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Hydrogeologic Framework, Ground-Water Quality, and Simulation of Ground-Water Flow at the Fair Lawn Well Field Superfund Site, Bergen County, New Jersey

Scientific Investigations Report 2004-5280

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

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

U.S. Department of the Interior
Gale A. Norton, Secretary

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Conversion Factors and Vertical Datum

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)
	Area	
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
	Flow rate	
gallon per minute (gal/min)	3.785	milliliter per minute (mL/min)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
cubic feet per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Pressure	
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

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).*

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

*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.

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

Hydrogeologic Framework, Ground-Water Quality, and Simulation of Ground-Water Flow at the Fair Lawn Well Field Superfund Site, Bergen County, New Jersey

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Abstract

Production wells in the Westmoreland well field, Fair Lawn, Bergen County, New Jersey (the “Fair Lawn well field Superfund site”), are contaminated with volatile organic compounds, particularly trichloroethylene, tetrachloroethylene, and 1,1,1-trichloroethane. In 1983, the U.S. Environmental Protection Agency (USEPA) placed the Westmoreland well field on its National Priority List of Superfund sites. In an effort to determine ground-water flow directions, contaminant-plume boundaries, and contributing areas to production wells in Fair Lawn, and to evaluate the effect of present pump-and-treat systems on flowpaths of contaminated ground water, the U.S. Geological Survey (USGS), in cooperation with the USEPA, developed a conceptual hydrogeologic framework and ground-water flow model of the study area. MODFLOW-2000, the USGS three-dimensional finite-difference model, was used to delineate contributing areas to production wells in Fair Lawn and to compute flowpaths of contaminated ground water from three potential contaminant sources to the Westmoreland well field. Straddle-packer tests were used to determine the hydrologic framework of, distribution of contaminants in, and hydrologic properties of water-bearing and confining units that make up the fractured-rock aquifer underlying the study area.

The study area consists of about 15 square miles in and near Fair Lawn. The area is underlain by 6 to 100 feet of glacial deposits and alluvium that, in turn, are underlain by the Passaic Formation. In the study area, the Passaic Formation consists of brownish-red pebble conglomerate, medium- to coarse-grained feldspathic sandstone, and micaceous siltstone. The bedrock strata strike N. 9^{o} E. and dip 6.5^{o} to the northwest. The bedrock consists of alternating layers of densely fractured rocks and sparsely fractured rocks, forming a fractured-rock aquifer.

Ground-water flow in the fractured-rock aquifer is anisotropic as a result of the interlayering of dipping water-bearing and confining units. Wells of similar depth aligned along the strike of the bedding intersect the same water-bearing units, but wells aligned along the dip of the bedding may intersect different water-bearing units. Consequently, wells aligned along strike are in greater hydraulic connection than wells aligned along dip.

The Borough of Fair Lawn pumps approximately 770 million gallons per year from 13 production wells. Hydrographs from six observation wells ranging in depth from 162 to 505 feet in Fair Lawn show that water levels in much of the study area are affected by pumping.

Straddle packers were used to isolate discrete intervals within six open-hole observation wells owned by the Fair Lawn Water Department. Transmissivity, water-quality, and static-water-level data were obtained from the isolated intervals. Measured transmissivity ranged from near 0 to 8,900 feet squared per day. The broad range in measured transmissivity is a result of the heterogeneity of the fractured-rock aquifer.

Eight water-bearing units and eight confining units were identified in the study area on the basis of transmissivity. The water-bearing units range in thickness from 21 to 95 feet; the mean thickness is 50 feet. The confining units range in thickness from 22 to 248 feet; the mean thickness is 83 feet. Water-level and water-quality data indicate effective separation of water-bearing units by the confining units.

Water-quality samples were collected from the six observation wells at 16 depth intervals isolated by the straddle packers in 2000 and 2001. Concentrations of volatile organic compounds generally were low in samples from four of the wells, but were higher in samples from a well in Fair Lawn Industrial Park and in a well in the Westmoreland well field.

The digital ground-water flow model was used to simulate steady-state scenarios representing conditions in the study area in 1991 and 2000. These years were chosen because during the intervening period, pumpage from the Westmoreland well field decreased by more than one-half, and a system of shallow wells (less than 19 feet deep) and trenches was installed at one of the contaminant sources to capture shallow ground water. Because precipitation was below average in 2000, a “high-recharge” scenario also was simulated to represent 2000 pumpage conditions during more typical ground-water-recharge conditions.

The digital model was used to delineate contributing areas to production well fields in Fair Lawn and contaminant plumes from three contaminant sources. Two of these sources, Fisher Scientific Company and Sandvik, Inc., are known contaminated sites that were previously identified by the N.J. Department of Environmental Protection as potential sources of volatile

organic compounds to the Westmoreland well field. The third source, Eastman Kodak Company, is a known contaminated site not previously identified as a potential source of volatile organic compounds to the Westmoreland well field. In 1991, when 130 million gallons of water was pumped from the Westmoreland well field, the contributing area to that well field included nearly all of the Fisher Scientific Company property, a small part (less than 1 percent) of the Sandvik, Inc., property, and about three-quarters of the Eastman Kodak Company property. In 2000, when only 40 million gallons of water was pumped from the Westmoreland well field, the contributing area included only small parts of the Fisher Scientific Company and Eastman Kodak Company properties, and none of the Sandvik, Inc., property. In the 2000 high-recharge scenario, contributing areas to every pumped well were similar to, but smaller than, the contributing areas in the 2000 scenario.

Contaminant plumes from the three potential contaminant sites were delineated using the ground-water flow model. In 1991, most of the plume from the overburden at Fisher Scientific Company discharged to a well in the Westmoreland well field; about half of the plume from the bedrock discharged to deep recovery wells at Fisher Scientific Company and half discharged to two wells in the Westmoreland well field. Only 3 percent of the water from the overburden and 4 percent of the water from the bedrock was not captured by any well.

In 1991, 3 percent of the plume from the overburden at Sandvik, Inc., discharged to wells in the Westmoreland well field; 93 percent of the plume from the bedrock discharged to wells in that well field. Nearly all (97 percent) of the water from the overburden and 7 percent of the water from the bedrock at Sandvik, Inc., was not captured by any well and flowed instead to Henderson Brook.

In 1991, 73 percent of the plume from the bedrock at Eastman Kodak Company discharged to a well in the Westmoreland well field; the remainder flowed to the Passaic River. No plume from the overburden at Eastman Kodak Company was delineated because simulation results indicate that the overburden was unsaturated.

In 2000, wells in the Westmoreland well field captured less water than in 1991 from all three sites because of the decreased pumpage. Only 6 percent of the plume from the overburden at Fisher Scientific Company discharged to a well in the Westmoreland well field; more than half (55 percent) was captured by the recently installed shallow recovery system and 4 percent was captured by the deep recovery wells at the site. Thirty-four percent of the plume from the bedrock discharged to a well in the Westmoreland well field, and 58 percent was captured by the deep recovery wells at the site. In this simulation, 35 percent of the water from the overburden and 9 percent of the water from the bedrock at Fisher Scientific Company flowed to Henderson Brook and the Passaic River rather than to any well.

In 2000, all of the water originating in the overburden at Sandvik, Inc., discharged to Henderson Brook; none was captured by any well. Twenty-three percent of the plume from the bedrock at Sandvik, Inc., discharged to two wells in the Westmoreland well field; 2 percent discharged to a deep recovery well at Fisher Scientific Company, and the remainder (74 percent) flowed to Henderson Brook and the Passaic River rather than to any well.

In 2000, 9 percent of the water from the bedrock at Eastman Kodak Company discharged to a well in the Westmoreland well field; the remainder discharged to Henderson Brook and the Passaic River.

Introduction

Since 1978, volatile organic compounds (VOCs) have been detected in ground water in three production wells in the Westmoreland well field in the Borough of Fair Lawn, Bergen County, New Jersey (U.S. Environmental Protection Agency, 2003). The most commonly occurring compounds in these wells are trichloroethylene (TCE), tetrachloroethylene (PCE), and 1,1,1-trichloroethane (1,1,1-TCA) (Kenneth Garrison, Fair Lawn Water Department, written commun., 2002). In 1983, the U.S. Environmental Protection Agency (USEPA) placed the well field on its National Priority List of Superfund sites. In 1987, the Borough of Fair Lawn installed air strippers to treat water pumped from the contaminated wells. An investigation by the N.J. Department of Environmental Protection (NJDEP) identified Fisher Scientific Company (Fisher) and Sandvik, Inc. (Sandvik), as contributing sources of the contamination (U.S. Environmental Protection Agency, 2003). These two companies are next to each other in Fair Lawn Industrial Park, northeast of the Westmoreland well field (fig. 1). During the course of this study, a third potential contributing source, Eastman Kodak Company (Kodak), also in Fair Lawn Industrial Park, was identified. Fisher, Sandvik, and Kodak are all on the NJDEP list of known contaminated sites (N.J. Department of Environmental Protection, 2001).

In 1999, the U.S. Geological Survey (USGS), in cooperation with the USEPA, began a study to determine:

- Ground-water flow patterns in the Borough of Fair Lawn,
- Contributing areas to production wells in Fair Lawn,
- Contaminant-plume boundaries, and
- The effect of present pump-and-treat systems at the Westmoreland well field and Fisher on flowpaths of contaminated ground water.

Purpose and Scope

This report describes the results of ground-water flow simulations that were done to (1) delineate contributing areas and potential sources of contamination to production wells in Fair Lawn, New Jersey; (2) delineate plumes of contaminated water originating from three potential sources of ground-water contamination in Fair Lawn—Fisher, Sandvik, and Kodak; and (3) determine the effect of present pump-and-treat systems at the Westmoreland well field and Fisher on flowpaths of contaminated ground water.

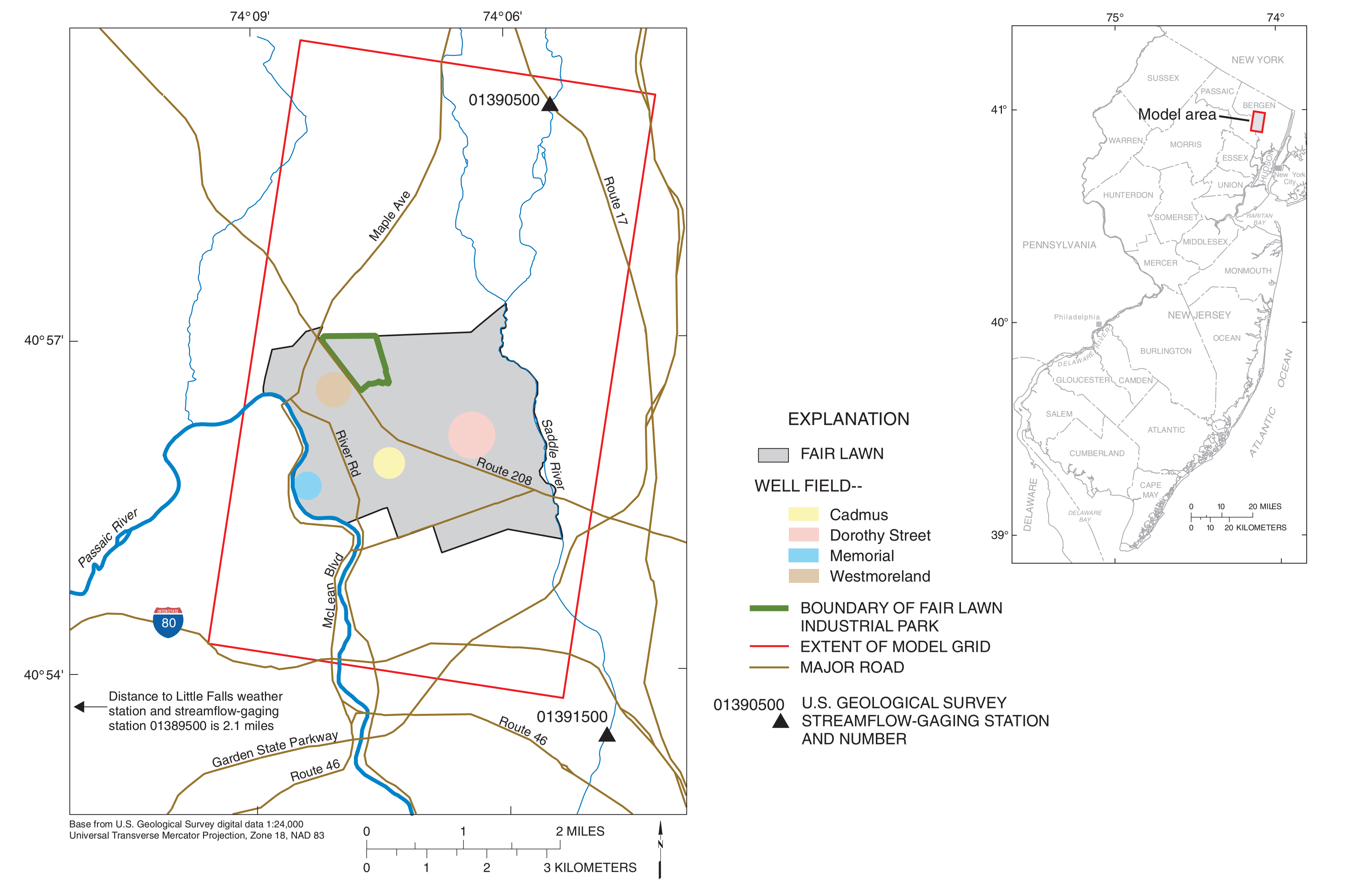


Figure 1. Location of model area, production well fields, and industrial park in and near Fair Lawn, New Jersey.

The ground-water flow model and the limitations of using the model to simulate movement of water are described. Data and interpretations used to develop the ground-water flow model are presented. The hydrogeologic framework in the Fair Lawn area, including the location, extent, and geometry of water-bearing and confining units, the character of the unconsolidated overburden, and its hydraulic connection with bedrock, is described, and the transmissivity of water-bearing and confining units is estimated.

The distribution of VOCs, metals, pesticides, semivolatile organic compounds (SVOCs), and polychlorinated biphenyls (PCBs) in discrete depth intervals in six observation wells is described, as are simulated water budgets for 10 surface-water basins in and near Fair Lawn.

Data collected during this project include borehole geophysical logs of six deep wells (162-505 ft deep), streamflow measurements at five sites, continuous water levels at eight observation wells, and static hydraulic heads and concentrations of VOCs in discrete depth intervals isolated by straddle packers in six observation wells. Water samples from one of the six wells were analyzed for VOCs plus total metals, SVOCs, pesticides, and PCBs.

Description of Study Area

The study area is the area represented by the active part of the ground-water flow model used in this study (fig. 2). It encompasses approximately 15 mi^2, extending beyond the boundaries of Fair Lawn Borough, as described in the Grid and Boundary Conditions section of this report. Most of the study area is bounded on the east and west by the Saddle and Passaic Rivers, respectively. Four tributaries to the Saddle River (Hohokus, Jordan, Beaver Dam, and Pehle Brooks) and four tributaries to the Passaic River (Diamond, Henderson, Lyncrest, and Fleischer Brooks) are in the study area. The drainage basins of these rivers and tributaries are shown in figure 2.

The Borough of Fair Lawn pumps water from 13 wells located in four well fields (fig. 1). Eight observation wells and one production well no longer in use also are owned by the municipality. The Memorial well field consists of production wells FL15, FL16, FL17, and FL19 (USGS well numbers 030460, 030319, 030318, and 030317, respectively), and observation wells FL18 and FLS-1 (USGS well numbers 030619 and 030618, respectively). The Dorothy Street well field consists of production wells FL25, FL26, and FL28 (USGS well numbers 030355, 030356, and 030354, respectively), and observation wells FL27 and FLP-1 (USGS well numbers 030357 and 030620, respectively). The Cadmus well field consists of production wells FL2, FL7, FL8, and FL9 (USGS well numbers 030423, 030352, 030411, 030353, respectively), and observation wells FL4 and FL29 (USGS well numbers 030531 and 030617, respectively). The Westmoreland well field consists of production wells FL10, FL11, and FL14 (USGS well numbers 030461, 030462, and 030424, respectively), and observation well FL12 (USGS well number 030512). Well FL11 has been out of service since 1997 and well FL12, although used sporadically as a production well in the past, has been out of service since 1999. For purposes of this study, well FL12 was used as an observation well and is referred to as such in this report. The other observation well owned by Fair Lawn Borough, FL23 (USGS well number 030621), is in Fair Lawn Industrial Park (fig. 1). The Fair Lawn Borough wells and other wells included in this study are shown in figure 3 and listed in table 1.

In 1991, the Borough of Fair Lawn pumped approximately 754 Mgal of water: 351 Mgal from the Memorial well field, 137 Mgal from the Dorothy Street well field, 136 Mgal from the Cadmus well field, and 130 Mgal from the Westmoreland well field. By 2000, the distribution of pumpage among the well fields had changed, mostly in response to the continued contamination of the Westmoreland well field. During the intervening period, pumpage from that well field decreased from 130 to 49 Mgal, whereas pumpage from the Cadmus well field increased from 136 to 234 Mgal. Total pumpage from all well fields in 2000 was nearly the same (approximately 770 Mgal) as in 1991, as was pumpage from the Memorial well field (332 Mgal) and the Dorothy Street well field (154 Mgal).

