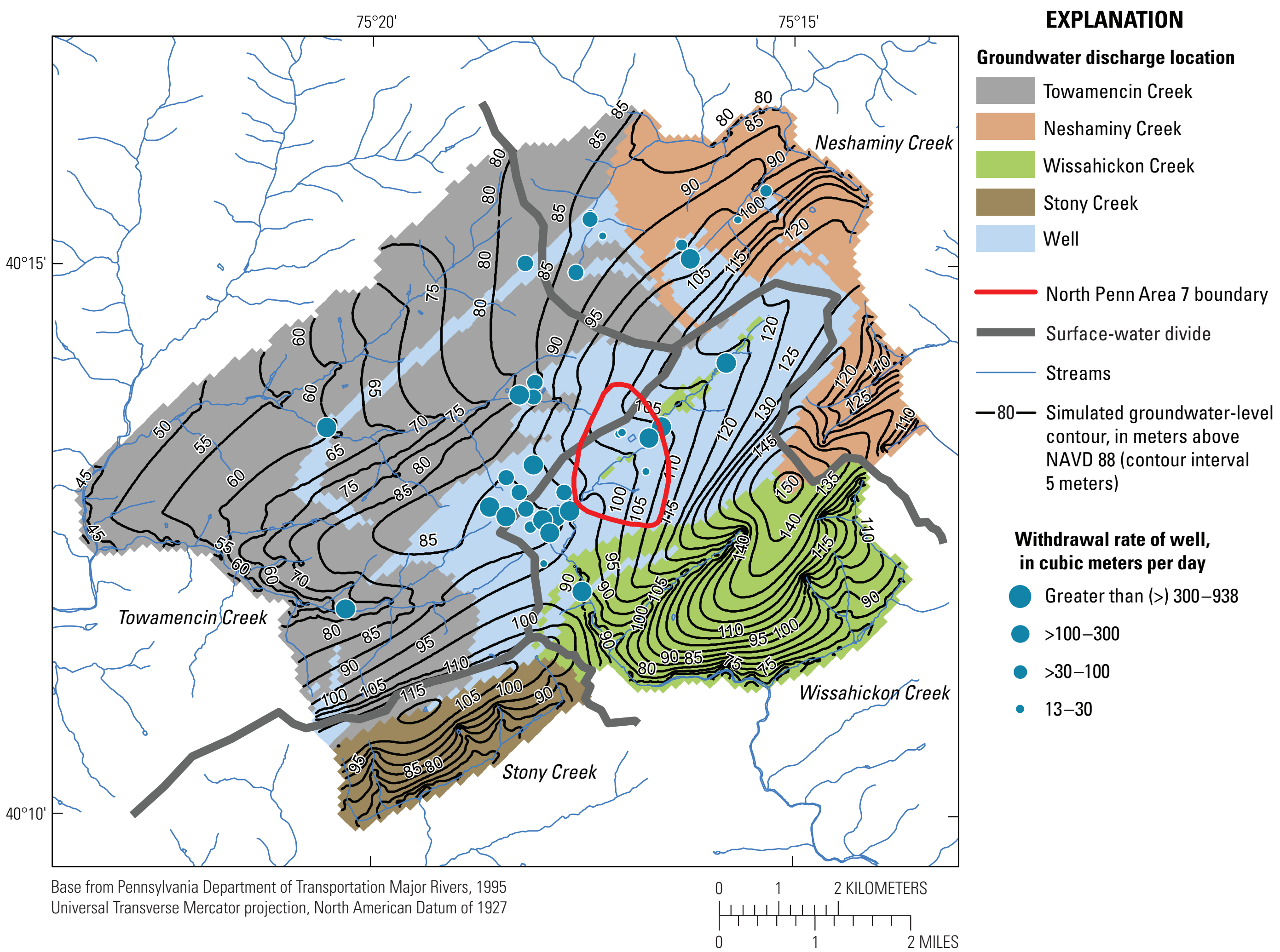

Figure 9. Location of simulated areas contributing recharge to discharging wells and streams, and well pumping rates for 2005 conditions, North Penn Area 7 Superfund site and vicinity, Montgomery County, Pennsylvania.

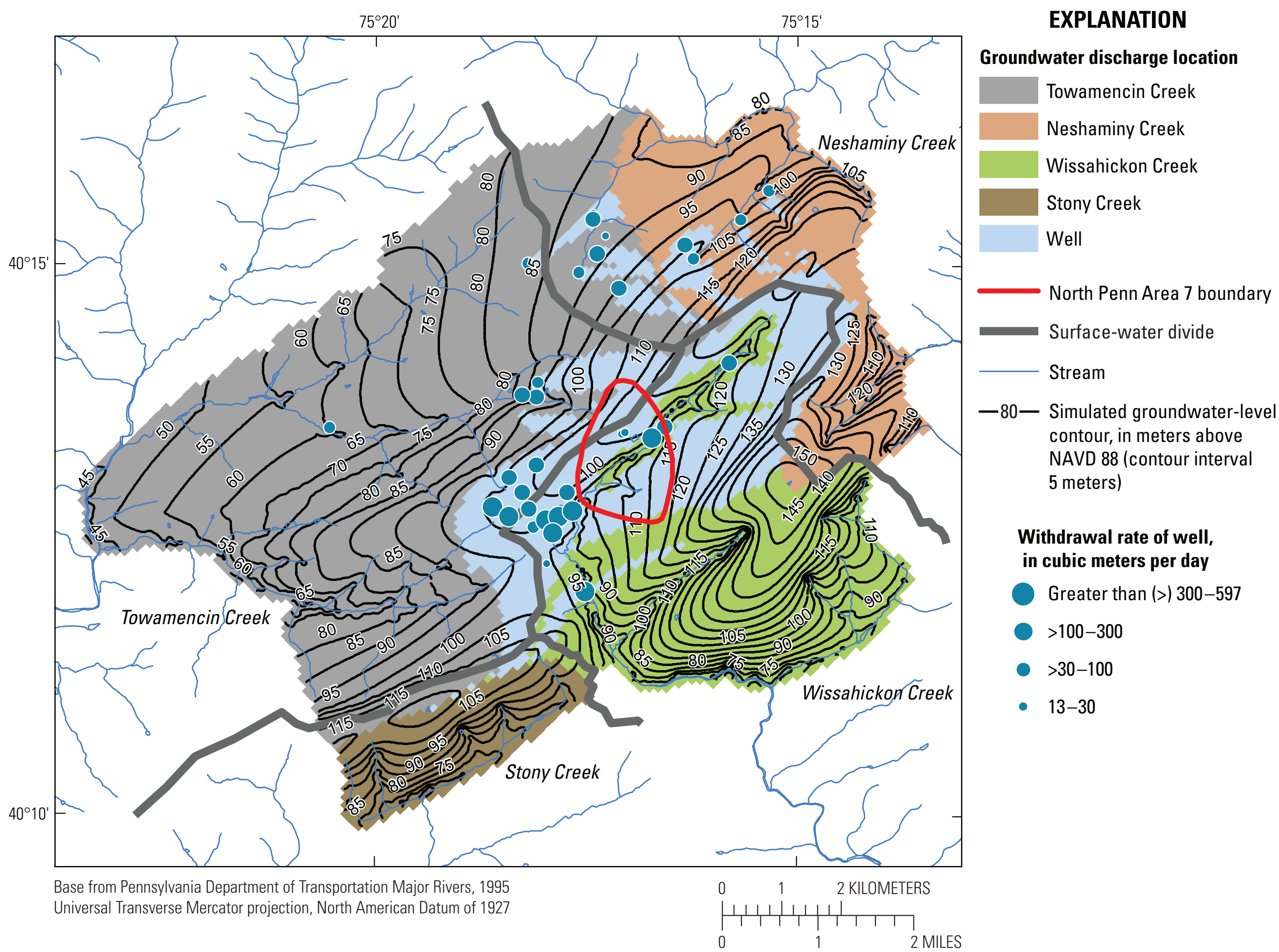

Figure 10. Location of simulated areas contributing recharge to discharging wells and streams, and well withdrawal rates for 2010 conditions, North Penn Area 7 Superfund site and vicinity, Montgomery County, Pennsylvania.

Regional Groundwater-Flow Paths and TCE Concentrations in 2005 and 2010

Groundwater-flow paths from identified contaminant-source areas in North Penn Area 7 were simulated for 2005 and 2010 conditions using the model described by Senior and Goode (2013) with a minor adjustment in the location of one source. On the basis of recent soil contamination mapping at the Teleflex site (David Turner, EPA, oral commun., 2013), the adjustment shifted the Teleflex source location one model cell to the southwest.

Results of the simulation for this study using 2005 conditions were very similar to those previously presented in Senior and Goode (2013) that showed simulated groundwater-flow paths were consistent with the spatial distribution of measured groundwater contamination. In 2005, the highest concentrations of TCE (greater than 50 µg/L) were measured in samples from many of the observation and pumped wells near or within the simulated groundwater-flow paths from contaminant sources at Ford and Teleflex (fig.11).

Simulated groundwater-flow paths for 2010 conditions (fig. 12) are similar to those for 2005 conditions, with some slight shifts, as indicated by a comparison of the flow paths (fig. 13). Most of the simulated 2005 and 2010 flow paths overlap, as shown by the pink (2005), blue (2010), and purple (overlapping 2005 and 2010) paths in figure 13. However, measured TCE concentrations in some observation and pumped wells were considerably lower in 2010 than in 2005. Differences between 2005 and 2010 TCE concentrations were greatest (decreases of about 40 to 400 µg/L) in 12 observation wells and 2 pumped wells on the western side of North Penn Area 7 (fig. 3), near or within simulated groundwater-flow paths from contaminant sources at Ford. For example, TCE concentrations ranged from about 100 to 400 µg/L lower in 2010 samples than in 2005 samples from observation well cluster RI-13 (USGS well names MG-2119, 2120, 2121) and production wells PW-2 and PW-12 (USGS well names MG-125 and MG-1423, respectively) (figs. 11 and 12; table 1).

Groundwater contaminant concentration changes from 2005 to 2010 do not appear to be strongly related to changes in groundwater-flow paths during that time period because flow paths from source areas were very similar for 2005 and 2010 (fig. 13). Decreases in TCE concentrations ranging from about 10 to 400 µg/L for some monitoring wells in the western part of North Penn Area 7 from 2005 to 2010 (fig. 3) may be partly related to source removal by soil excavation at the Ford property from late 2004 to early 2005. The differences in TCE concentrations between 2005 and 2010 samples collected from monitoring wells at and near the North Penn Area 7 are similar to, and consistent with, decreases in TCE concentrations measured during that period in samples from observation and production wells at the Merck facility (figs. 3 and 4). At the Merck facility, decreases in TCE concentrations from 2005 to 2010 were greatest in samples from the production wells PW-2 (USGS well name MG-125) and PW-12 (USGS well name MG-1423); under 2010 conditions, these wells withdrew groundwater that originated as recharge at or near the Ford contaminant source as shown by tan flow paths in figure 12.

Thus, the results of the groundwater simulations indicate that the decreases in TCE concentrations in samples from selected wells at and near North Penn Area 7 from 2005 to 2010 may be the result of processes other than, or in addition to, changes in pumping rates. Possible processes other than changes in pumping rates include the contaminant source removal at the Ford property completed in early 2005 and degradation of TCE, although extensive TCE degradation is not indicated because increases in degradation products such as *cis*-1,2-DCE were not observed.

Vertical Characteristics of Flow Paths from Contaminant Sources

Awareness of vertical flow components is important in understanding and describing the contaminant distribution in groundwater at North Penn Area 7. Information about the vertical distribution of groundwater contamination is gained from monitoring wells open to different depth intervals. Interpretation of these data may be aided by understanding the properties of flow paths through different depth intervals of the aquifer.

Groundwater enters the aquifer system from the land surface as infiltrating recharge or direct loss from streams. This water then follows three-dimensional flow paths, ultimately discharging to streams at the land surface or to withdrawal wells at different depths. The three-dimensional characteristics of flow paths may reflect only shallow penetration into the aquifer where discharge occurs to a shallow withdrawal well or to a stream. In contrast, flow paths may be deep in the aquifer where discharge occurs to deep withdrawal wells. Regional flow paths from recharge at high elevations near regional groundwater divides may also pass through deep parts of the aquifer system en route to discharge in low-elevation streams. The relative travel time along flow paths from recharge (and contaminant source) areas to discharge areas is greater for longer paths, such as deep regional flow paths, than for shallow local paths. Hydraulic gradients, and thus groundwater velocity, are also generally low along deep regional flow paths, with possible steep gradients and high velocities near withdrawal wells.