Hydrogeologic Framework

Data obtained from the results of borehole geophysical logging and slug testing of small volumes of rock were used to determine the location of water-bearing and confining zones in the study area. The water-bearing and confining zones were then connected on the basis of the regional strike and dip of the bedrock strata to form water-bearing and confining hydrogeologic units, respectively. The hydrogeologic units in the bedrock comprise a fractured-rock aquifer, and the fractured-rock aquifer and the overlying unconsolidated overburden comprise the aquifer system in the study area. In this report,

- An interval is defined as the part of a well's borehole that is isolated by straddle packers;
- A zone is the volume of rock around the interval; and
- A hydrogeologic unit (water-bearing or confining unit) is an areally extensive layer of rock.

Geology

Unconsolidated glacial sediments and alluvium that range in thickness from 6 to 100 ft overlie bedrock throughout the study area. Bedrock consists of the Passaic Formation.

Unconsolidated Overburden

The unconsolidated sediments are described in table 2 and their distribution is shown in figure 4. Throughout most of the study area, the Rahway till forms a 10- to 30-ft-thick veneer over bedrock. Other glacial sediments and alluvium overlie the till in most of the study area. Near the Passaic River, the

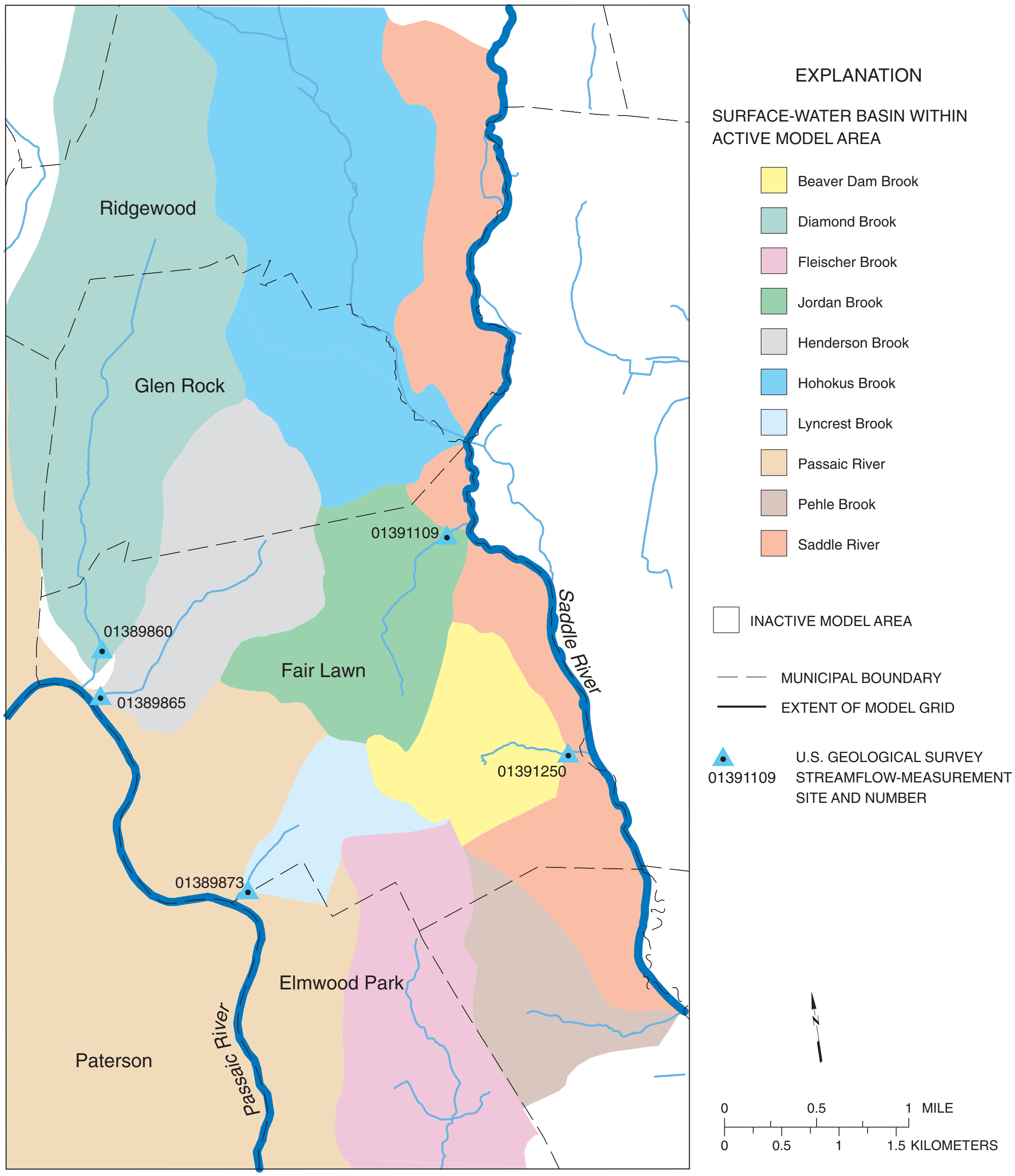


Figure 2. Location of study area (active area of the ground-water flow model), surface-water basins, and streamflow-measurement sites in and near Fair Lawn, New Jersey. (Location of model area shown in figure 1)

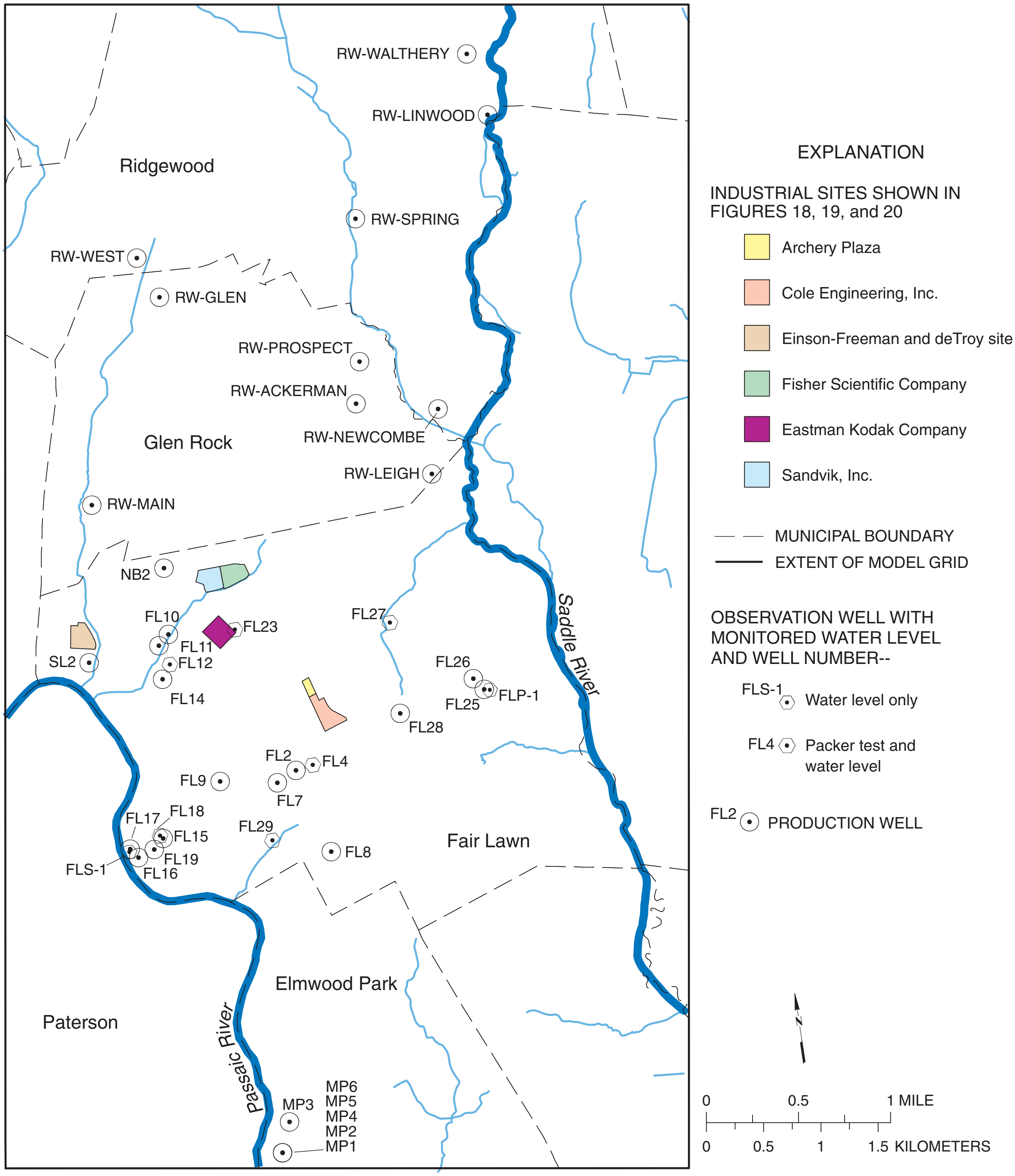


Figure 3. Wells with monitored water levels, and production wells within the study area (active area of the ground-water flow model) in and near Fair Lawn, New Jersey. (Location of model area shown in figure 1)

Table 1. Well-construction and pumpage data for selected wells in and near Fair Lawn, New Jersey.

[NJDEP, New Jersey Department of Environmental Protection; PF, Passaic Formation; AV, alluvium; GL, undifferentiated glacial sediments; Ridgewood WD, Village of Ridgewood Water Department; FLWD, Fair Lawn Borough Water Department; FS, Fisher Scientific Company; Hayward, Hayward Industries, Inc.; Sandvik, Sandvik, Inc.; EFD, Einson Freeman and deTroy; na, no data available; Steam Leasing Co, Steam Leasing Company]

Owner	Well name	U.S. Geological Survey well number	NJDEP well permit number	Geologic unit	Screened or open interval (feet below land surface)		Depth of well (feet below land surface)	Pumpage (million gallons)	
					Top	Bottom		1991	2000
FLWD	FL2	030423	46-00147	PF	na	na	300	21.568	15.414
FLWD	FL4[1]	030531	46-00149	PF	na	na	300	0	0
FLWD	FL7	030352	46-00151	PF	60	458	458	87.485	77.925
FLWD	FL8	030411	46-00152	PF	na	na	430	17.314	107.903
FLWD	FL9	030353	46-00153	PF	47.75	404	404	9.326	32.771
FLWD	FL10	030461	23-00249	PF	35	300	300	39.042	22.659
FLWD	FL11	030462	23-00250	PF	54	400	400	39.042	0
FLWD	FL12[1]	030512	23-00251	PF	40	400	400	0	0
FLWD	FL14	030424	43-00097	PF	na	na	400	52.056	26.744
FLWD	FL15	030460	26-00393	PF	46	402	402	88.306	109.178
FLWD	FL16	030319	26-00465	PF	49	413	413	72.645	60.010
FLWD	FL17	030318	26-01032	PF	52	350	350	78.084	63.799
FLWD	FL18[1]	030619	na	PF	na	na	162	0	0
FLWD	FL19	030317	26-01197	PF	47	400	400	112.409	98.883
FLWD	FL23[1]	030621	na	PF	na	na	400	0	0
FLWD	FL25	030355	23-07538	PF	59	370	370	15.447	62.607
FLWD	FL26	030356	23-07539	PF	51	400	400	0	33.389
FLWD	FL27[1]	030357	23-07540	PF	69	340	340	0	0
FLWD	FL28	030354	23-07541	PF	50	355	355	121.064	58.407
FLWD	FL29[1]	030617	26-13928	PF	53	505	505	0	0
FLWD	FLP-1	030620	23-11661	AV	18.35	21.35	21.35	0	0
FLWD	FLS-1	030618	na	AV	na	na	20.15	0	0
EFD	MW-1	030657	23-09962-3	GL	19.7	34.7	34.7	0	0
EFD	MW-2	030658	23-09963-1	GL	13.5	28.5	28.5	0	0
EFD	MW-3	030659	23-09964-0	GL	20.3	35.3	35.3	0	0
EFD	MW-4	030682	23-10505-4	GL	15.3	30.3	30.3	0	0
EFD	MW-5	030680	23-11085	GL	12	22	22	0	0
EFD	MW-6	030681	23-11086	GL	9	19	19	0	0
FS	PW-2	030539	23-05038	PF	50	335	335	7.357	4.585
FS	PW-4	030538	23-08701	PF	28	400	400	15.432	15.825
FS	PW-5	030537	23-08700	PF	24	350	350	12.420	19.143
FS	TPW1R	030576	23-14311	GL	na	na	17	0	.006
FS	TPW2	030575	23-14020	GL	na	na	12	0	.007
FS	TPW3	030574	23-14021	GL	na	na	12	0	.022
FS	TPW4	030572	23-14023	GL	na	na	12	0	.006

Table 1. Well-construction and pumpage data for selected wells in and near Fair Lawn, New Jersey.—Continued

[NJDEP, New Jersey Department of Environmental Protection; PF, Passaic Formation; AV, alluvium; GL, undifferentiated glacial sediments; Ridgewood WD, Village of Ridgewood Water Department; FLWD, Fair Lawn Borough Water Department; FS, Fisher Scientific Company; Hayward, Hayward Industries, Inc.; Sandvik, Sandvik, Inc.; EFD, Einson Freeman and deTroy; na, no data available; Steam Leasing Co, Steam Leasing Company]

Owner	Well name	U.S. Geological Survey well number	NJDEP well permit number	Geologic unit	Screened or open interval (feet below land surface)		Depth of well (feet below land surface)	Pumpage (million gallons)	
					Top	Bottom		1991	2000
FS	TPW5	030573	23-14018	GL	na	na	12	0	.120
FS	TPW6	030571	23-14019	GL	na	na	12	0	.028
FS	TPW7	030570	23-14017	GL	na	na	12	0	.010
FS	FS-02	030696	23-7399A	GL	5	25	25	0	0
FS	FS-05	030712	na	PF	19	40	40	0	0
FS	FS-07	030688	23-7404A	GL	3	23	23	0	0
FS	FS-9R	030693	23-13429	PF	74	99	99	0	0
FS	FS-11	030711	na	PF	70	100	100	0	0
FS	FS-14	030718	na	PF	21	50	50	0	0
FS	FS-15R	030689	23-13428	PF	44	54	54	0	0
FS	FS-17	030716	na	PF	20	40	40	0	0
FS	FS-18	030715	na	PF	70	100	100	0	0
FS	FS-19	030697	23-08699	PF	72	125	125	0	0
FS	FS-20	030694	23-08693	GL	5	17	17	0	0
FS	FS-21	030683	23-08694	GL	6	16	16	0	0
FS	FS-22	030692	23-08695	GL	5	25	25	0	0
FS	FS-23	030691	23-08696	GL	5	19	19	0	0
FS	FS-39	030698	23-12443	GL	30.5	55	55	0	0
FS	FS-40	030719	23-12444	PF	75	100	100	0	0
FS	FS-41	030717	23-12445	PF	75	100	100	0	0
FS	FS-42	030710	23-12446	PF	75	100	100	0	0
FS	PZ-4R	030714	23-13427	GL	4	19	19	0	0
FS	PZ-5	030713	23-13426	GL	10	20	20	0	0
Marcal Paper Mills	MP1	030484	46-00008	PF	na	na	150	0	26.438
Marcal Paper Mills	MP2	030485	46-00009	PF	na	na	280	0	68.906
Marcal Paper Mills	MP3	030233	46-00010	PF	30	325	325	31.640	61.524
Marcal Paper Mills	MP4	030486	46-00011	PF	na	na	80	4.646	0
Marcal Paper Mills	MP5	030487	46-00012	PF	na	na	125	0	30.762
Marcal Paper Mills	MP6	030488	46-00013	PF	na	na	300	52.113	0
National Biscuit Co	NB2	030324	23-03369	PF	58	393	393	82.939	36.094
Ridgewood WD	RW-Ackerman	030360	23-02227	PF	49	303	303	270.852	0
Ridgewood WD	RW-Glen Rock	030327	23-01835	PF	49	300	300	27.606	52.251
Ridgewood WD	RW-Leigh	030325	23-04171	PF	86	300	300	126.390	33.119
Ridgewood WD	RW-Linwood	030369	23-01445	PF	45	300	300	33.261	22.085
Ridgewood WD	RW-Main	030229	23-01443	PF	52.5	302	302	.998	101.190

Table 1. Well-construction and pumpage data for selected wells in and near Fair Lawn, New Jersey.—Continued

[NJDEP, New Jersey Department of Environmental Protection; PF, Passaic Formation; AV, alluvium; GL, undifferentiated glacial sediments; Ridgewood WD, Village of Ridgewood Water Department; FLWD, Fair Lawn Borough Water Department; FS, Fisher Scientific Company; Hayward, Hayward Industries, Inc.; Sandvik, Sandvik, Inc.; EFD, Einson Freeman and deTroy; na, no data available; Steam Leasing Co, Steam Leasing Company]

Owner	Well name	U.S. Geological Survey well number	NJDEP well permit number	Geologic unit	Screened or open interval (feet below land surface)		Depth of well (feet below land surface)	Pumpage (million gallons)	
					Top	Bottom		1991	2000
Ridgewood WD	RW-Newcombe	030359	23-04170	PF	70	300	300	43.348	76.442
Ridgewood WD	RW-Prospect	030362	23-01770	PF	50	300	300	416.201	122.962
Ridgewood WD	RW-Spring	030586	23-01644	PF	na	na	300	5.100	93.494
Ridgewood WD	RW-Walthery	030376	23-01643	PF	64	300	300	.998	0
Ridgewood WD	RW-West End	030463	23-05931	PF	41	300	300	77.608	105.191
Steam Leasing Co	SL2	030598	23-13895	PF	56	310	310	0	26.980
Sandvik	SV-4s	030684	23-7692	PF	28	40	40	0	0
Sandvik	SV-5s	030686	23-7691	PF	20	41.5	41.5	0	0
Sandvik	SV-6s	030690	23-7690	PF	22	41.5	41.5	0	0
Sandvik	SV-1D	030699	23-7689	PF	70	100	100	0	0
Sandvik	SV-2D	030695	23-7688	PF	65	99.5	99.5	0	0
Sandvik	SV-4D	030685	23-7687	PF	71	100	100	0	0
Sandvik	SV-5D	030687	23-7686	PF	72	104	104	0	0
Hayward	MW-1s	030678	23-9614-4	GL	7.6	17.6	17.6	0	0
Hayward	MW-4s	030675	23-10245	GL	10	25	25	0	0
Hayward	MW-5s	030670	23-10247	GL	8	23	23	0	0
Hayward	MW-6s	030673	23-10249	GL	8	23	23	0	0
Hayward	MW-7s	030676	23-10265	GL	5	20	20	0	0
Hayward	MW-8s	030668	23-11629	GL	5	20	20	0	0
Hayward	MW-9s	030664	23-11630	GL	10	25	25	0	0
Hayward	MW-10s	030662	23-11631	GL	7	17	17	0	0
Hayward	MW-13s	030666	23-11633	GL	5	20	20	0	0
Hayward	MW-14s	030667	23-11634	GL	10	25	25	0	0
Hayward	GMW-15s	030701	23-13804	GL	6	16	16	0	0
Hayward	GMW-17s	030708	23-13490	GL	5	15	15	0	0
Hayward	MW-18s	030707	23-13491	GL	5	15	15	0	0
Hayward	GTW-4	030705	na	GL	13	18	18	0	0
Hayward	MW-1d	030702	23-10244	PF	20	44.5	44.5	0	0
Hayward	GMW-4d	030674	23-10246	PF	28	53.5	53.5	0	0
Hayward	GMW-15d	030679	23-13803	PF	33	58	58	0	0
Hayward	GMW-17d	030709	23-13489	PF	28	48	48	0	0
Hayward	GTW-1	030703	na	PF	23	33	33	0	0
Hayward	GTW-3	030706	na	PF	15	40	40	0	0
Hayward	MW-7d	030677	23-10266	PF	22	48	48	0	0
Hayward	MW-8d	030669	23-11653	PF	30	55	55	0	0

Table 1. Well-construction and pumpage data for selected wells in and near Fair Lawn, New Jersey.—Continued

[NJDEP, New Jersey Department of Environmental Protection; PF, Passaic Formation; AV, alluvium; GL, undifferentiated glacial sediments; Ridgewood WD, Village of Ridgewood Water Department; FLWD, Fair Lawn Borough Water Department; FS, Fisher Scientific Company; Hayward, Hayward Industries, Inc.; Sandvik, Sandvik, Inc.; EFD, Einson Freeman and deTroy; na, no data available; Steam Leasing Co, Steam Leasing Company]

Owner	Well name	U.S. Geological Survey well number	NJDEP well permit number	Geologic unit	Screened or open interval (feet below land surface)		Depth of well (feet below land surface)	Pumpage (million gallons)	
					Top	Bottom		1991	2000
Hayward	MW-10d	030663	23-11655	PF	37	62	62	0	0
Hayward	MW-5d2	030672	na	PF	51	76	76	0	0
Hayward	MW-11d	030700	23-11656	PF	30	55	55	0	0
Hayward	MW-13d	030661	23-11658	PF	35	43	43	0	0
Hayward	GMW-5d3	030671	23-13805	PF	117	132	132	0	0
Hayward	MW-9d	030665	23-11654	PF	50	75	75	0	0
Hayward	GMW-16d2	030660	23-13807	PF	190	215	215	0	0
Hayward	MW-19d	030704	23-14983	PF	120	140	140	0	0

[1]Well for which borehole geophysical logs and straddle-packer test data are available.

Table 2. Characteristics of unconsolidated overburden sediments in and near Fair Lawn, New Jersey.

[<, less than]

Geologic unit (Stanford and others, 1990) (fig. 4)	Geologic name (Stone and others, 1995)	Age	Generalized description of sediments (Stone and others, 1995)	Thickness (feet)
Continuous till	Rahway till	Late Wisconsinan	Sandy to clayey till; compact, firm to hard consistency	10–30
Deltaic and lacustrine-fan deposits	Hohokus deposits	Late Wisconsinan	Deltaic and esker deposits	< 100
Fluvial deposits	Glacial Lake Paramus deposits	Late Wisconsinan	Fluvial sand, silt, and gravel	<20
Fluvial over lacustrine deposits	Glacial Lake Paramus deposits	Late Wisconsinan	Fluvial sand, silt, and gravel overlying lake-bottom silt, fine sand, and clay	< 70
Ice-contact deposits	Ice-contact deposits, undifferentiated	Late Wisconsinan	Sand and gravel	<150
Alluvium in flood plains of major rivers	Alluvium	Holocene and Late Wisconsinan	Laminated and thinly bedded silt, clay, and sand overlying gravel and sand	6–30
Alluvium in tributaries to major rivers	Alluvium	Holocene and Late Wisconsinan	Poorly sorted sand and gravel	< 13

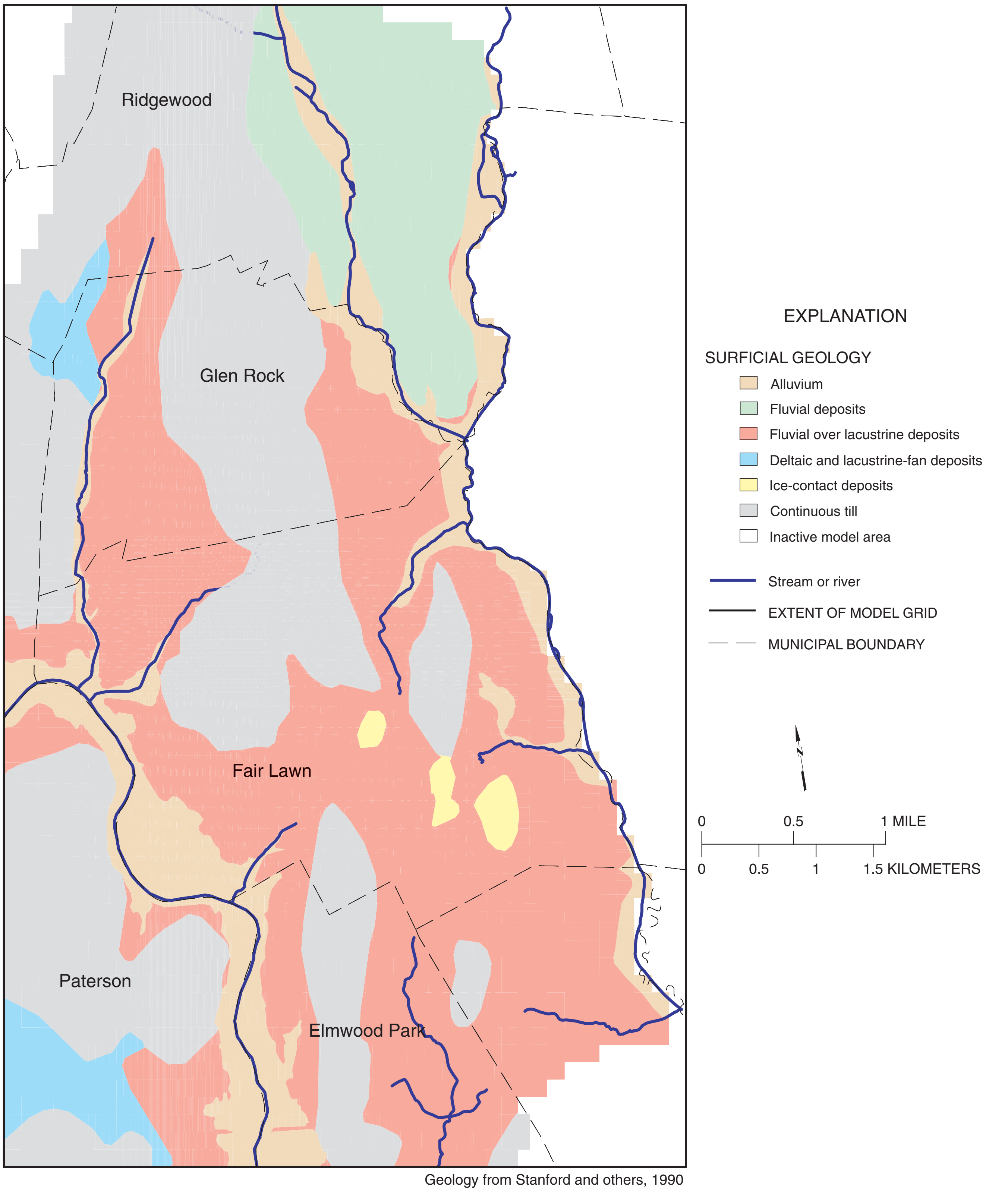


Figure 4. Surficial geology and streams within the study area (active area of the ground-water flow model) in and near Fair Lawn, New Jersey. (Location of model area shown in figure 1)

Rahway till and any glacial sediments that may have been present probably have been eroded so that alluvium directly overlies the bedrock. Discontinuous undifferentiated ice-contact deposits consisting of sand and gravel of Late Wisconsinan age overlie the till in some areas. Glacial Lake Paramus deposits include Late Wisconsinan-age lake-bottom deposits of fine sand, silt, and clay overlain by deltaic and glaciolacustrine fan deposits consisting of sand, silt, and gravel.

Bedrock

At Fair Lawn Borough, the Passaic Formation consists of layers of brownish-red pebble conglomerate, medium- to coarse-grained feldspathic sandstone, and micaceous siltstone. North and west of Fair Lawn, the Passaic Formation consists of a reddish-brown quartzite pebble conglomerate, pebbly sandstone, and sandstone (Drake and others, 1996). The rock layers are inclined, striking slightly east of north and dipping 7 to 9 degrees northwest. The mean regional orientation of the bedrock was determined from three strike and dip measurements made in the Borough of Fair Lawn (Parker, 1993) (table 3).

Table 3. Strike and dip measurements of sedimentary bedrock layers in outcrops, Fair Lawn, New Jersey.

[From Parker, 1993]

Location	Strike direction	Dip angle and direction
Northeastern corner of Fair Lawn Borough (Lincoln Avenue at intersection with Conrail tracks)	North 11^{o} East	7^{o} Northwest
Central part of Fair Lawn Borough (Fair Lawn Avenue at intersection with Conrail tracks)	North 3^{o} East	8^{o} Northwest
Western part of Fair Lawn Borough (Saddle River at intersection with Route 208)	North 12^{o} East	9^{o} Northwest
Mean strike and dip	**North 9^{o} East**	**8^{o} Northwest**

Borehole-Geophysical Logging

Borehole geophysical logs collected by the USGS were used to determine the location of potential water-bearing and confining zones in the study area. Natural gamma, spontaneous electric potential, resistivity, caliper, fluid temperature, and heat-pulse flowmeter logs were collected from six deep observation wells owned by the Borough of Fair Lawn. The six wells are shown in figure 3 and identified in table 1. The potential water-bearing zones identified from geophysical logs were later isolated by straddle packers for determination of hydraulic properties and for water-quality sampling.

Potential water-bearing zones were first identified using caliper and temperature logs. Zones where the caliper log indicates a high degree of fracturing and zones where the temperature log indicates a change in the gradient of fluid temperature are zones where water may be entering or leaving the borehole and, therefore, are potential water-bearing zones. The heat-pulse flowmeter was then used to test each potential water-bearing zone. The flowmeter measures the rate of vertical ground-water flow at discrete points in the borehole. The flowmeter was placed above and below each potential water-bearing zone. Where the rate of flow above the targeted zone was different from the flow rate below the zone, it was assumed that water is entering or leaving the borehole in that zone, and that the zone may be water bearing.

Borehole video surveys also were run in the six observation wells. The videos indicate the location and character of fractures, vugs, and seeps in the boreholes. Video logs were used to determine the optimum position of packers in order to obtain a tight seal against the borehole wall.

Straddle-Packer Testing

Straddle-packer testing is a means of isolating discrete intervals within open-hole wells. In this study, three types of data were obtained from the isolated intervals:

- Water-level changes in response to introducing a slug of pressurized air (slug testing). This data set was used to determine the transmissivity of each isolated zone, which, in turn, was used to determine the hydrogeologic framework in the study area.
- Water-quality data. These data were used to determine the distribution of contaminants in the study area and are discussed in the Ground-Water Quality section of this report.
- Static water levels. These data were used to calibrate the ground-water flow model and are discussed in the Ground-Water Levels section of this report.

The methods and results of slug testing are discussed in this section. Methods and results of water-quality sampling and static-water-level measurements are discussed in subsequent sections of this report. Zones to be packer tested were selected primarily on the basis of results of heat-pulse flowmeter logging. In parts of boreholes where heat-pulse logging was not possible, zones were selected on the basis of temperature logs and (or) caliper logs. All zones identified as potential water-bearing zones were packed off and slug tested for determination of transmissivity.

Methods of Slug Testing

Each packed interval was isolated with straddle packers, and then the packed zone was slug tested using a procedure modified from Greene and Shapiro (1995). The slug-test procedure involved pressurizing the headspace above the packed interval with nitrogen gas; the release of the pressure started the slug test. The slug testing in a well was done from the uppermost zone to the lowermost zone. If a water-quality sample was collected from the packed interval, the sample was collected first and then the interval was slug tested. This sequence was changed only when more than 12 hours had elapsed between the slug test and sampling of the packed interval. The packed intervals were approximately 12 ft long. The procedure used to isolate the selected zone and slug test the isolated zone was:

1. The packer assembly was lowered into the borehole on 2-in. pipe until the packers straddled the selected zone (fig. 5). A steel tape graduated to 0.01 ft attached at the top of the packer assembly was used to position the packers accurately to isolate the specified packed interval. If a water sample was collected from the packed zone, the packed interval was located such that the major fracture(s) in the zone would be adjacent to the pump used to sample the zone. The pump was lowered into the packed interval and rested on a bolt 2.06 ft from the bottom of the packed interval. If no sample was to be collected, the packed interval was located such that the major fracture in the zone was in the center of the interval.

2. When the packers were in position to isolate the selected interval, the 2-in. pipe was secured at the surface, and the upper and lower packer inflation lines were connected to the pressure gauge attached to the nitrogen gas cylinder. Depth to water from a common measuring point was measured for the upper open, packed, and lower open intervals. The inflation pressure of each packer was then calculated using the formula

$$IP = [(Head \times 0.433 + K) \times 1.3] \qquad (1)$$

where

"*IP*"	is the inflation pressure, in pounds per square inch (lb/in^2, or psi);
"*Head*" (ft)	= (Depth in feet below land surface to middle of the packer) – (Depth to water in feet below land surface);
0.433	is the conversion factor from feet of water to psi;
"*K*"	is a well constant representing the pressure required to seat the packers in the well in psi. (For an 8-in.-diameter well, *K* = 40; for a 10-in.-diameter well, *K* = 160; for a 12-in.-diameter well, *K* = 180);

and

1.3	is a "protection factor" that was used to ensure that the packers were inflated to a pressure great enough to compensate for the head of water pushing against them when inflated at depth in a well.

3. The slug-test apparatus was attached to the top of the 2-in. pipe (fig. 5).

4. The upper open, packed, and lower open interval transducers were placed in the well, 2-in. pipe, and 1-in. pipe, respectively (fig. 5).

5. The transducers were connected to the data logger and the data logger was connected to the laptop computer. Using the laptop computer, the transducers were calibrated to the water levels measured in step 2. Recording of water levels from the transducers was then started.

6. The upper packer was inflated. When the pressure gauge that measured pressure in the upper packer indicated a pressure equal to the pressure calculated in step 2, inflation was stopped. The lower packer was inflated in the same manner. The valves between the inflation lines and the nitrogen cylinder and the valve on the nitrogen cylinder were closed, and the lines were disconnected from the pressure gauge.

7. Water levels in the three intervals, measured with the transducers, were monitored until the levels stabilized. If the stable water levels in the upper and lower open intervals were different from the stable water level in the packed interval, it was assumed that the packers had seated and isolated the packed interval. If the water level in the upper and (or) lower open zone did not differ from the water level in the packed interval, it was assumed there was a connection between the intervals with the same water levels. This connection could be the result of interconnecting fractures or of inadequate seating of a packer. Occasionally, the water level in an interval did not stabilize. If the level had not stabilized after a reasonable period of time (typically about 1 hour after both packers were inflated completely), preparations for slug testing proceeded to step 8.

8. The manual measuring port in the slug-test apparatus was sealed.

9. The valve used to release pressure in the packed interval was closed.

10. The transducer used to monitor the pressure in the headspace of the packed interval was placed into the slug-test apparatus.

11. A different, more sensitive gauge was attached to the nitrogen cylinder, and the pressure line from the top of the slug-test apparatus was connected to this gauge.

12. The valve on the nitrogen cylinder was opened and the headspace in the packed interval was pressurized until the gauge read 5 psi. The valve on the nitrogen cylinder was then closed.