Although the regional groundwater-flow model provides only an approximation of actual flow, the simulated groundwater-flow paths from recharge at contaminant source areas to discharge at streams or wells have vertical components as well as the horizontal directions depicted on maps such as those shown in figures 11–13. Historical changes in pumping in the area of contaminant sources changed the horizontal and vertical flow paths. Simulated flow paths from many of the contaminant sources discharged to local withdrawal wells near the sources in 1990 (Senior and Goode, 2013, fig. 49B). However, most of the pumping near the contaminant sources had ceased

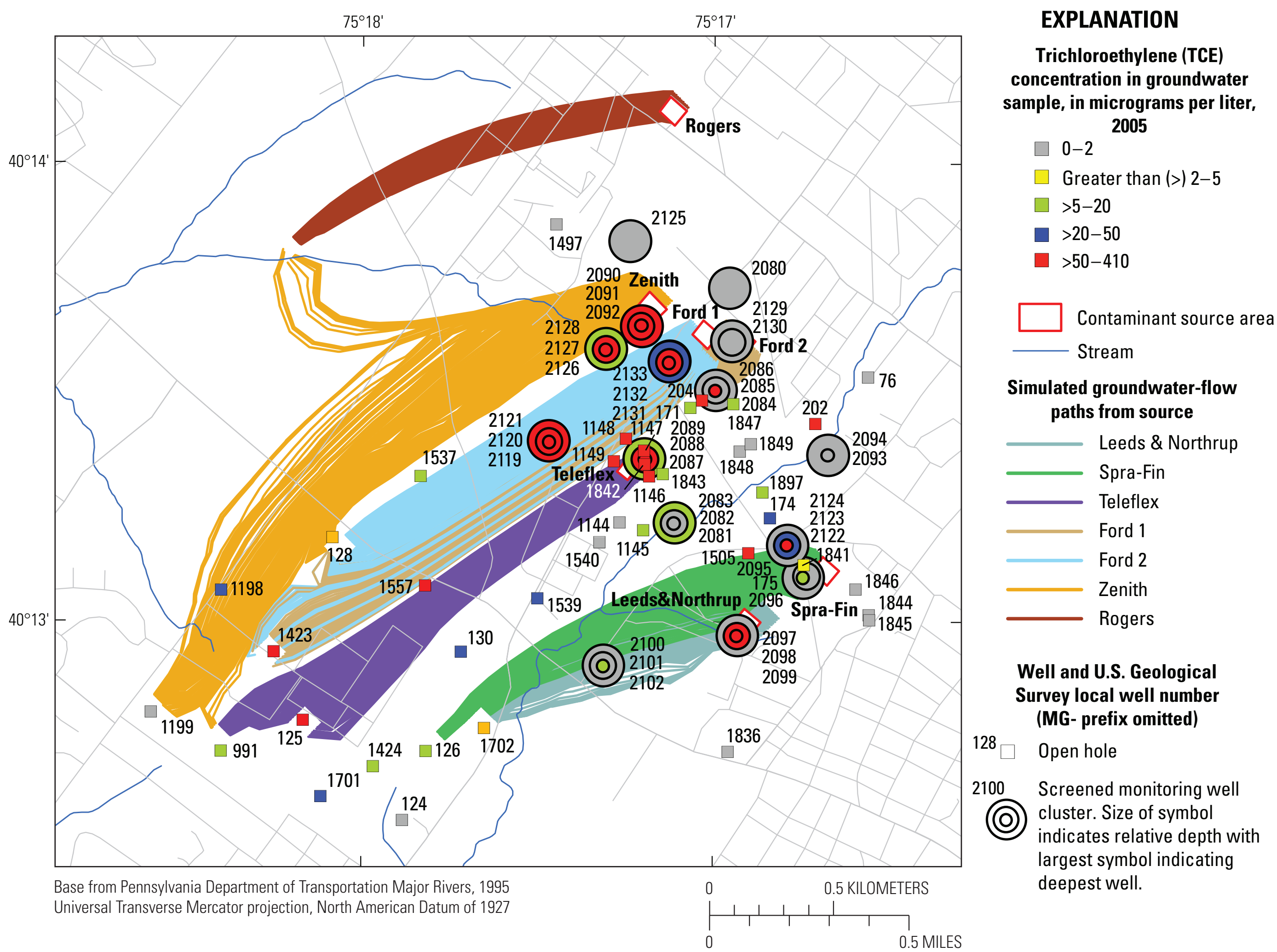

Figure 11. Simulated groundwater-flow paths for 2005 conditions and measured trichloroethylene (TCE) concentrations in samples collected from wells in autumn 2005, North Penn Area 7 Superfund site and vicinity, Montgomery County, Pennsylvania. (Modified from Senior and Goode, 2013, fig. 49, p. 80).

by 2000, and flow paths from contaminant sources discharged to withdrawal wells farther away from the sources in 2000 (Senior and Goode, 2013, fig. 42), 2005 (fig. 11), and 2010 (fig. 12) than in 1990 (Senior and Goode, 2013, fig. 49B).

The simulated three-dimensional flow paths under 2010 conditions (figs. 14 and 15) showed highly variable characteristics for different contaminant source areas. The flow path from the southeast source area at Ford (Ford 2) has the shortest relative travel time and the shallowest penetration, about 47 m (154 ft) down into a well cell. The flow path from the northwest source area at Ford (Ford 1) is the longest flow path from any of the simulated sources and discharges to a deep well cell about 141 m (463 ft) below the model top. This flow path has the second longest relative travel time. The flow path from the Zenith source area has the longest relative travel time (fig. 15). This flow path discharges to an even deeper well cell about 168 m (551 ft) below the model top and follows a curved path to the well. All simulated flow paths from contaminant source areas discharge to withdrawal-well cells under 2010 conditions. Pumping of deep wells induces or enhances downward vertical gradients. In samples from monitoring wells located some distance from a contaminant source area, contaminant concentrations may be greater at depth than in shallower intervals. For example, TCE concentrations were highest in the deepest of three wells in well cluster RI-2 (wells MG-2081, 2082, 2083; figs. 11 and 12); the wells are not near a known source but are downgradient from several potential sources. In 2005, 2006, and 2010, TCE

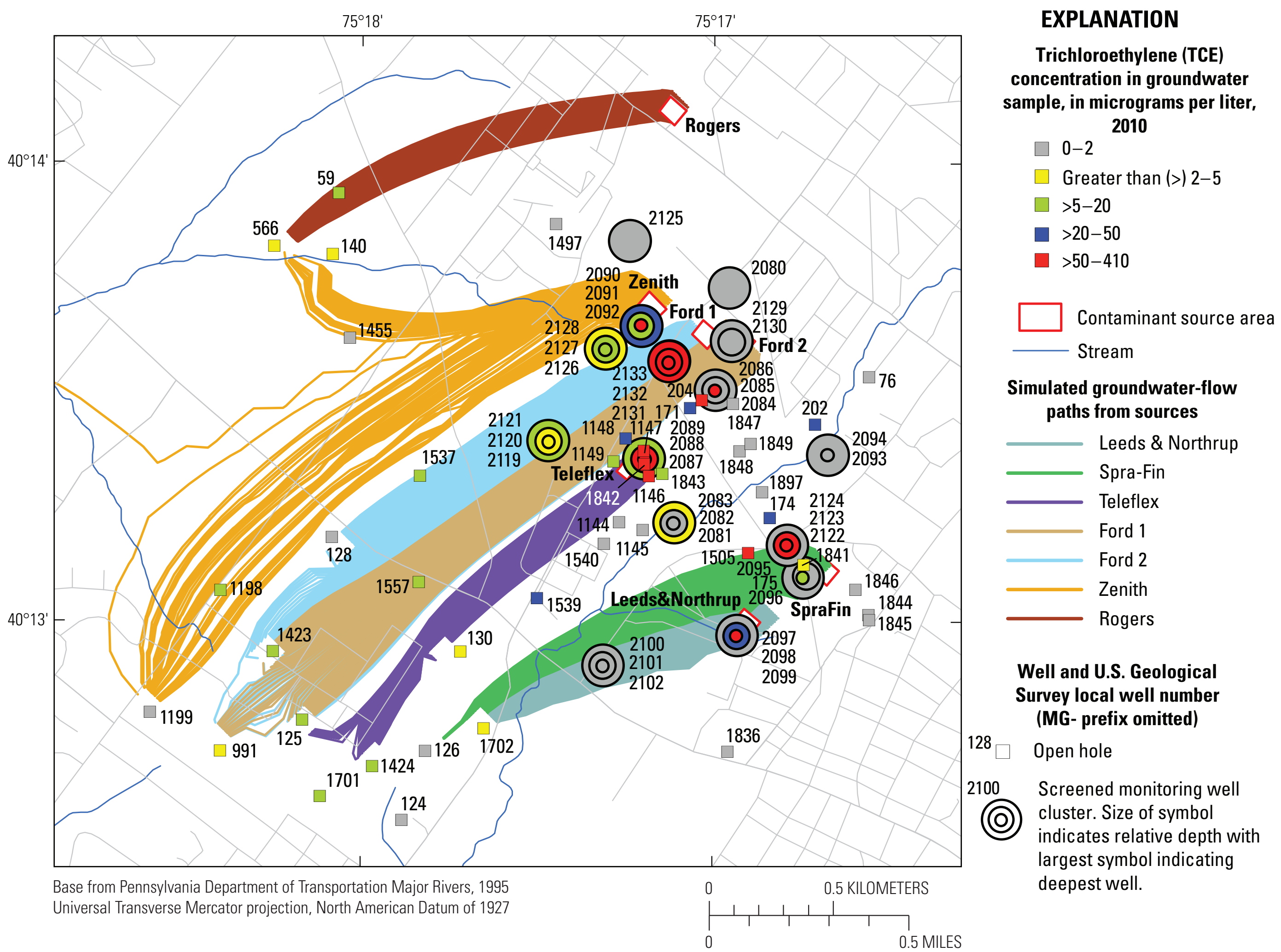

Figure 12. Simulated groundwater-flow paths for 2010 conditions and measured TCE concentrations in samples collected from wells in autumn 2010, North Penn Area 7 Superfund site and vicinity, Montgomery County, Pennsylvania.

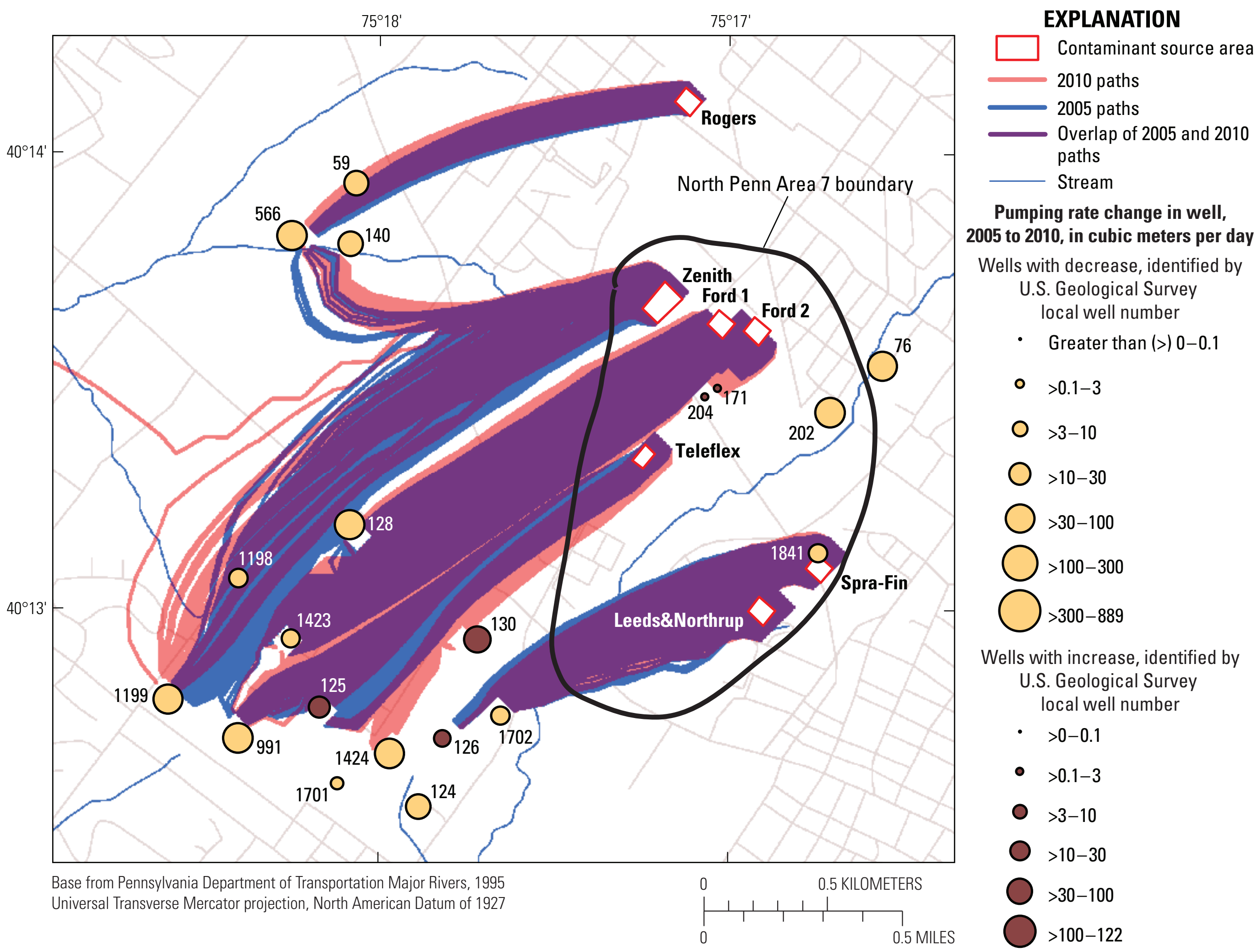

Figure 13. Simulated groundwater-flow paths for 2005 and 2010 conditions and location of wells with decreased or increased pumping rate, North Penn Area 7 Superfund site and vicinity, Montgomery County, Pennsylvania.

concentrations were 7.4, 9.6, and 3.5 µg/L, respectively, in water samples from the deepest well MG-2081 [open from 276 to 296 ft below land surface (84.1 to 90.2 m)] but consistently less than 0.9 µg/L in samples from the intermediate depth well MG-2082 [open from 176 to 186 ft below land surface (53.6 to 56.7 m)] and shallowest well MG-2083 [open from 40 to 60 ft below land surface (12.2 to 18.3 m)] (data from CDM Federal Programs Corporation, 2011a).