13. The water levels in the three intervals and the pressure in the headspace were again monitored with the transducers. When the levels were stable, the slug test could begin. Occasionally, the water level in one of the zones did not stabilize. If the level had not stabilized after a reasonable period of time (typically about 1 hour after the headspace was pressurized), the slug test was started.

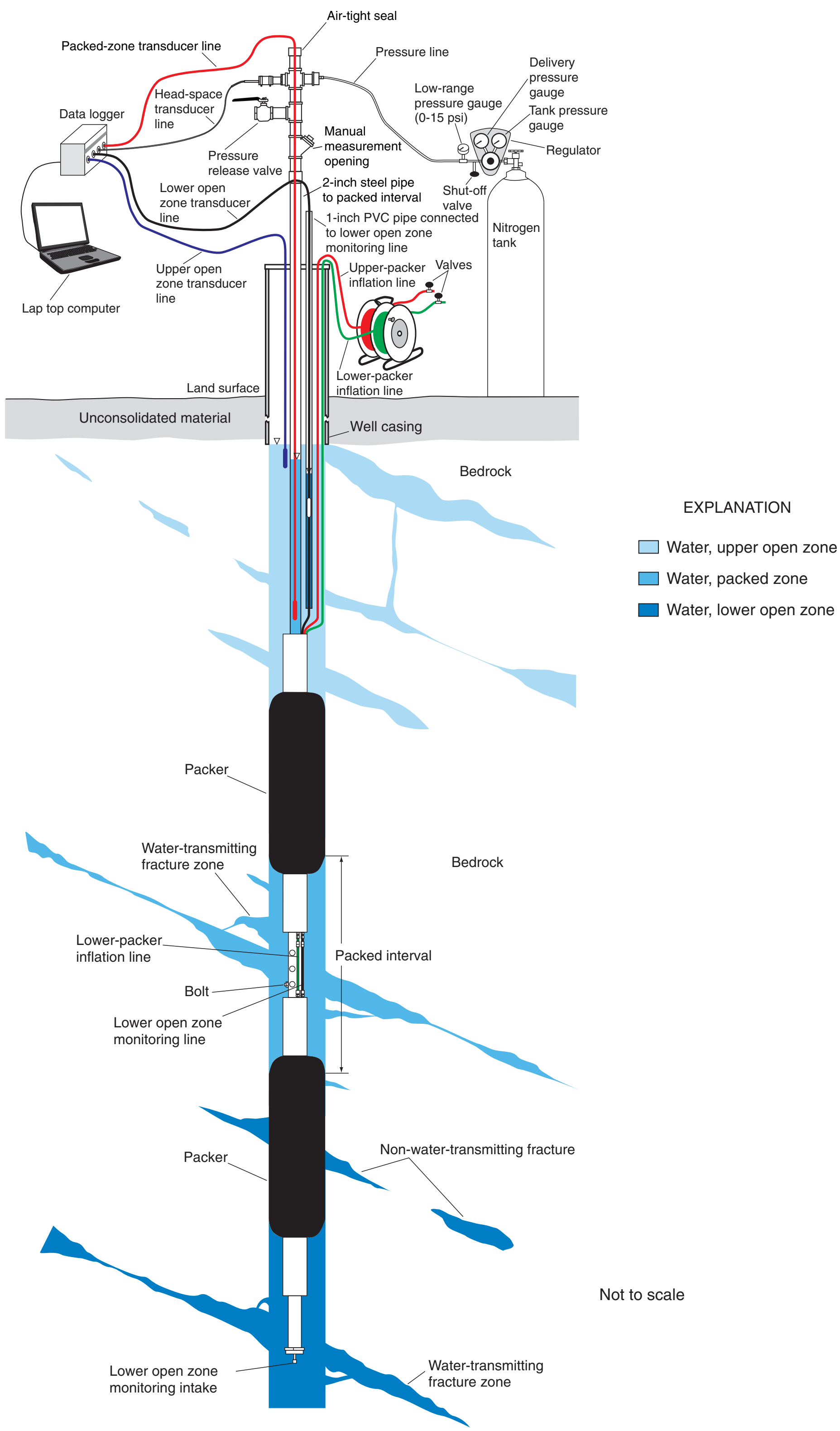


Figure 5. Schematic diagram of straddle-packer assembly and air-slug apparatus with conceptual representation of bedrock hydrogeology.

14. All transducers were set to record the time elapsed from the beginning of the test on a log scale. This setting allowed rapid recording of water levels during the first minutes of the slug test, and as the slug test progressed and the change in water levels slowed, the time interval between measurements lengthened.
15. The pressure-release valve was opened to begin the slug test.
16. The water level in the packed interval was monitored. When the water level had stabilized at or near the level prior to pressurization of the packed interval, the test was finished and recording of water levels from the transducers was stopped.
17. A second slug test was then run for all intervals where pressurization of the headspace had resulted in water levels depressed below the static level in the packed interval. The valve used to release pressure in the packed interval was closed, and steps 12 to 16 were repeated.
18. When slug testing was complete, the recording of transducer water levels was stopped and the water-level data from the transducers were saved to a file on both the laptop and a floppy disk. The data logger was disconnected from the laptop, and the transducers were disconnected from the data logger.
19. The packers were deflated and the slug-test apparatus was detached from the 2-in. pipe. The transducers were removed from the well and decontaminated using a soap and deionized-water rinse followed by a deionized-water rinse.

The transducers in the upper open, packed, and lower open intervals effectively measured total head (water level above NAVD 88), which is the sum of pressure head, elevation head, and velocity head. Velocity head is negligible and is considered to have a value of zero, and before pressurization, pressure head was due only to the atmospheric pressure, which was compensated for by the vented transducer.

Pressurizing the packed interval with nitrogen gas to about 5 psi, or about 11.55 ft of water (2.31 ft/psi), effectively confined the water-bearing zone isolated by the packers. As pressurization progressed, the elevation head in the packed interval was decreased until a new equilibrium was reached within the water-bearing zone isolated by the packers. The elevation head in the packed interval was reduced by exactly the amount that the pressure was increased. At this new equilibrium, the packed-interval transducer indicated a total head equal to the pressure head plus the elevation head, which also equaled the total head before pressurization. For example, if the elevation in the packed interval were 50 ft before pressurization, the new elevation head after pressurization would be 38.45 ft. The total head after pressurization in this example would be 38.45 ft + 11.55 ft of pressure head, or 50 ft.

The test began when the nitrogen-gas pressure was released nearly instantaneously, returning pressure head to atmospheric pressure. For an instant, then, the depth to water remained lower than the static level by an amount equal to the pressure formerly exerted by the nitrogen gas. Generally, the water level in the packed interval began to rise rapidly, with the packed-zone transducer recording this increase in elevation head. When the water level in the packed interval had stabilized at the initial static water level, the equilibrium between elevation head and total head in the packed zone was re-established, and the test was ended.

Transmissivity and Hydraulic Connection Between Adjacent Zones

Two data sets were obtained during slug testing. Water-level recovery data from the packed interval were used to calculate the transmissivity of the packed zone. Water-level data from the upper and lower open zones were examined to determine whether these zones responded to the pressurization of the packed zone. A substantial response in these zones was an indication that the packed zone was interconnected with the responding zone. This connection could have been the result of interconnecting fractures or of inadequate seating of a packer.

Transmissivity

The transmissivity of the packed zones was determined from the slug-test data by using three methods. The method of Cooper and others (1967) was used to analyze most of the slug-test data. Some packed intervals did not respond to the slug-test stress; it was assumed that these packed intervals isolated a zone with a transmissivity near zero. Some of the slug-test data from the packed intervals did indicate a response to the slug-test stress but, when graphed, the data did not fall on any of the Cooper type curves and could not be analyzed with this method. The transmissivity of these zones was evaluated qualitatively—that is, designated as being high or medium. The transmissivity of the packed zones determined from the slug tests is listed in table 4.

The broad range in measured transmissivity (from near 0 to 8,900 ft^2/d) is a result of the heterogeneity of the fractured-rock aquifer. Zones in which measured transmissivities were high probably are those in which one or more vertical fractures intersect horizontal fractures, whereas zones in which measured transmissivities were low probably are between vertical fractures.

The method described by Cooper and others (1967) was used to analyze the results of slug tests with a normal response to the pressurizing of the slug-test zone. A normal response is considered to be an initial rapid rise in water level when the pressure was released instantaneously, followed by a slower recovery to the initial, unstressed water level within the packed interval. Additionally, a normal response is considered to be one in which the water levels in the packed interval recorded during the slug test, when plotted in relation to elapsed time from the start of the test, fell approximately on a Cooper type curve.

Table 4. Transmissivity of slug-tested zones, Fair Lawn, New Jersey.

Well	Zone	Top (feet below land surface)	Bottom (feet below land surface)	Transmissivity (feet squared per day)
FL4	1	55	66.74	Medium[1]
FL4	2	64.09	75.83	2.4
FL4	3	163.76	175.5	6.2
FL4	4	251.83	263.57	Medium[1]
FL4	5	260.52	272.26	78
FL12	1	35	47.09	High[2]
FL12	2	95	111	8,900
FL12	3	154	170.49	1,000
FL12	4	177	193.49	1,700
FL12	5	223.74	240.23	2,000
FL12	6	275	291.49	1.1
FL12	7	326	365	9.8
FL18	1	26	39	2,000
FL18	2	60.33	160	1,400
FL23	1	40.65	52.39	850
FL23	2	59.98	71.72	High[2]
FL23	3	249.57	261.31	High[2]
FL23	4	271	282.74	High[2]
FL23	5	314.11	325.85	High[2]
FL23	6	349.83	361.57	860
FL27	1	64	75.74	29
FL27	2	85.06	96.8	High[2]
FL27	3	107.06	118.8	400
FL27	4	177.4	189.2	Not determined
FL27	5	204.22	215.96	High[2]
FL27	6	241.98	253.7	670
FL27	7	266.72	278.44	[3]0
FL27	8	319.85	340	[3]0
FL29	1	64.04	75.78	780
FL29	2	81.95	93.69	780
FL29	3	129.15	140.89	590
FL29	4	147.03	158.77	1,400
FL29	5	205.53	217.27	840
FL29	6	309.03	320.77	[3]0
FL29	7	309.03	495	50

[2]Transmissivity assumed to be from 10 to 100 feet squared per day.

[3]Transmissivity assumed to be greater than 100 feet squared per day.

[4]Approximate value. The zone did not respond to the slug-test stress; transmissivity assumed to be near 0 feet squared per day.

In the Cooper slug-test analysis, the aquifer (in this case, a single water-bearing unit) is assumed to be confined and apparently infinite in areal extent; to be isotropic, homogeneous, and of uniform thickness over the area affected by the slug test; and to be penetrated completely by the well (or packed interval) being tested, which therefore receives water only by horizontal flow. It is probable that the packers isolated zones within the aquifer that were confined and sufficiently extensive to approximate infinite areal extent within the zone of influence of the test; therefore, this assumption is reasonable. It is also reasonable to assume that the packed interval completely penetrated the aquifer. It is uncertain, however, whether the packers isolated homogeneous and isotropic zones within the aquifer. Transmissivities calculated from slug-test data can be assumed to be representative of only the aquifer volume immediately adjacent to the slug-test interval. It is probable that these limited aquifer volumes were homogeneous and isotropic; if not, however, this assumption should be considered a limitation of the analysis of slug-test data by the Cooper method.

All unique numerical values of transmissivity greater than zero in table 4 were obtained using the Cooper method. Two slug tests were run for all intervals with a transmissivity greater than zero. The transmissivities obtained by the Cooper method, reported in table 4, are either the result that best fit a Cooper type curve, or, if results of both slug tests for an interval appeared to be similar (that is, fit the same Cooper type curve), the higher of the two transmissivity values.

The water level in three of the packed intervals (intervals 7 and 8 in well FL27 and interval 6 in well FL29) did not decline below the static water level in the packed zone when the pressure was released at the start of the slug test (table 4). It is likely that no fractures were present within these three intervals; therefore, when the interval was pressurized, water could not enter the aquifer. Consequently, the displaced water could go only up into the 2-in. pipe connected to the packed interval. In these three tests, the water level in the 2-in. pipe rose approximately 12 ft when the packed zone was pressurized. After the pressure was released, the water level immediately returned to the static water level. These three zones are assumed to have a transmissivity near zero.

In 10 slug tests, water levels responded normally to the pressurization of the packed interval but could not be analyzed by the Cooper method. Two of these tests were in isolated intervals in well FL4, one was in well FL12, four were in well FL23, and three were in well FL27. Long-term water-level data (discussed in the Ground-Water Levels section of this report) indicate that water levels in these four wells are affected by unknown stresses, probably pumping in nearby wells. Water levels in the isolated intervals during these 10 tests might have been responding not only to the pressurization of the packed interval, but also to pumping stresses. The pumping stress could result in a declining water level during pumping and (or) a rising water level soon after pumping ended.

In 4 of these 10 tests, the plot of the slug-test data, although in the general shape of a Cooper type curve, did not fall on any of the type curves. These four slug tests are for intervals 1 and 4 in well FL4, and intervals 2 and 3 in well FL23. A quantitative analysis for these four intervals was not possible; instead, the transmissivity for these intervals was evaluated qualitatively. As an indicator of the relative transmissivity associated with these four intervals, the time required for the depressed water levels to recover to within 10 percent of the respective static levels was examined. These times were compared to the equivalent times for the slug-test data analyzed with the Cooper method. The “10-percent time” is defined as the time required for the depressed water level to recover to a water level equal to the initial static water level minus 1.155 ft, or 10 percent of 11.55 ft, which is the approximate water-level decline in the slug-tested intervals. The 10-percent times for slug tests analyzed by the Cooper method and for the four tests described above are listed in table 5. The 10-percent time is inversely related to transmissivity. Therefore, for the four intervals for which the Cooper method could not be used, a qualitative transmissivity of high was assigned to those intervals with a 10-percent time of less than 1 min, and a transmissivity of medium was assigned to those intervals with a 10-percent time of 1 to 5 min. None of the 10-percent times for these four intervals was greater than 5 min.

In 6 of the 10 tests that could not be analyzed by the Cooper method, the plot of the slug-test data was not in the general shape of a Cooper type curve, but rather showed a regular oscillation in water level. This result occurred in intervals in wells FL12, FL23, and FL27. A plot of head in relation to elapsed time for an oscillating slug test in interval 4 in well FL27 is shown in figure 6. Water-level oscillations can occur during a slug test in a highly permeable aquifer when the inertia of the slug of displaced water is high (Springer and Gelhar, 1991). The length of the oscillation period and the percent recovery from the depressed water level (11.55 ft below the static level) to the static level at the end of that period were examined (table 6). The length of the oscillation period for interval 4 in well FL27 extended through the entire test; therefore, a qualitative transmissivity for this interval could not be determined. The other four intervals had an oscillation period of less than 1 min with at least 89-percent recovery. This result is believed to indicate that transmissivity in these intervals in high. This assessment is in agreement with those of Van Der Kamp (1976) and Springer and Gelhar (1991).

Approximate numerical values were assigned to the high- and medium-transmissivity designations to facilitate comparison with the transmissivities determined using the Cooper method. As a generalization, it is assumed that “high” corresponds to a transmissivity of 100 ft^2/d or greater and “medium” corresponds to a transmissivity of 10 to 99 ft^2/d.

Table 5. 10-percent times and quantitative and estimated qualitative transmissivities for selected slug-test zones, Fair Lawn, New Jersey.

[ft^2/d, feet squared per day; >, greater than]

Well	Zone[1]	10-percent time[2] (minutes)	Transmissivity[3] (ft^2/d)
FL18	1	0.1073	2,000
FL23	2	.108	High[4]
FL23	3	.1902	High[4]
FL23	6	.2989	860
FL12	2	.432	8,900
FL23	1	.4384	850
FL27	3	.494	400
FL18	2	.6965	1,400
FL29	4	.879	1,400
FL27	6	.9307	670
FL29	3	1.124	590
FL29	2	1.351	780
FL12	4	1.369	1,700
FL12	5	1.37	2,000
FL4	1	1.609	Medium[4]
FL29	5	1.668	840
FL29	1	2.855	780
FL12	3	3.42	1,000
FL4	4	4.633	Medium[4]
FL29	7	11.84	50
FL27	1	13.32	29
FL4	2	>15	2.4
FL4	5	16.74	78
FL12	7	>17	9.8
FL4	3	>59.49	6.2

[5] Zones are listed in order of increasing 10-percent times.

[6] 10-percent time is the time required for the water level to recover to within 10 percent of the static water level prior to the slug test.

[7] Transmissivity was determined using the method of Cooper and others (1967).

[8] Qualitative transmissivity was estimated from the 10-percent times of the quantitatively determined transmissivities.

Hydraulic Connection Between Adjacent Zones

Water levels in the upper and lower open intervals near the start of the slug test (when pressure was released) were examined to determine whether these water levels responded similarly to those in the packed interval. A substantial response in these intervals is an indication of a connection to the packed zone. The connection could be the result of either a packer not sealing off the packed interval completely or of interconnecting fractures between the packed zone and the upper or lower open zone. It is believed that the packers did isolate the packed interval because (1) a 1.3 “safety factor” multiplier was built into the calculated inflation pressure, (2) caliper and video logs of the boreholes were examined to ensure that the packers were inflated against smooth sections of the borehole, and (3) the difference among water levels in the three intervals increased after packer inflation. Therefore, if the water levels in the upper and lower open intervals responded to the change in water level in the packed interval during the slug test, the response was assumed to be a result of interconnecting fractures.