Model Limitations for Flow-Path Delineation

The regional model used for simulation of groundwater-flow paths at North Penn Area 7 (Senior and Goode, 2013) has some important limitations. The regional model has limited vertical resolution, and local heterogeneity within strata was not incorporated into the model. The model was used for steady-state flow path simulation, whereas the actual

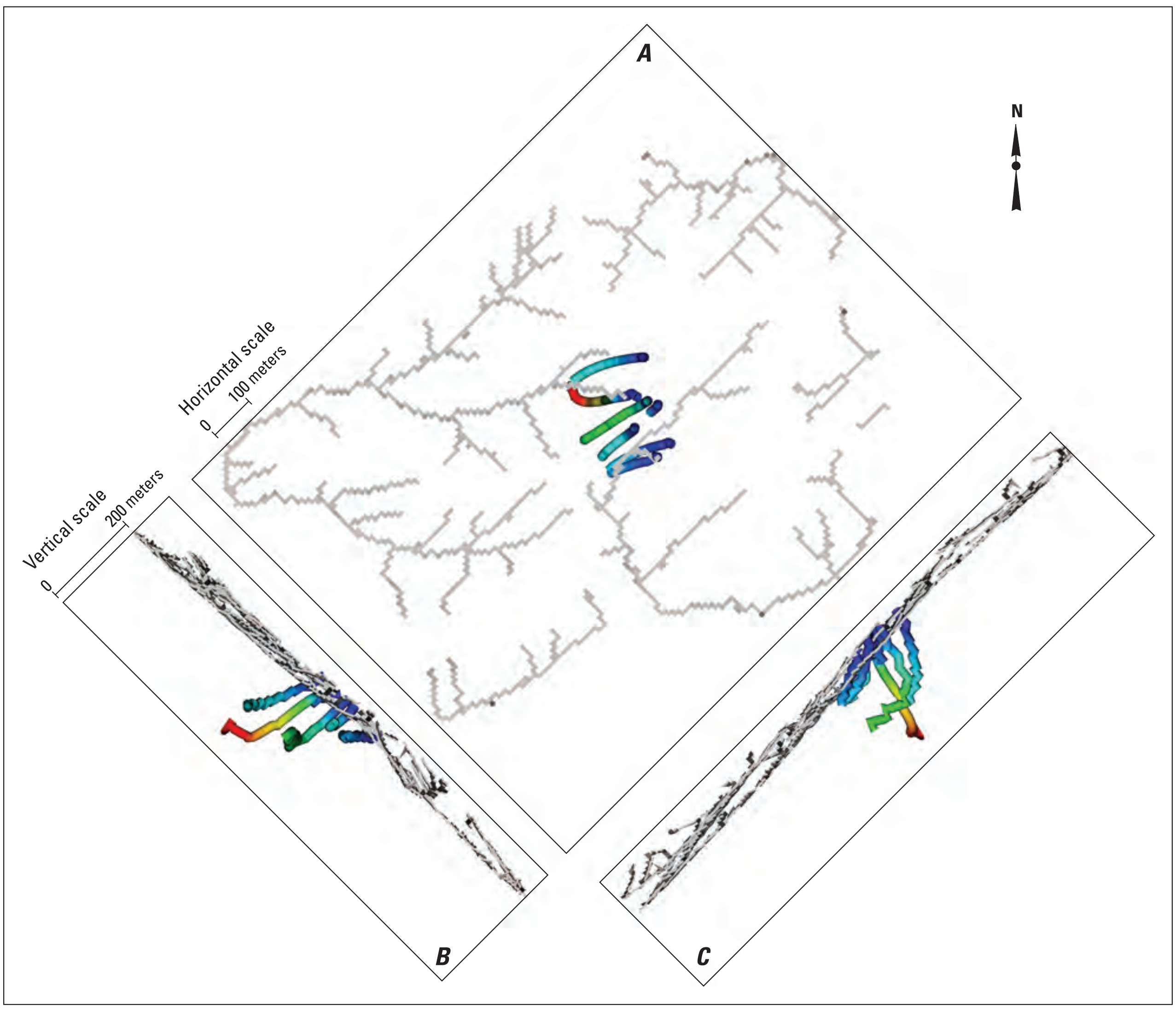

Figure 14. Map and cross section views of simulated groundwater-flow paths from contaminant source areas for 2010 conditions, North Penn Area 7 Superfund site and vicinity, Montgomery County, Pennsylvania, where paths are shown in *A*, map view, *B*, vertical cross-section, looking northeast along strike, and *C*, vertical cross section looking northwest downdip. Portions of the flow paths are colored by the relative time of travel from the recharge source: short (blue) to long (red). Model stream cells are also shown (gray). All flow paths shown discharge to withdrawal well cells of the model. The three-dimensional perspective is shown in figure 15.

aquifer has continually changing water levels and thus changing hydraulic gradients and flow paths. In reality, the water sampled from a well may represent a mixture of water from multiple flow paths that entered the well at different times. However, the steady-state flow model produced flow paths passing through an individual monitoring-well interval that occupy only a narrow region of the aquifer, and all recharge originates within a small area. Simulations do not account for the temporary withdrawals associated with water-quality sampling at monitoring wells, and incorporating these withdrawals would produce different flow paths. The travel time along each path was computed assuming a uniform effective porosity for advective transport (due to lack of data) and is thus considered only a "relative" depiction of travel time. The absolute magnitudes of the simulated travel times are unlikely to correspond to magnitudes of actual travel times.