The maximum decline in water levels in the upper and lower open intervals and the associated elapsed time from the start of the slug test are shown in table 7. A small decline over a long time indicates little interconnection with the packed zone; a large decline over a short time indicates substantial interconnection. Results of 10 of the 35 tests indicated a connection to an adjoining zone.

After the start of the slug test in interval 1 in well FL4, the water level in the upper open interval declined by 0.236 ft in 0.215 min. Because the water level in the packed interval was only 6.17 ft above the top of the packed interval, the packed interval was pressurized with only 2 psi of nitrogen gas to prevent the gas from entering the packed interval. If the packed interval had been pressurized with 5 psi (2-1/2 × 2 psi) of nitrogen gas, the water-level decline in the upper open interval likely would have been about 2-1/2 times 0.236 ft, or 0.59 ft. This decline represents a substantial response to the slug test in a short period of time; therefore, it is probable that the packed and upper open zones were connected.

Responses of less than 0.8 ft in more than 0.29 minutes were observed in the upper open interval in well FL18 interval 2, the lower open intervals in well FL12 intervals 3 and 5, and the lower open interval in well FL23 interval 5. The responses in these four intervals, although modest, occurred sufficiently soon after the start of the slug tests to conclude that the zones probably are connected to the corresponding packed zones.

The borehole video log of well FL18 revealed a ¾-in. pipe in the borehole starting at about 50 ft below land surface. Efforts to remove all or part of this pipe were unsuccessful. A 4-in. cap was attached to the bottom of the packer assembly in this well, in the hope that the cap might help break off or crush the pipe while the packers were being lowered down the well. It is not known whether this attempt was successful. It was clear, however, that the inflated packers did not isolate a packed interval at 80 to 93 ft below land surface in this well because water levels in upper and lower open intervals were nearly identical to the water level in the packed interval. Because that interval could not be isolated by the packers, no attempt was made to perform slug tests in it. Instead, the entire zone from 60.33 ft below land surface to the bottom of the well (interval 2) was tested by inflating only the packer above the packed interval. The difference in water levels between the upper open interval and the packed interval for interval 2 was 0.15 ft, a sufficiently large difference to indicate that the upper packer had successfully isolated the upper open zone from the packed zone. The response observed in the upper open interval during the slug test, however, might contradict this conclusion.

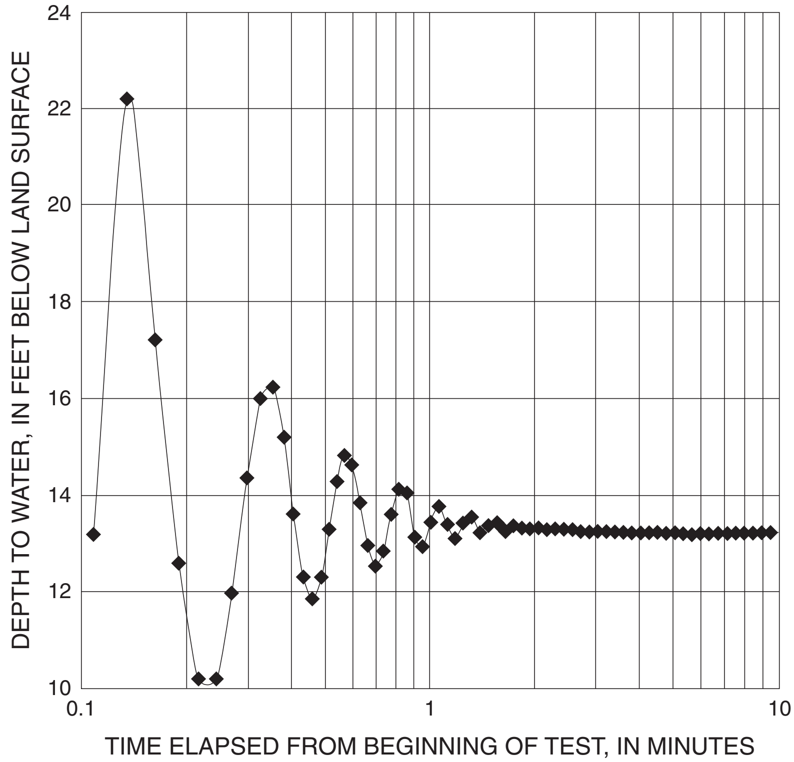


Figure 6. Slug-test data showing depth of water in relation to elapsed time for well FL27, interval 4, Fair Lawn, New Jersey. (Well location shown in figure 3)

Table 6. Oscillation period, percent recovery, and qualitative transmissivity for zones with oscillating water levels during slug tests, Fair Lawn, New Jersey.

[>, greater than]

Well	Zone	Oscillation period (minutes from start of test)	Percent recovery to static water level	Qualitative transmissivity
FL12	1	0.216	99	High
FL23	4	.9924	99	High
FL23	5	.8748	98.2	High
FL27	2	.2683	89	High
FL27	4	> 21	Unknown	Not determined
FL27	5	.607	96.1	High

Table 7. Water-level decline in the upper and lower open intervals and the associated time from the start of the slug test to the maximum decline for wells in Fair Lawn, New Jersey.

[--, not applicable]

Well (fig. 3)	Packed interval	Depth of packed interval (feet below land surface)		Upper open interval		Lower open interval	
		Top	Bottom	Water-level decline (feet)	Time (minutes)	Water-level decline (feet)	Time (minutes)
FL4	1	55	66.74	[1]0.236	[1]0.215	Indeterminate	--
FL4	2	64.09	75.83	Rising water level	--	0	0
FL4	3	163.76	175.5	Rising water level	--	Rising water level	--
FL4	4	251.83	263.57	0	0	.798	3.04
FL4	5	260.52	272.26	0	0	.079	.03
FL12	1	35	47.09	0	0	.072	0
FL12	2	95	111	0	0	.23	.38
FL12	3	154	170.49	0	0	.77	1.3
FL12	4	177	193.49	0	0	.06	0
FL12	5	223.74	240.23	0.11	.51	.39	.88
FL12	6	275	291.49	0	0	0	0
FL12	7	326	365	0	0	Indeterminate	--
FL18	1	26	39	.167	.4	0	0
FL18	2	60.33	160	.365	.43	Indeterminate	--
FL23	1	40.65	52.39	Rising water level	--	Indeterminate	--
FL23	2	59.98	71.72	Rising water level	--	Falling water level	--
FL23	3	249.57	261.31	.013	.08	Falling water level	--
FL23	4	271	282.74	.035	.93	.136	.73
FL23	5	314.11	325.85	.047	.82	.345	.3
FL23	6	349.83	361.57	.094	.22	Falling water level	--
FL27	1	64	75.74	0	0	0	0
FL27	2	85.06	96.8	Rising water level	--	.029	.32
FL27	3	107.06	118.8	0	0	0	0
FL27	4	177.4	189.2	.014	.8	.093	.44
FL27	5	204.22	215.96	Oscillation	--	.05	.14
FL27	6	241.98	253.7	0	0	Falling water level	--
FL27	7	266.72	278.44	0	0	Falling water level	--
FL27	8	319.85	340	0	0	0	0
FL29	1	64.04	75.78	0	0	.943	1.04
FL29	2	81.95	93.69	.37	3.77	.036	.81
FL29	3	129.15	140.89	.017	.83	1.007	.72
FL29	4	147.03	158.77	.227	2.23	1.93	.49
FL29	5	205.53	217.27	Falling water level	--	.194	.49
FL29	7	309.03	495	Rising water level	--	Indeterminate	--

[9] Slug test done at 2 pounds per square inch.

In three intervals in well FL29—1, 3, and 4—the water level in the lower open interval declined by at least 0.9 ft. The declines occurred in the first minute of the slug test. These large declines in a short time indicate a substantial interconnection between the packed zones and the lower open zones.

In two intervals—the lower open interval in well FL4 interval 4 and the upper open interval in well FL29 interval 2—the water-level response was small but occurred more than 3 min after the start of the slug test; this result probably indicates a slight connection between these zones and the packed zone.

When the bottom packer was not inflated for a slug test, there was no lower open interval, and the water-level change is reported as "indeterminate." When the water level in the lower open interval did not rise into the 1-in. pipe connected to the interval (fig. 5), the water level could not be measured, and this water-level change also is reported as "indeterminate." During some slug tests, the water level in the upper or lower interval rose part of the time and fell part of the time, so it was not possible to determine a water-level change.

Orientation and Location of Bedrock Hydrogeologic Units

The strike of the bedrock hydrogeologic units in the study area was assumed to be equal to the mean measured strike of bedding in Fair Lawn (N. 9^{o} E.). The dip of the units was assumed to approximate the mean measured dip (8^{o} to the northwest).

The location of water-bearing and confining units within the fractured-rock aquifer was determined primarily on the basis of transmissivity measurements made during straddle packer testing (table 4) and results of geophysical logging. The six wells that were packer-tested were plotted on a cross section oriented along the dip of the units, with each well projected onto the section (fig. 7). The transmissivity of each packed zone also was plotted on the section. The transmissivities of the packed zones were divided into three categories. Transmissivities of 0 to 10 ft^2/d were considered to be low, and the entire packed zone for which a low transmissivity was measured was considered to be in a confining unit. Transmissivities of 10 to 100 ft^2/d were considered to be moderate, and a packed zone for which a moderate transmissivity was measured was considered to be in either a leaky confining unit or a unit that is marginally water-bearing. Transmissivities greater than 100 ft^2/d were considered to be high, and at least part of a packed zone for which a high transmissivity was measured was considered to be in a water-bearing unit. Packer testing was done only on intervals that were determined to be in possible water-bearing zones on the basis of geophysical logs. All other intervals were assumed to be in confining units.

Eight water-bearing units and eight confining units were identified in the study area on the basis of transmissivity. The dip of the units, 6.5^{o} to the northwest, was determined by connecting water-bearing and confining zones along the section to form continuous hydrogeologic units. The water-bearing and confining units are shown in figure 7, a section along the dip of the beds, and figure 8, a map view of the subcrops of the units below the unconsolidated overburden. The water-bearing units range in thickness from 21 to 95 ft; the mean thickness is 50 ft. The confining units range in thickness from 22 to 248 ft; the mean thickness is 83 ft.

In most instances in which water-level data indicated a hydraulic connection between the packed zone and adjacent strata, the packed zone and adjacent strata were interpreted as being part of the same water-bearing or confining unit. However, although water-level data indicated hydraulic connections between packed zone 5 in well FL23 and the strata below it, between zone 4 in well FL29 and the strata below it, and between zone 1 in well FL4 and the strata above it, low to moderate transmissivity measurements for packed zones 1 and 2 in well FL4 indicate the presence of a leaky confining unit (confining unit 6) between water-bearing units 6 and 7 (fig. 7).

The open intervals of the wells that were packer-tested span nearly all of the stratigraphic section in Fair Lawn, including the Westmoreland well field and Fair Lawn Industrial Park. For purposes of simulation of ground-water flow, hypothetical water-bearing and confining units were assigned in areas where no transmissivity data are available (east of well FL27 and west of well FL18). The hypothetical units were assigned the same strike and dip as the defined units and the mean thickness of the defined units.

The location of all Fair Lawn Borough production and observation wells projected onto a section along the dip of the beds is shown in figure 9. Because the section is oriented along dip, wells that are near each other on the section are aligned along the strike of the beds. This section illustrates the reasons for the patterns in water-level responses in observation wells when pumps in production wells are turned on or off. For example, production wells FL28 and FL26 are approximately the same distance from observation well FL27, with well FL28 along strike and well FL26 updip. Well FL28 is open to two of the same water-bearing units as well FL27 (water-bearing units 8 and 9), but well FL26 does not intersect any of the same units as well FL27. Consequently, the water level in well FL27 responds by declining 5 to 6 ft when the pump in well FL28 is turned on, but does not decline at all when the pump in well FL25 or FL26 is turned on. Similarly, observation wells FL4 and FL29 and production wells FL2 and FL7 all are open to water-bearing zone 7. Water-level data from the continuous recorders indicate strong responses in the observation wells when the pumps in one or both of the production wells are turned on.

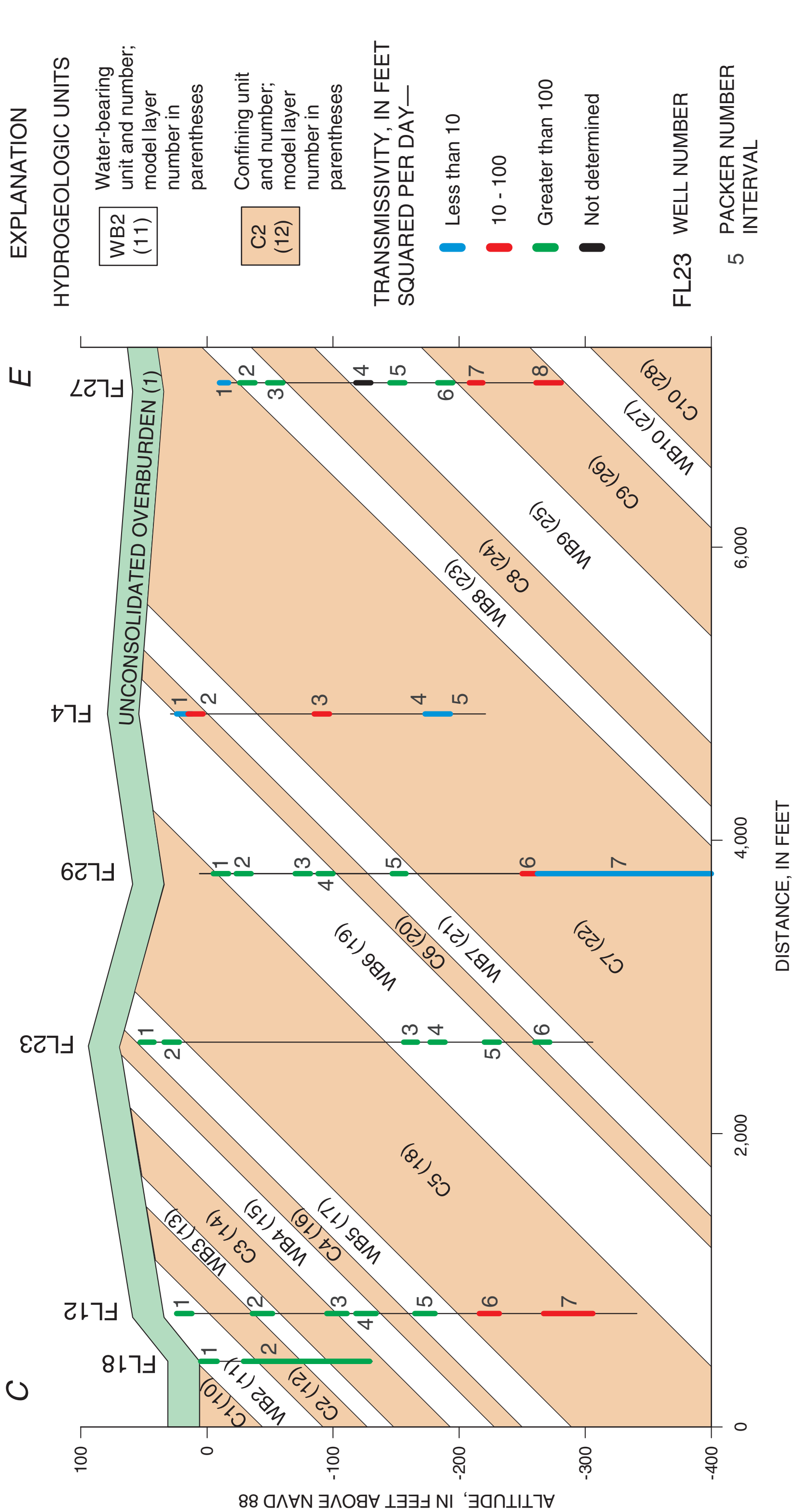


Figure 7. Section C-E along dip of bedding units showing wells that were packer-tested and interpreted water-bearing and confining units, Fair Lawn, New Jersey. (All wells projected onto line of section; location of section shown in figure 8)

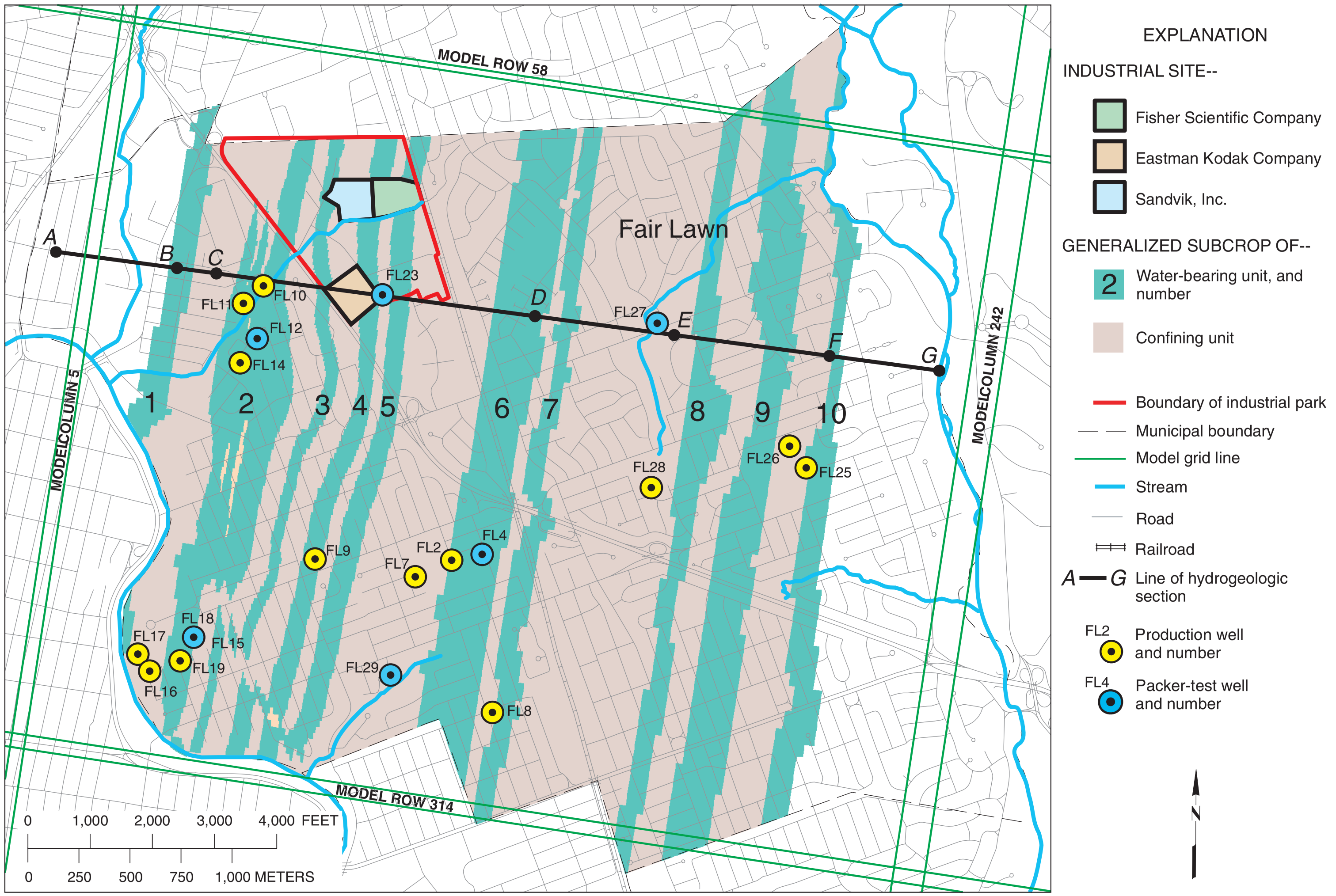


Figure 8. Subcrops of interpreted water-bearing units and confining units and line of section, Fair Lawn, New Jersey. (Location of Fair Lawn shown in figure 1)

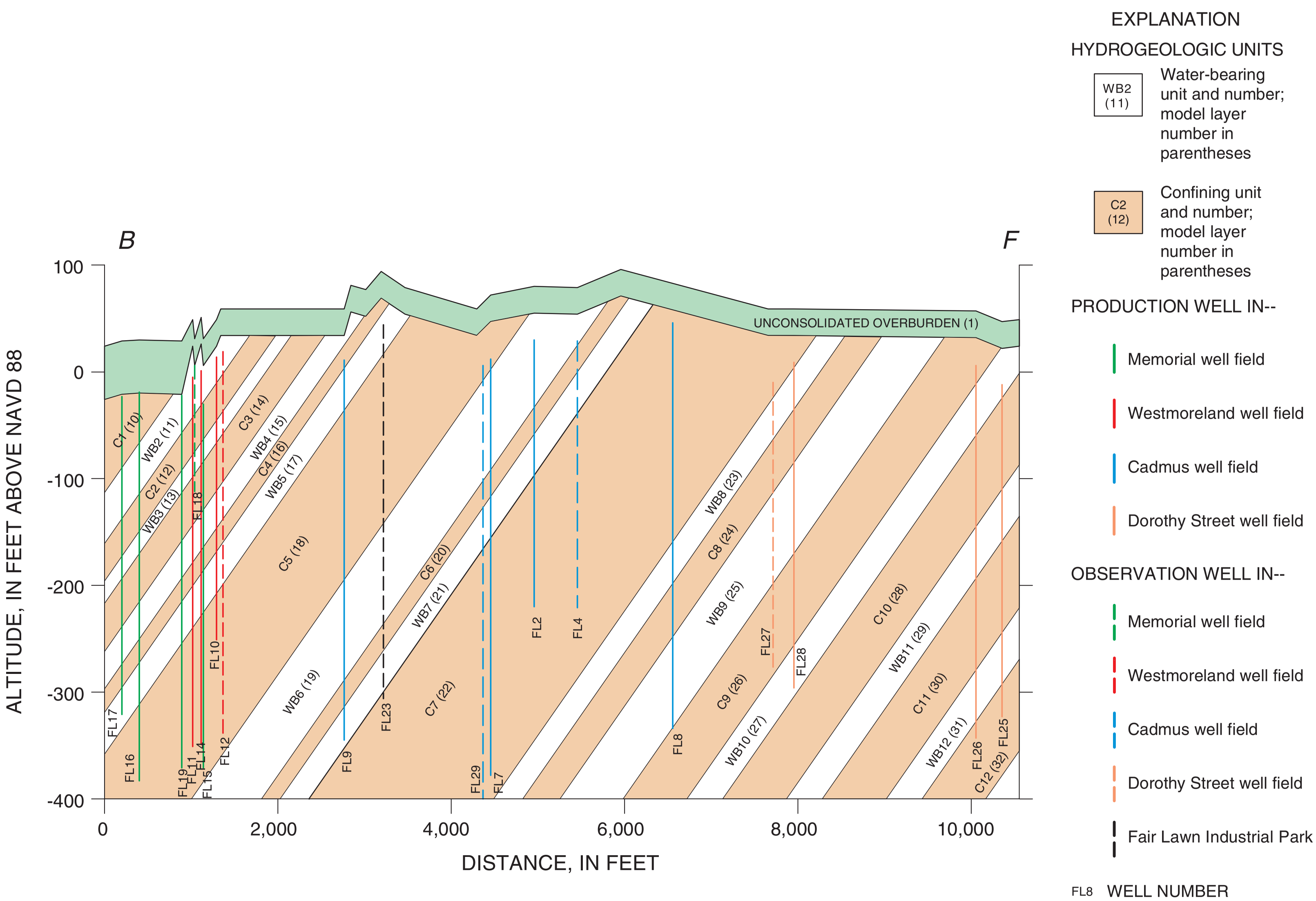


Figure 9. Section B-F along dip of bedding units showing interpreted water-bearing and confining units and Fair Lawn Water Department production wells and observation wells, Fair Lawn, New Jersey. (All wells projected onto line of section; line of section shown in figure 8)

Ground-Water Levels

Continuous water-level data from eight wells in Fair Lawn during 2000–02 supplemented transmissivity data used to develop the hydrogeologic framework. Water-level responses in wells to nearby pumping and to precipitation can be used to determine the degree of connection between bedrock water-bearing units and confining units, between the bedrock and the overburden, and between the overburden and streams.

Overburden Observation Wells

Water-level recorders were installed in two shallow observation wells (wells FLS-1 and FLP-1) screened in the overburden (fig. 3 and table 1). These wells are about 20 ft deep. Water-level depth was recorded every 15 min from early June 2000 until late March 2002. Precipitation data from the National Weather Service precipitation gage (National Oceanic and Atmospheric Administration, 2000-02) at Little Falls, New Jersey (fig. 10), were used to aid in the interpretation of seasonal fluctuations in water levels.

Well FLS-1

Observation well FLS-1 (fig. 11), in the Memorial well field, is less than 200 ft from the bank of the Passaic River and 150 to 1,200 ft from the four production wells in the well field. The well was drilled into the alluvial overburden to a depth of 20 ft below land surface. Water levels ranged from about 9 ft to 13 ft below land surface. Water levels generally declined from late August 2000 to mid-December 2000, increasing only in response to precipitation, a pattern typical of normal seasonal fluctuations. The water-level decline from October 2001 to spring 2002 was the result of drought. Large water-level increases in the well were caused by infiltration of precipitation and possibly in part by increases in the stage of the Passaic River (fig. 12). Although about 330 Mgal/yr of water is withdrawn from wells in the Memorial well field, no effect of the withdrawals on water levels in well FLS-1 is apparent. The lack of response indicates either that the bedrock aquifer is not well connected to the alluvial overburden, or that a strong connection between the Passaic River and the alluvium moderates the water levels in well FLS-1. It is likely that the alluvium is well connected to the river because the alluvium contains abundant sand and gravel.

Well FLP-1

Observation well FLP-1 (fig. 11), in the Dorothy Street well field, is approximately 0.5 mi west of the Saddle River, 170 ft east of production well FL25, and 620 ft southeast of production well FL26. The well was drilled in the overburden to a depth of 21 ft below land surface. Although the well is not near a stream, alluvium is present at land surface. The alluvium probably was formed by an abandoned tributary to Beaver Dam Brook. Water levels in well FLP-1 ranged from about 6.5 ft to 11.75 ft below land surface for the period of record (early June 2000 to late March 2002). Water levels were high in summer 2000 and declined from late August through mid-November 2000. Drought conditions from October 2001 through spring 2002 resulted in the lowest water levels for the period of record. Large water-level increases clearly were caused by precipitation. Withdrawals from nearby production wells FL25 and FL26 had no apparent effect on water levels in well FLP-1, probably because the overburden in this area is poorly connected to the bedrock aquifer; the hard-packed Rahway till at the base of the overburden impedes flow between the overburden and the bedrock. Water levels in well FLP-1 also did not appear to be affected by fluctuations in the stage of the Saddle River (fig. 12), probably because the well is more than 2,000 ft from the river.

Bedrock Observation Wells

Water-level recorders were installed in the six deep Fair Lawn Water Department bedrock observation wells (FL4, FL12, FL18, FL23, FL27, and FL29) (fig. 3 and table 1). These wells range in depth from 162 ft to 505 ft below land surface. Water levels recorded in these wells reflect a composite head of all water-bearing units within the open interval. Water-level depth was recorded every 15 min beginning in early May 2001 in well FL12 and beginning in early April 2000 in the other five wells. Recording was discontinued in all six wells in late March 2002. Gaps in the data reflect short periods when the recorders were removed from the wells for geophysical logging, packer testing, or recorder malfunction.

Hydrographs of the six deep observation wells (fig. 13) show that water levels were stressed during most of the data-collection period. About 770 Mgal was withdrawn in 2000 from Fair Lawn Water Department production wells. Water-level recoveries of 5 to 13 ft occurred when pumps in the production wells were turned off for static-water-level measurements, scheduled maintenance, or repairs. These documented shutdowns are useful markers for determining the effects of withdrawals from production wells on water levels in observation wells. Other fluctuations in water levels in some of the wells can be attributed to the cycling off and on of nearby pumps used by local industrial or commercial users. An area-wide rise in water levels from late December 2000 through March 2001 probably was caused by increased recharge from precipitation and decreased ground-water withdrawals from Fair Lawn Water Department wells. Water-level declines in the study area from fall 2001 through winter 2002 were from 1.5 to 4 ft greater than those during the same period in 2000 as a result of drought.

Well FL4

Water levels in observation well FL4 (fig. 13), in the Fair Lawn Water Department Cadmus well field, ranged from about 33 to 69 ft below land surface during the period of record (April 2000 through March 2002). Fair Lawn Water Department production wells FL2 and FL7 were in operation in the Cadmus

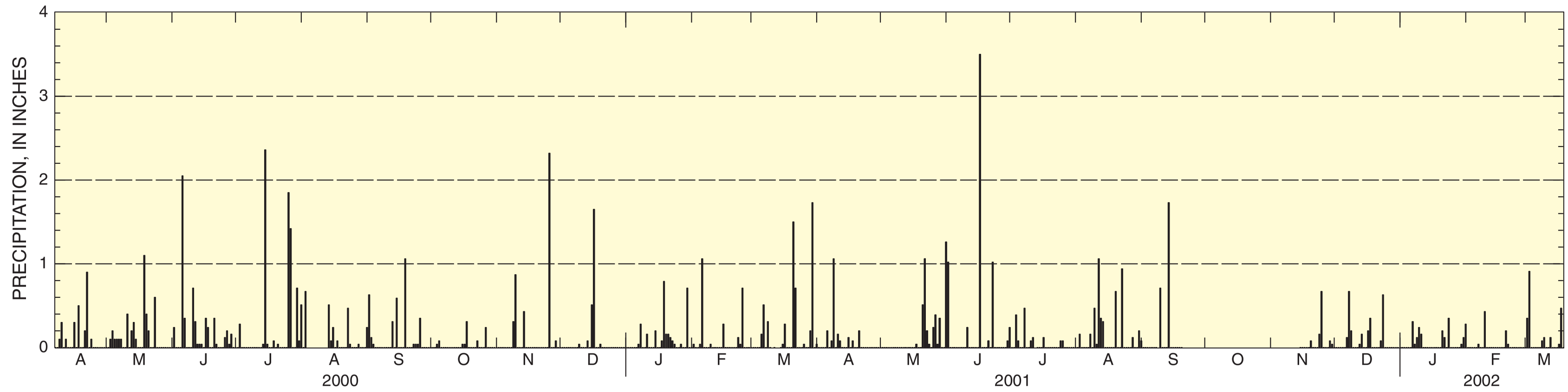


Figure 10. Daily precipitation recorded at the National Weather Service precipitation gage at Little Falls, New Jersey, April 7, 2000-March 19, 2002.

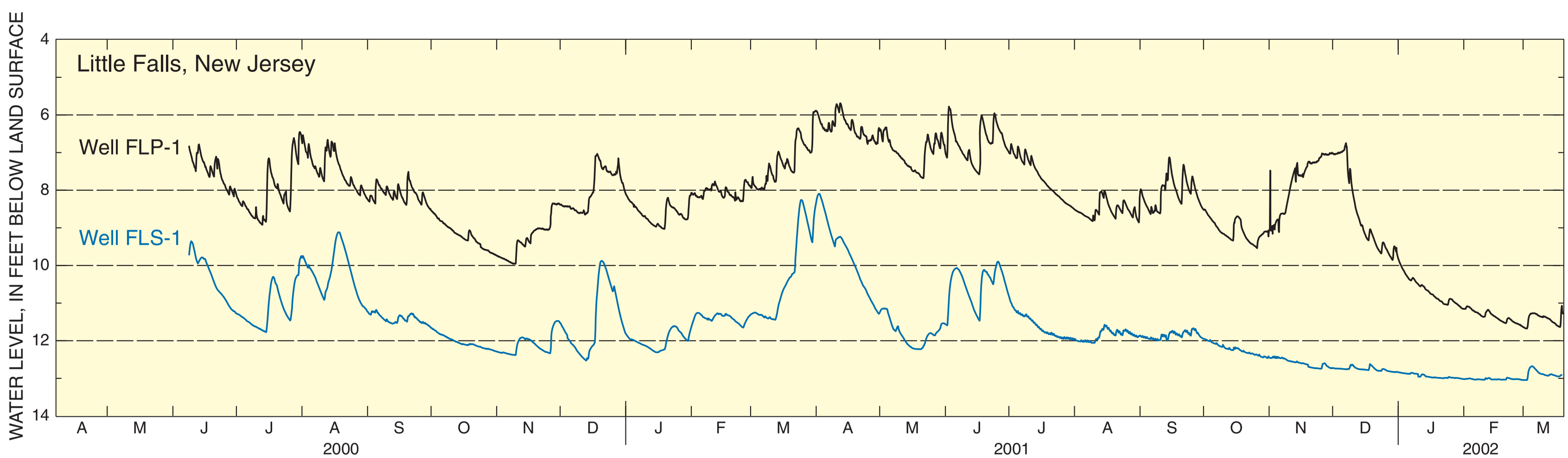


Figure 11. Ground-water hydrographs from two observation wells open to the water table in Fair Lawn, New Jersey, June 8, 2000-March 19, 2002. (Well locations shown in figure 3)

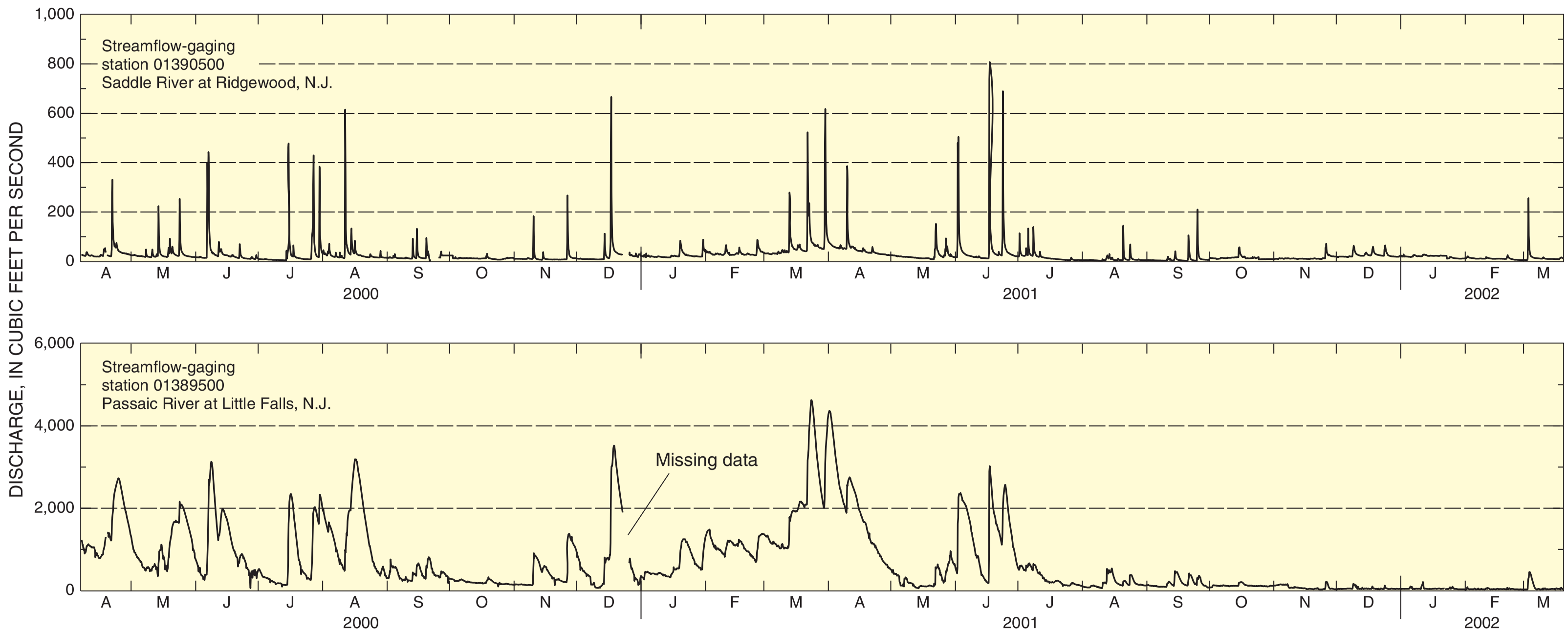


Figure 12. Discharge of the Passaic River at Little Falls, and the Saddle River at Ridgewood, New Jersey, April 7, 2000-March 19, 2002.