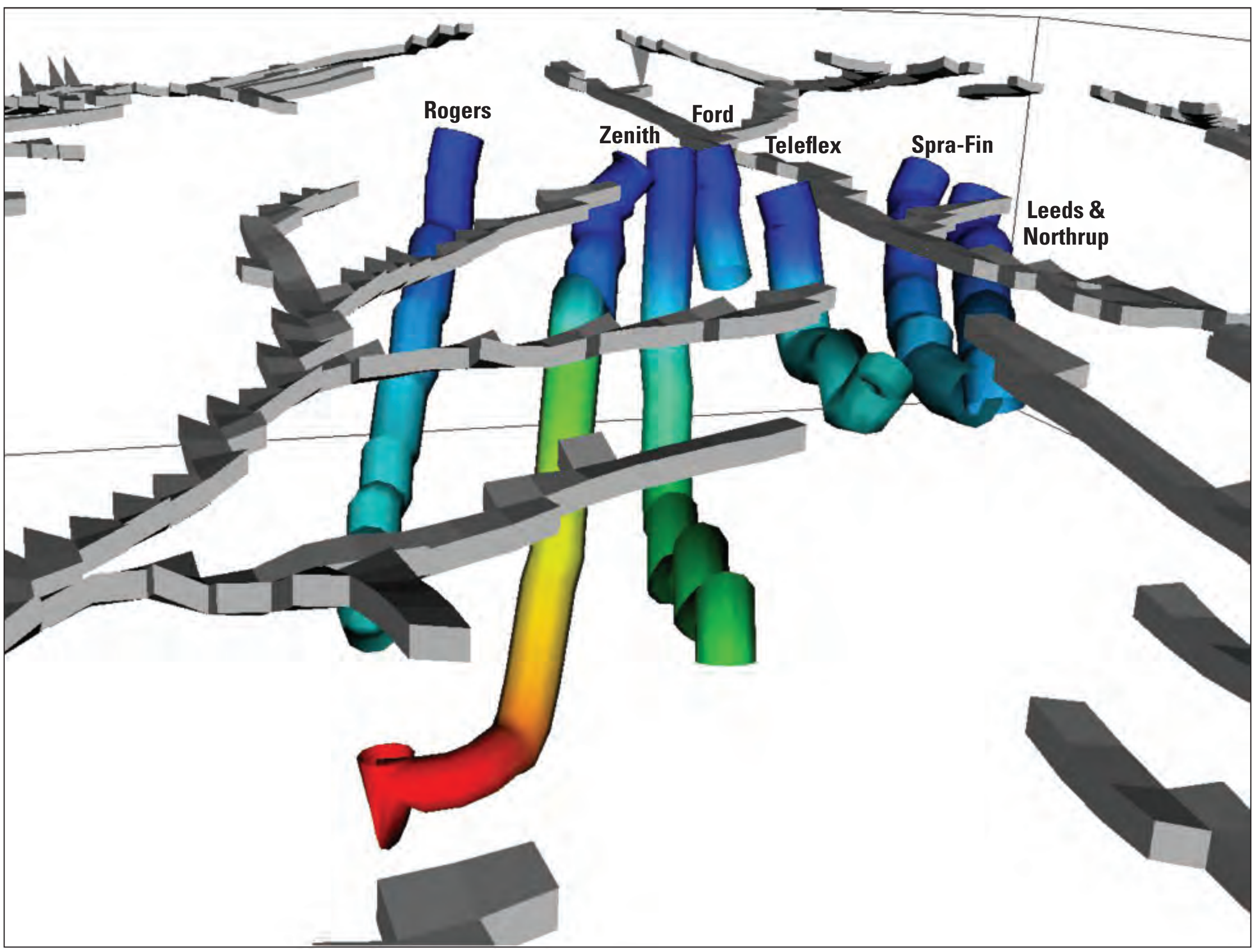

Figure 15. Three-dimensional perspective view from the southwest of simulated groundwater-flow paths under 2010 conditions, North Penn Area 7 Superfund site and vicinity, Montgomery County, Pennsylvania. Portions of the flow paths are colored by the relative time of travel from the recharge source: short (blue) to long (red). Stream cells in the top layer of the model are also shown (gray), and each cell has dimensions of 100 × 100 × 6 meters. Map and cross section views of the same flow paths are shown in figure 14.

Summary and Conclusions

Groundwater in and around Lansdale Borough and Upper Gwynedd Township, Montgomery County, Pennsylvania, was found to be contaminated with organic chemicals, such as trichloroethylene (TCE) and tetrachloroethylene (PCE), in 1979, and the area was placed on the National Priorities List as the North Penn Area 7 Superfund site by the U.S. Environmental Protection Agency (EPA) in March 1989. At the time contamination was discovered, groundwater was the main source of supply for public and private drinking water and industrial use. From 2000 to 2005, the U.S. Geological Survey (USGS) provided technical support to EPA for the Remediation Investigation (RI) of the site. As part of this technical support, the USGS developed a numerical model of regional groundwater flow to simulate changes in groundwater flow and contaminant directions as a result of changes in pumping. Subsequently, relatively large decreases in contaminant concentrations (as much as 404 micrograms per liter for TCE) in groundwater between sampling rounds conducted by EPA in 2005 and 2010 prompted an inquiry into changes in pumping as a possible cause of contaminant declines. Additional data showing decreases in TCE concentrations after 2005 in some pumped and monitoring wells at an industrial facility (Merck & Co., Inc.) about 3,000 to 4,000 feet (about 915 to 1,220 meters) southwest and downgradient from known contaminant sources in North Penn Area 7 supported findings from the EPA 2005 and 2010 sampling rounds, which also showed decreases in TCE concentrations in monitoring wells.

The USGS conducted simulations of groundwater flow using the previously developed calibrated groundwater-flow model for North Penn Area 7 (Senior and Goode, 2013) to evaluate the effect of changes in pumping from 2005 to 2010 on directions of groundwater flow and potential distribution of contaminants in groundwater. Additional simulations of regional groundwater flow under No Pumping, 1990, 2000, 2005, and 2010 conditions were done to delineate the areas contributing recharge to discharging wells and streams, and thus, to help understand the potential effects of pumping on overall plume control.

Simulated water budgets for 1990, 2000, 2005, and 2010 indicate that groundwater withdrawal (pumping) rates for the modeled area were greatest in 1990, generally decreased through time, and were lowest in 2010. The recharge rate was lowest in 2000, a relatively dry year. North Penn Area 7 is in the upper Wissahickon Creek Basin, where the stream has been observed to be dry periodically. Simulations show that all the recharge in the upper Wissahickon Creek Basin, including North Penn Area 7, discharged to withdrawal (mostly production) wells under 1990 through 2000 conditions. Thus, results of the simulations indicate that groundwater contamination resulting from recharge through contaminated soils likely discharged to withdrawal wells during these periods. Under 2005 and 2010 conditions, some recharge in the upper Wissahickon Creek Basin, including parts of North Penn Area 7, was simulated as discharging to streams and not to withdrawal wells. All simulations showed that groundwater divides and surface-water divides are not coincident, partly because of differences in stream elevations in adjacent basins and because of geologic structure and spatial distribution of pumping.

Simulated groundwater-flow paths for 2010 conditions were similar to those for 2005 conditions, differing only slightly. The minor differences in flow path directions do not appear to account for observed differences in TCE concentrations in some observation and pumped wells between 2005 and 2010, especially in the western part of North Penn Area 7. Source removal (soil excavation) at a facility during 2004–05 may be a factor that led to decreases in groundwater TCE concentrations in some wells from 2005 to 2010. Another possible process that may contribute to deceases in groundwater TCE concentrations is degradation, although increases of TCE degradation products generally were not observed. Reported concentrations of TCE from 1994 to 2013 in groundwater samples from a set of pumped industrial wells that capture recharge from North Penn Area 7 provide additional data to support recent (2005–13) observed decreases in groundwater contamination in some parts of North Penn Area 7; concentrations of TCE degradation product *cis*-1,2-DCE remained relatively constant during 1994–2013 in samples from most of these wells.

Awareness of three-dimensional flow components is important in understanding and describing the contaminant distribution in groundwater at North Penn Area 7. Simulated and actual groundwater-flow paths have vertical and horizontal components, which may affect the interpretation of two-dimensional maps of those flow paths. Higher concentrations of contaminants tended to occur in shallow groundwater near sources of contamination in soils (recharge area) but may occur in deeper groundwater downgradient from these sources as a result of the effects of pumping or differences in topography on regional flow.

The regional model used for simulation of groundwater-flow paths at North Penn Area 7 has some important limitations. The regional model has limited vertical resolution, and local heterogeneity within strata was not incorporated into the model. Changes in the directions of vertical flow paths also may affect the vertical distribution of contaminants in the aquifer. Thus, vertical flow-path change may be a factor contributing to the decreases in contaminant concentrations, although this was not evaluated formally in the simulations. The model is used for steady-state flow path simulation, whereas the actual aquifer has continually changing water levels and thus changing hydraulic gradients and flow paths. Additionally, the preliminary finding that changes in groundwater-contaminant concentrations between 2005 and 2010 in some wells may be related to source removal could be strengthened by continued groundwater monitoring to confirm the decrease, and more extensive characterization of groundwater quality could be used to assess the extent of possible contaminant degradation.

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Appendix 1

Reported total annual precipitation and 3-month total precipitation at two meteorological stations near North Penn Area 7 (fig. 1-1) and for a composite of stations in southeastern Pennsylvania prior to dates of water-level measurements used in model calibration are listed in table 1-1, as is annual base flow determined by hydrograph separation for two streams near North Penn Area 7.

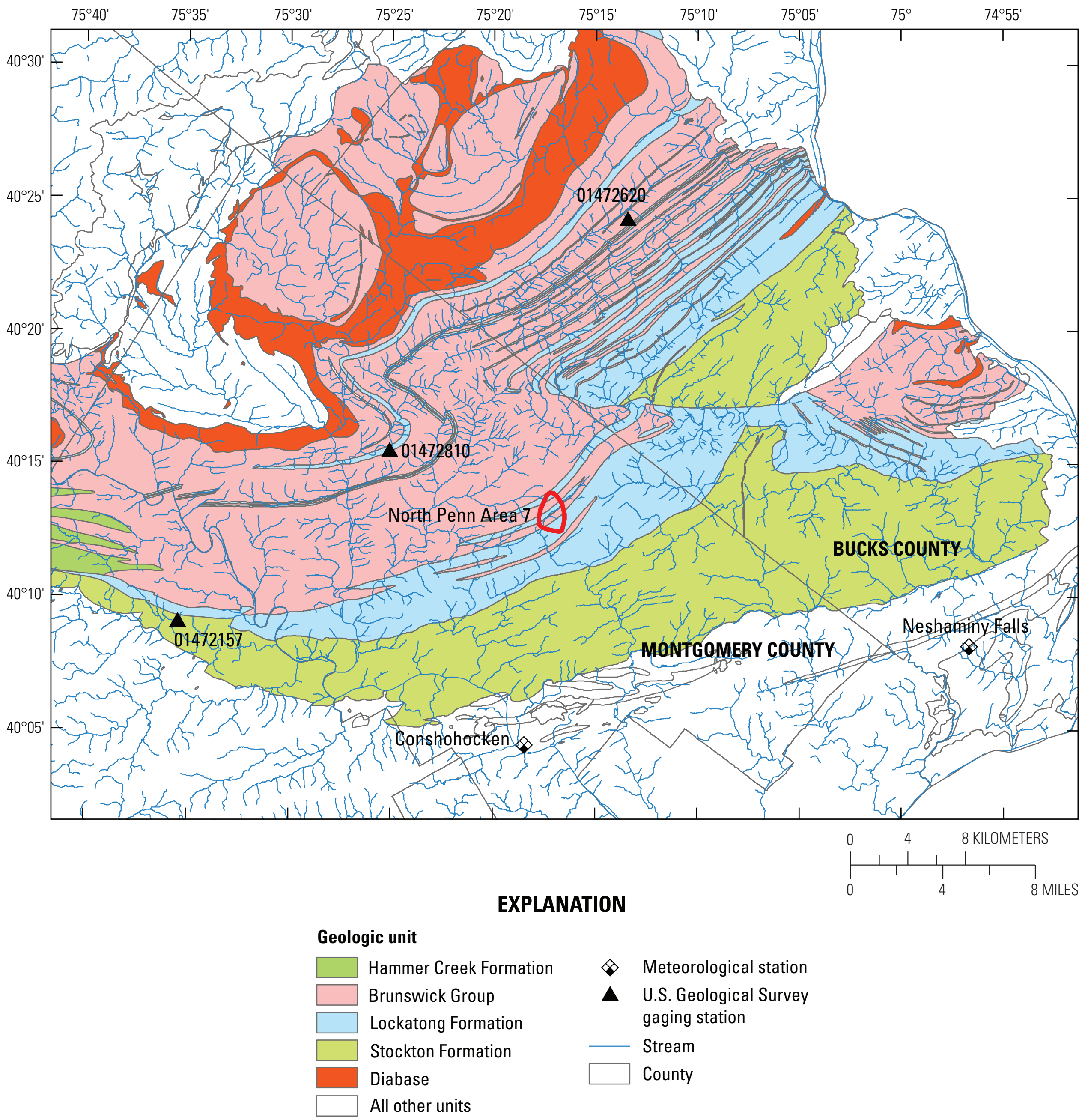

Figure 1-1. Geologic units of the Newark Basin and location of meteorological stations measuring precipitation and gaging stations measuring streamflow at selected locations near North Penn Area 7 Superfund site, Montgomery County, Pennsylvania.