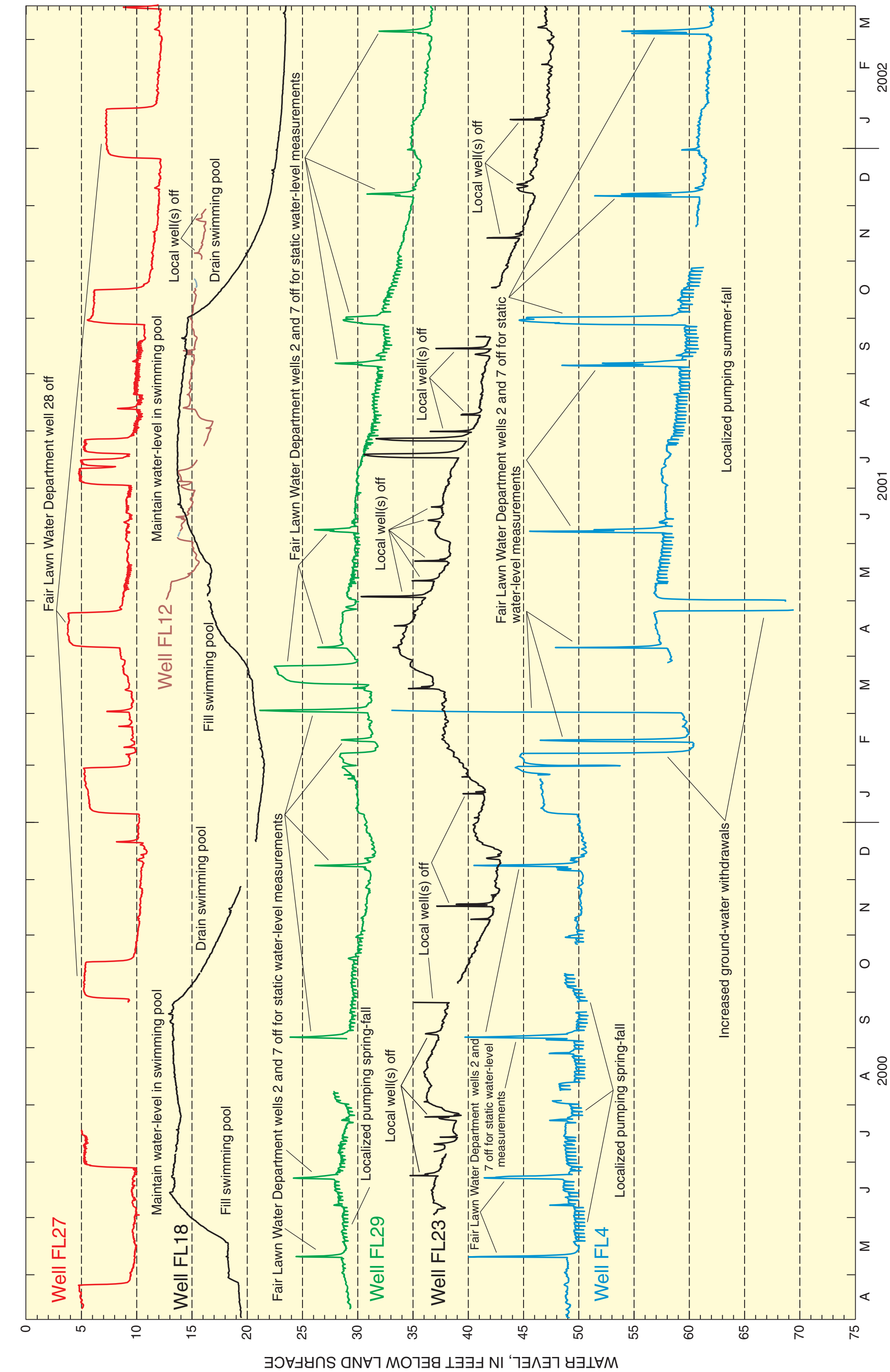


Figure 13. Ground-water hydrographs from six deep Fair Lawn Water Department observation wells, Fair Lawn, New Jersey, April 7, 2000-March 19, 2002. (Well locations shown in figure 3)

well field during that period. Well FL2 is approximately 500 ft west-southwest of well FL4, and well FL7 is more than 1,100 ft from well FL4 in the same general direction (fig. 8). The three wells (FL2, FL4, and FL7) are hydraulically connected because all are open to water-bearing unit 7 (fig. 9). Scheduled minimum 12-hour shutdowns for static-water-level measurements at wells FL2 and FL7 resulted in 8- to 27-ft rises in water levels in well FL4 (fig. 13). In early February 2001, an increase in ground-water withdrawals from the Cadmus well field caused water levels to fall from about 45 to about 60 ft below land surface. Long-term static water levels ranged from 33 ft to almost 54 ft below land surface. Daily cyclical fluctuations of about 1.5 ft occurred between mid-May and early November of each year. These fluctuations apparently were caused by pumping at another nearby well.

Well FL12

A water-level data recorder was installed in observation well FL12, in the Fair Lawn Water Department Westmoreland well field (fig. 8), in May 2001. Westmoreland production wells FL10 and FL14 were pumped during the period of the hydrograph (May 2001 through March 2002). Water levels in well FL12 ranged from 12 to 17 ft below land surface. The many irregular spikes in the record indicate that the well probably is affected by nearby pumping. Well FL12 is hydraulically connected to production wells FL10 and FL14 because all three are open to water-bearing units 3, 4, and 5 (fig. 9). The small rise (about 1 ft) in the water level in well FL12 during September 11-13, 2001, probably is a result of that connection. Well FL14 was turned off for 12 hours on each of those days, and well FL10 was turned off for 12 hours on September 11.

Well FL18

Water levels in observation well FL18 (fig. 13), in the Memorial well field near the Borough swimming pool, ranged from about 12.5 to 23.5 ft below land surface during the period of record (April 2000 through March 2002). Well FL18, the shallowest of the six bedrock observation wells, is 162 ft deep. Wells in operation in the Memorial well field during 2000-02 are wells FL15, FL16, FL17, and FL19 (fig. 8). These wells range in depth from 350 to 413 ft, are within 900 ft of observation well FL18, and are open to the same two water-bearing units (2 and 3) as well FL18 and to two deeper water-bearing units (4 and 5) (fig. 9). Leakage from the swimming pool apparently creates a water-level mound in the area, as shown on the hydrograph for well FL18. Each year, the pool is filled with water from Fair Lawn production wells in May and is drained into the Passaic River in September. The water level in well FL18 rose 9 ft from mid-May to late June 2000 and remained about constant until late September, when it began to fall.

Well FL23

Water levels in Fair Lawn Water Department observation well FL23 (fig. 13), in Fair Lawn Industrial Park, ranged from about 30 to 47.5 ft below land surface during the period of record (June 2000 through March 2002). The Westmoreland well field, where wells FL10 and FL14 were pumped during the period, is only about 1,850 ft west of well FL23. Wells FL10, FL14, and FL23 are open to one common water-bearing unit, unit 5 (fig. 9). Withdrawals from the Westmoreland well field appear to have had a small effect on water levels in well FL23, as the hydrograph of water levels in well FL23 shows 1- to 2-ft rises in water levels on the days when wells in the Westmoreland well field were off line for 12 hours (September 11-13, 2001).

Production well FL9 is about 4,300 ft southwest of and along strike with well FL23. Although these two wells are open to the same three water-bearing units, well FL9 probably is too far from well FL23 to cause the small, irregular spikes in water levels in well FL23. Rather, the fluctuations probably are caused by changes in pumpage at one or more nearby commercial wells. The water level in well FL23 declined 14 ft from mid-April 2001 to February 2002 as a result of drought conditions.

Well FL27

Water levels in observation well FL27, in the Dorothy Street well field and more than 3,400 ft east of Fair Lawn Industrial Park (fig. 8), ranged from about 3.5 to 12 ft below land surface during the period of record (April 2000 through March 2002) (fig. 13). Withdrawals from Fair Lawn Water Department production well FL28 apparently resulted in 5 to 6 ft of drawdown in well FL27. Well FL28 is approximately 2,200 ft south of and along strike with well FL27. Both wells are open to water-bearing units 8 and 9 (fig. 9). Because the pump in well FL28 was shut off for more than 15 days six times during the period of record, water levels in well FL27 reached near-static conditions during these shutdowns. Effects of local pumping by other users are evident in the hydrograph record for the spring and summer months.

Well FL29

Fair Lawn Water Department observation well FL29 is in the Cadmus well field (fig. 8). Water levels ranged from about 21 to 37 ft below land surface during the period of record (April 2000 through March 2002) (fig. 13). The hydrograph of water levels in this well mimics the hydrograph for observation well FL4 (also in the Cadmus well field), indicating that these two wells are hydraulically connected. Both wells are open to water-bearing unit 7 (fig. 9). Pump shutdowns at production wells FL2 and FL7 in the Cadmus well field resulted in 4- to 10-ft rises in the water level in observation well FL29. These three wells are open to the same water-bearing units (6 and 7) (fig. 9). The water level in well FL29 declined from 28 to 32 ft below land surface in early February 2001, when pumpage from production well FL2 increased from about 26,000 to about 140,000 gal/d.

The water level in well FL29 declined steadily from 28 ft below land surface in April 2001 to 37 ft below land surface by March 2002. As in observation well FL4, daily cyclical water-level fluctuations from mid-May to early November each year were caused by other, local withdrawals. Fluctuations in water levels in well FL29 were smaller than those in well FL4 because well FL29 is farther from pumping sources.

Ground-Water Quality

The contaminants of concern in the study area, as identified by the USEPA (U.S. Environmental Protection Agency, 2003), are the volatile organic compounds (VOCs) found in production wells in the Westmoreland well field (wells FL10, FL11, and FL14) and at the two industrial sites identified by the NJDEP as contributing sources of those VOCs (Fisher and Sandvik). The location of these wells and source-area sites are shown in figure 8. Although some production wells in other Fair Lawn well fields (Cadmus and Memorial) also are contaminated, concentrations of contaminants in these well fields generally are lower than those in the Westmoreland well field. VOCs detected in wells in the Westmoreland, Cadmus, and Memorial well fields are listed in tables 8, 9, and 10, respectively.

VOCs detected in water samples from monitor wells at Fisher and Sandvik are listed in table 11. Because the results of ground-water flow simulation indicate that some contaminated water from the Kodak site flows to the Westmoreland well field, as described in the Simulated Contaminant Plumes section of this report, VOCs detected in water samples from monitor wells at that site also are listed in table 11. Kodak is a known contaminated site (N.J. Department of Environmental Protection, 2001) in Fair Lawn Industrial Park.

The wells at Fisher are from 19 to 125 ft deep; those at Sandvik are 40 to 104 ft deep (table 1). The monitor wells at Kodak are described as being open to shallow bedrock (Quest Environmental and Engineering Services, Inc., 2002). Although no wells at Sandvik are completed in the overburden, soil samples from this site contained VOCs at concentrations that exceed drinking-water standards (Metcalf & Eddy, Inc., 1994).

The compounds detected in wells in the Westmoreland well field also are found at Fisher, Sandvik, and Kodak, and the Westmoreland wells, which draw water from water-bearing units 2, 3, 4, and 5 (fig. 9), are hydraulically connected to water-bearing units underlying all three of these sites. The subcrops of water-bearing units 3 and 4 underlie the Sandvik and Kodak sites; the subcrops of water-bearing units 4 and 5 underlie the Fisher site (fig. 8).

Sampling Methods

Water samples were collected from intervals isolated by straddle packers in Fair Lawn Water Department observation wells FL4, FL12, FL18, FL23, FL27, and FL29. At well FL12, all potential water-bearing zones were sampled. At the other five wells, all zones for which the heat-pulse flowmeter data indicated that water was entering the borehole (receiving zones) and all water-bearing zones for which it could not be determined whether water was entering or leaving the borehole were sampled. Samples were not collected from losing intervals in these wells (intervals for which the heat-pulse flowmeter data indicated that water was leaving the borehole) because the water in these intervals likely would be a composite of water entering at one or more receiving intervals. Packed intervals were pumped for sampling using a variable-rate stainless-steel and Teflon submersible pump (Grundfos Redi-Flo 2) attached to ¾-in.-diameter Teflon-lined high-density polyethylene (HDPE) tubing. U.S. Environmental Protection Agency low-flow sampling procedures (U.S. Environmental Protection Agency, 1998) were followed:

1. The Grundfos pump was lowered through the 2-in. pipe connected to the packed interval until the pump rested on the bolt within the packed interval (fig. 5).
2. Water levels in the upper open, packed, and lower open intervals were measured manually prior to sampling. These measurements were used to calibrate the pressure transducers, which then were set to record water-level measurements at 15-second intervals during sampling.
3. The pump was started and a flow rate of 500 mL/min was established. Water-level drawdown never was greater than 0.3 ft, so this rate was maintained during purging.
4. Field water-quality parameters (pH, dissolved-oxygen concentration, turbidity, temperature, and specific conductance) were measured at approximately 5-min intervals during purging and were allowed to stabilize before a sample was collected.
5. Purge water generated by low-flow sampling was disposed of on the ground, approximately 30 ft from the well.
6. When purging was completed, the samples were collected in VOC vials preserved with hydrochloric acid.
7. For well FL12 only, samples to be analyzed for the following constituents also were collected:
   - Total metals, in a 1-L HDPE bottle preserved with nitric acid;
   - Cyanide, in a 1-L HDPE bottle preserved with sodium hydroxide;
   - SVOCs, in two 1-L amber glass bottles; and
   - Pesticides/arochlors in 1-L amber glass bottles.

Table 8. Volatile organic compounds detected in water samples from wells in the Westmoreland well field, Fair Lawn, New Jersey, 1991, 1996, and 2000[1].

[Concentrations in micrograms per liter; --, not detected; data from Kenneth Garrison, Fair Lawn Water Department, written commun., 2000]

Compound	1991			1996-2000		
	Well FL10 (7/23/91)	Well FL11 (7/30/91)	Well FL14 (7/30/91)	Well FL10 (2/2/00)	Well FL11 (1/23/96)[2]	Well FL14 (2/2/00)
Carbon tetrachloride	10	1.3	0.5	7.15	--	2.62
Chloroform	24.8	5.5	2.8	13.2	14.0	2.64
1,1-Dichloroethane	4.6	--	2.2	4.22	3.11	2.37
1,2-Dichloroethane	1.1	--	--	--	1.33	--
1,1-Dichloroethylene	24.8	--	--	22.0	19.80	8.56
cis-1,2-Dichloroethylene	29.4	7.9	3.2	81.6	36.2	3.88
trans-1,2-Dichloroethylene	--	--	--	1.75	--	--
Methyl *tert*-butyl ether	1.1	--		1.52	2.65	--
Tetrachloroethylene	538	83.8	11.6	580	406	16.5
1,1,1-Trichloroethane	83	12	25.3	23.90	30.80	6.98
Trichloroethylene	35.5	8.8	5.2	57.80	41.4	4.44
Trichlorofluoromethane	--	--	--	--	1.19	--

[10]Data in this table are not in any U.S. Geological Survey database.

[11]No samples were collected from well FL11 in 2000; results of analysis of the most recently collected sample are listed here.

Table 9. Volatile organic compounds detected in water samples from wells in the Cadmus well field, Fair Lawn, New Jersey, 1991 and 2000[1].