Table 1-1. Total annual precipitation at three meteorological stations and base flow in two streams draining basins with relatively low-intensity land development and underlain by Triassic-age rocks near North Penn Area 7 Superfund site, Montgomery County, Pennsylvania, for 1990, 1996, 2000, 2005, and 2010.

[NOAA, National Oceanic and Atmospheric Administration; USGS, U.S. Geological Survey; L, lower than actual total due to some missing daily precipitation data; --, no or missing data; precipitation data from NOAA (2015, 2016); streamflow data from U.S. Geological Survey; Pa., Pennsylvania]

NOAA meterological station	Total annual precipitation (inches)					
	30-year normal (1981–2010)	1990	1996	2000	2005	2010
Conshohocken, Pa.[1]	48.71	46.86	L63.22	51.09	L43.44	48.97
Neshaminy Falls, Pa.[2]	49.30	46.43	L55.66	50.78	50.49	43.84
Southeastern Pa.	45.57	47.39	60.78	44.45	46.46	43.94

	3-month total precipitation prior to date of water-level measurements used for model calibration (inches) and [percent of normal total annual precipitation]		
	8/22–23/1996	12/4–6/2000	6/6–8/2005
Conshohocken, Pa.[1]	L13.65 L[28.0]	11.26 [23.1]	L10.28 L[21.1]
Neshaminy Falls, Pa.[2]	19.4 [39.4]	12.36 [25.1]	L10.29 L[20.8]

USGS streamflow gaging station	Base flow[3] (inches)					
	30-year median (1981–2010)	1990	1996	2000	2005	2010
French Creek near Phoenixville, Pa.[4]	12.02	11.98	19.92	12.06	15.10	14.70
East Branch Perkiomen Creek near Schwenksville, Pa. corrected for inflow at Dublin[5]	--	--	8.67	5.64	7.71	7.58

[1] Station is about 10 miles south-southwest of North Penn Area 7.

[2] Station is about 18 miles east-southeast of North Penn Area 7.

[3] Base flow determined by hydrograph separation of mean daily values computed by local mininum method using HYSEP program (Sloto and Crouse, 1996).

[4] USGS station 01472157 drains 59.1 square miles of area predominantly underlain by the Triassic-age Stockton Formation and is about 14 miles southwest of North Penn Area 7.

[5] USGS station 014727810 drains 58.7 square miles of area predominantly underlain by Triassic-age Brunswick Group and Lockatong Formation and is about 8 miles northwest of North Penn Area 7. Flow is corrected by subtracting base flow at station 01472620 East Branch Perkiomen Creek near Dublin, Pa., which receives pumpage (interbasin transfer) from the Delaware River.

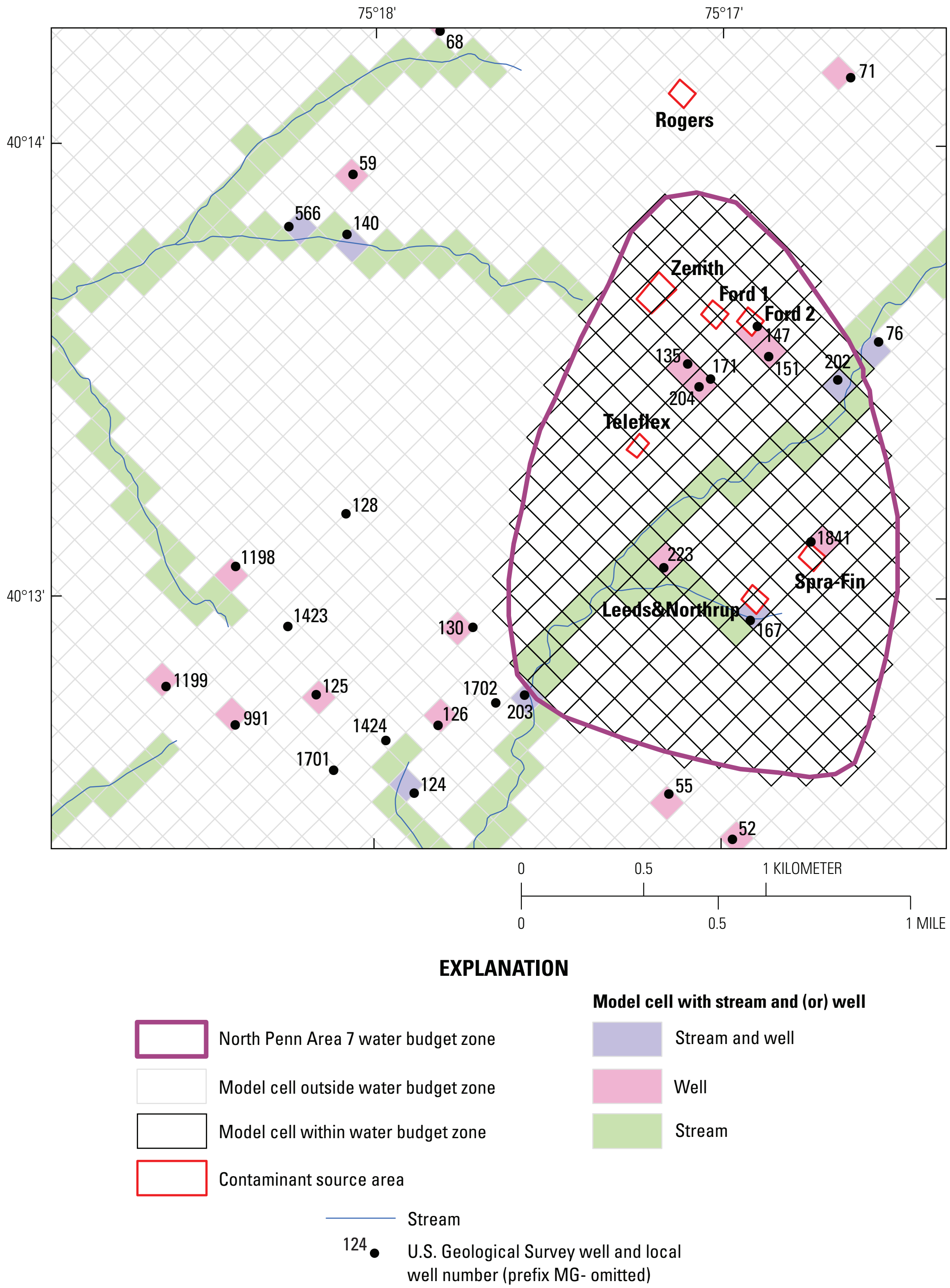

Figure 1-2. Location and type of groundwater-flow model cells within zone used to calculate water budgets for North Penn Area 7 Superfund site, Montgomery County, Pennsylvania.

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For additional information, contact:
Director, Pennsylvania Water Science Center
U.S. Geological Survey
215 Limekiln Road
New Cumberland, PA 17070-2424

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