[Concentrations in micrograms per liter; --, not detected; data from Kenneth Garrison, Fair Lawn Water Department, written commun., 2002]

Compound	1991				2000			
	Well FL2 (3/5/91)	Well FL7 (3/5/91)	Well FL8 (2/13/91)	Well FL9 (2/13/91)	Well FL2 (1/4/00)	Well FL7 (1/4/00)	Well FL8 (1/11/00)	Well FL9 (1/11/00)
Carbon tetrachloride	--	--	--	--	--	--	--	1.52
Chloroform	--	--	--	9	0.58	0.67	1.66	3.81
1,1-Dichloroethylene	--	--	--	--	--	--	--	1.99
1,2-Dichloroethylene	--	--	--	28.0	1.34	1.57	--	11.80
Tetrachloroethylene	11.01	19.87	--	--	14.00	23.60	1.68	4.22
1,1,1- Trichloroethane	--	--	--	--	--	--	--	.87
Trichloroethylene	--	--	--	25.0	2.11	2.15	.82	8.21

[12] Data in this table are not in any U.S. Geological Survey database.

Table 10. Volatile organic compounds detected in water samples from wells in the Memorial well field, Fair Lawn, New Jersey, 1991 and 2000[1].

[Concentrations in micrograms per liter; --, not detected; data from Kenneth Garrison, Fair Lawn Water Department, written commun., 2000]

Compound	1991				2000			
	Well FL15 (1/22/91)	Well FL16 (1/22/91)	Well FL17 (3/5/91)	Well FL19 (3/5/91)	Well FL15 (2/12/00)	Well FL16 (2/12/00)	Well FL17 (2/20/00)	Well FL19 (2/15/00)
Carbon tetrachloride	--	--	--	--	1.56	0.98	--	0.43
Chloroform	--	--	--	--	.91	--	--	3.44
1,1-Dichloroethane	--	--	--	--	--	--	--	--
1,2-Dichloroethylene	--	59.21	--	--	--	111.00	32.80	.78
Methyl tert-butyl ether	3.70	41.63	13.38	40.41	--	2.00	111.00	6.20
Tetrachloroethylene	14.43	28.53	--	--	11.10	12.00	10.20	10.70
Toluene	3.79	--	--	--	--	--	--	--
1,1,1-Trichloroethane	5.27	11.14	--	--	--	--	--	--
Trichloroethylene	--	9.97	--	--	--	2.83	3.66	.44

[1]Data in this table are not in any U.S. Geological Survey database.

A limitation of the Grundfos pump is the 300-ft power-cord length. Several packed intervals were more than 300 ft below land surface. Because it was not possible to lower the Grundfos pump to these packed intervals, a Bennett Model 140 submersible piston pump was used instead. The Bennett pump used nitrogen gas to drive the piston; therefore, by using 500-ft drive and pressure-relief lines, the pump could be lowered into the packed interval. The sampling procedure used with the Bennett pump was the same as that used with the Grundfos pump.

New Teflon-lined HDPE tubing was used in every sampled interval. The tubing used for sampling was flushed with deionized water prior to use. The submersible pumps used for sampling were decontaminated between intervals within each well by an external and internal wash with laboratory-grade detergent and deionized water, an external and internal deionized water rinse, and an internal flush. After all intervals in a well had been sampled, the pump was disassembled in the laboratory and cleaned thoroughly. All equipment used to collect samples was wrapped in aluminum foil until use. To minimize any cross-contamination by the packers, the packer assembly, the pipe used to lower the equipment into the well, and the inflation lines were steam-cleaned between wells using potable water.

A quality-assurance/quality-control (QA/QC) plan for collection of samples was used to ensure that any sources of error introduced by field practices were identified. The plan called for collection and analysis of the following QA/QC samples:

- One field-duplicate sample per well,
- One field blank per sampling day,
- One trip blank per sampling day, and
- One equipment blank each time sampling equipment was decontaminated in the field.

Additionally, to ensure the quality of the laboratory analysis, at least one matrix spike/matrix spike duplicate (MS/MSD) sample was collected per well. All coolers were shipped overnight and were received at a laboratory contracted by the USEPA less than 24 hours after the samples were collected.

Water-quality samples were collected from a total of 16 isolated intervals: 1 interval in well FL4, 5 in well FL12, 1 in well FL18, and 3 intervals each in wells FL23, FL27, and FL29. Samples from all intervals were analyzed for VOCs. Samples from intervals in well FL12 also were analyzed for total metals, cyanide, SVOCs, pesticides, and PCBs. Samples from the four wells nearest to the Fisher site (FL4, FL12, FL18, and FL23) also were analyzed for acetonitrile because high concentrations (higher than 200,000 µg/L) of that compound had been detected there (table 11).

An MS/MSD sample used for laboratory QA/QC checks was collected from six intervals (well FL4, interval 1; well FL12, intervals 1 and 2; well FL18, interval 1; well FL23, interval 1; and well FL27, interval 6). Field-duplicate samples for VOC analysis were collected from four intervals (well FL4, interval 1; well FL12, interval 2; well FL18, interval 1; and well FL23, interval 2). The field-duplicate sample from well FL12, interval 2, also was analyzed for total metals, cyanide, SVOCs, pesticides, and PCBs. The following QA/QC blank samples were prepared and analyzed:

- Equipment blanks (all intervals except well FL29, interval 2),
- Trip blanks (all intervals except well FL27, interval 3, and well FL29, interval 4), and
- Field blanks (well FL4, interval 1; well FL18, interval 1; well FL23, intervals 1, 2, and 6; well FL27, intervals 2 and 6; and well FL29, intervals 2 and 3).

Analysis results for these blank samples, summarized in table 12, are discussed along with the associated environmental samples from the sampled packed intervals within each well.

Field parameters were monitored prior to sampling each interval. The final field-parameter measurements before sampling are listed in table 13. Dissolved-oxygen concentrations in the sampled intervals were low to moderate (less than 1 mg/L) in the sampled intervals in wells FL18 and FL29, and in well FL23 interval 6. Dissolved-oxygen concentrations in the other sampled intervals ranged from 1.09 to 5.51 mg/L. The range in pH (6.86-8.22) was small, but the range in specific conductance (265-1,242 µS/cm) was large. The range in final turbidity measurements also was large (0.18-46.5 nephelometric turbidity units).

Table 11. Maximum reported concentration of volatile organic compounds in ground water at three contaminated sites, Fair Lawn, New Jersey, 1997, 1998, and 2002[1].

[Concentrations in micrograms per liter; data for Fisher Scientific Company from Jacqueline Bobko, N.J. Department of Environmental Protection, written commun., 2002; data for Sandvik, Inc., from Metcalf & Eddy, Inc., 1998; data for Eastman Kodak Company from Jamie MacBlane, N.J. Department of Environmental Protection, written commun., 2002; --, not detected, NA, the sample was not analyzed for this compound; NR, not reported]

Compound	Eastman Kodak Company (6/24-25/97)	Fisher Scientific Company (11/4-8/02)	Sandvik, Inc. (5/21-22/98)
Acetone	NA	3,600	NR
Acetonitrile	NA	230,000	NR
Benzene	3.2	2,700	9.1
Bromodichloromethane	7.1	--	--
Carbon tetrachloride	.23	1,500	37.8
Chlorobenzene	--	120	--
Chloroform	40.4	32,000	152
Dibromochloromethane	1.2	--	--
1,2-Dichlorobenzene	--	--	1.6
1,3-Dichlorobenzene	1.5	--	NR
1,1-Dichloroethane	92.7	69	14
1,2-Dichloroethane	--	5,500	8.4
1,1-Dichloroethylene	198	130	58.8
1,2-Dichloroethylene (total)	NA[2]	NA[2]	53.5
cis-1,2-Dichloroethylene	13.4	14,000	NA[3]
trans-1,2-Dichloroethylene	--	2.2	NA[3]
Ethyl benzene	--	1,500	NR
Methylene chloride	--	25,000	--
Tetrachloroethylene	--	78	551
Toluene	--	5,400	NR
1,1,1-Trichloroethane	2,920	410	103
Trichloroethylene	4.6	2,000	96.4
Trichlorofluoromethane	--	2.8	NR
Vinyl chloride	73.6	570	--
Xylenes (total)	--	6,600	NR

[13]Data in this table are not in any U.S. Geological Survey database.

[14]Reported separately as *cis*-1,2-dichloroethylene and *trans*-1,2-dichloroethylene.

[15]Reported as total 1,2-dichloroethylene.

Table 12. Constituents detected in quality-assurance/quality-control blank samples for packed intervals in wells in Fair Lawn, New Jersey[1].

[Concentrations in micrograms per liter, --, not detected; NA, sample was not analyzed for this constituent; B, estimated result (result is less than reporting limit); J, estimated; QF, estimated value because of failure of one or more quality-control criteria]

Well	Packed interval	Depth of interval, in feet below land surface		Sample type	Volatile organic compounds									Semi-volatile organic compound	Metals	
		Top	Bottom		Acetone	2-Butanone	Carbon disulfide	Chloromethane	1,1-Dichloroethylene	*cis*-1,2-Dichloroethylene	Methylene chloride	Toluene	Trichloroethylene	bis (2-Ethylhexyl)-phthalate	Potassium	Sodium
FL4	1	55	66.74	Equipment blank	--	--	--	--	--	--	--	--	--	NA	NA	NA
				Field blank	--	--	--	--	--	--	0.6 J	--	--	NA	NA	NA
				Trip blank	--	--	--	--	--	--	--	--	--	NA	NA	NA
FL12	1	35	47.09	Equipment blank	--	--	--	--	--	--	--	--	--	--	80.4 B	577 B
				Trip blank	--	--	--	--	--	--	--	--	--	NA	NA	NA
FL12	2	95	111	Equipment blank	1.6 QF	--	--	--	--	--	--	--	--	--	104 B	617 B
				Trip blank	--	--	--	--	--	--	--	--	--	NA	NA	NA
FL12	3	154	170.49	Equipment blank	1.2 QF	--	--	--	--	--	--	--	--	--	105 B	731 B
				Trip blank	--	--	--	--	--	--	--	--	--	NA	NA	NA
FL12	4	177	193.49	Equipment blank	--	--	--	--	--	--	--	--	--	2.4 J	133 B	846 B
				Trip blank	--	--	--	--	--	--	--	--	--	NA	NA	NA
FL12	5	223.74	240.23	Equipment blank	--	--	--	--	--	--	--	--	--	--	88.8 B	614 B
				Trip blank	--	--	--	--	--	--	--	--	--	NA	NA	NA
FL18	1	26	39	Equipment blank	--	--	--	--	--	--	--	--	--	NA	NA	NA
				Field blank	--	5.4 J	--	--	--	--	--	0.9	--	NA	NA	NA
				Trip blank	--	--	--	--	--	--	--	--	--	NA	NA	NA
FL23	1	40.65	52.39	Equipment blank	--	--	--	--	--	--	--	--	--	NA	NA	NA
				Field blank	--	--	--	--	--	--	--	--	--	NA	NA	NA
				Trip blank	--	--	--	--	0.9	13	--	0.5 J	13	NA	NA	NA
FL23	2	59.98	71.72	Equipment blank	--	--	--	--	--	--	0.6 J	--	--	NA	NA	NA
				Field blank	--	--	--	--	--	--	--	--	--	NA	NA	NA
				Trip blank	--	--	--	--	--	--	--	--	--	NA	NA	NA
FL23	6	349.83	361.57	Equipment blank	7 J	--	--	--	--	--	--	--	--	NA	NA	NA
				Field blank	15 J	--	--	--	--	--	1 J	--	1	NA	NA	NA
				Trip blank	8 J	--	--	--	--	--	4 J	--	--	NA	NA	NA
FL27	2	85.06	96.8	Equipment blank	--	--	--	--	--	--	--	--	0.2 J	NA	NA	NA
				Field blank	4 J	--	--	--	--	--	--	--	--	NA	NA	NA
				Trip blank	--	--	--	--	--	--	--	--	--	NA	NA	NA
FL27	3	107.06	118.8	Equipment blank	--	--	2	--	--	--	--	--	--	NA	NA	NA

Table 12. Constituents detected in quality-assurance/quality-control blank samples for packed intervals in wells in Fair Lawn, New Jersey[1].—Continued

[Concentrations in micrograms per liter, --, not detected; NA, sample was not analyzed for this constituent; B, estimated result (result is less than reporting limit); J, estimated; QF, estimated value because of failure of one or more quality-control criteria]

Well	Packed interval	Depth of interval, in feet below land surface		Sample type	Volatile organic compounds									Semi-volatile organic compound	Metals	
		Top	Bottom		Acetone	2-Butanone	Carbon disulfide	Chloromethane	1,1-Dichloroethylene	*cis*-1,2-Dichloroethylene	Methylene chloride	Toluene	Trichloroethylene	bis (2-Ethylhexyl)-phthalate	Potassium	Sodium
FL27	6	241.98	253.7	Equipment blank	--	--	--	8	--	--	--	--	--	NA	NA	NA
				Field blank	--	--	--	--	--	--	--	--	--	NA	NA	NA
				Trip blank	--	--	--	10	--	--	--	--	--	NA	NA	NA
FL29	2	81.95	93.69	Field blank	--	--	--	0.3 J	--	--	--	--	--	NA	NA	NA
				Trip blank	--	--	--	0.3 J	--	--	--	--	--	NA	NA	NA
FL29	3	129.15	140.89	Equipment blank	--	--	--	--	--	--	--	--	--	NA	NA	NA
				Field blank	11	--	--	--	--	--	--	--	--	NA	NA	NA
				Trip blank	13	--	--	--	--	--	--	--	--	NA	NA	NA
FL29	4	147.03	158.77	Equipment blank	--	--	--	--	--	--	--	--	--	NA	NA	NA

[16]Data in this table are not in any U.S. Geological Survey database.

Table 13. Field parameters for samples from packed intervals in wells in Fair Lawn, New Jersey.[1]

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25° C ; ° C degrees Celsius; NTU, nephelometric turbidity units]

Well	Interval	Depth of packed interval (feet below land surface)		Dissolved oxygen (mg/L)	pH (standard units)	Specific conductance (µS/cm)	Temperature (° C)	Turbidity (NTU)
		Top	Bottom					
FL4	1	55	66.74	2.67	7.29	479	16.1	2.17
FL12	1	35	47.09	4.17	6.86	751	16.7	4.5
	2	95	111	2.17	7.35	844	16.2	2.26
	3	154	170.49	3.87	6.86	700	15.8	10.7
	4	177	193.49	1.09	6.87	708	14.7	46.2
	5	223.74	240.23	1.22	8.1	470	14.5	8.04
FL18	1	26	39	0.74	7.28	704	14.5	0.85
FL23	1	40.65	52.39	4.19	7.01	1242	17.4	.18
	2	59.98	71.72	4.45	7.19	820	17.4	.4
	6	349.83	361.57	.18	7.94	1051	15.8	1.07
FL27	2	85.06	96.8	4.13	8.17	265	16.1	11
	3	107.06	118.8	5.51	8.22	345	16.2	3.11
	6	241.98	253.7	4.2	8.1	420	15	13.1
	2	81.95	93.69	.16	7.73	551	14.9	2.09
		129.15	140.89	.23	7.19	584	15.3	2.04
		147.03	158.77	.2	7.12	590	15.4	1.82

[17]Data in this table are not in any U.S. Geological Survey database.

Compounds Detected in Individual Wells

Water samples were collected from intervals isolated by straddle packers in six Fair Lawn Water Department observation wells. The purpose of sampling was to determine the distribution of the contaminants of concern in discrete water-bearing units throughout Fair Lawn Borough.

Well FL4

Well FL4, in the Cadmus well field, is about 5,600 ft south-southeast of Fisher and Sandvik and 4,200 ft south-southeast of Kodak. Four water samples were collected from the sampled interval in well FL4. Five compounds were detected in these four samples (table 14). Toluene, at low concentrations (less than 1 µg/L), was detected in all four samples. The other detected compounds were found in one or two of the samples, at concentrations of 2 µg/L or less. Only one compound—methylene chloride, a common laboratory contaminant—was detected in the QA/QC blank samples from well FL4 (table 12). This compound was found only in the field blank.

The sampled interval in the well is in confining unit 6 (fig. 7). The subcrop of confining unit 6 is about 2,300 ft east of the Fisher property and 2,600 ft east of the Kodak property (fig. 8). Confining unit 5 lies between well FL4 and the Fisher, Sandvik, and Kodak sites. Therefore, well FL4 is not hydraulically connected to any of these sites, and the low concentrations of VOCs detected in well FL4 probably are not related to the contamination originating at Fisher, Sandvik, or Kodak.

Well FL12

Well FL12, in the Westmoreland well field, is about 2,200 ft south-southwest of Fisher and Sandvik and 1,350 ft west-southwest of Kodak. Samples were collected from intervals 1 through 5 in well FL12. A duplicate sample was collected from interval 2. Intervals 6 and 7 could not be sampled because of low well yield. Sampled intervals 1 through 5 are in water-bearing units 2, 3, 4, and 5 (fig. 7). The subcrops of water-bearing units 3 and 4 underlie the Sandvik and Kodak property; the subcrops of water-bearing units 4 and 5 underlie the Fisher property (fig. 8).

Table 14. Volatile organic compounds detected in samples from a packed interval in well FL4, Fair Lawn, New Jersey.[1]

[Concentrations in micrograms per liter; J, estimated; --, not detected]

Packed interval	Depth of interval, in feet below land surface		Sample type	Chloro-benzene	Chloro-methane	4-Methyl-2-pentanone	Tetrachloro-ethylene	Toluene
	Top	Bottom						
1	55	66.74	Environmental[2]	--	--	2 J	--	0.6
			Environmental[2]	--	--	2 J	--	.6
			Field duplicate	--	0.5	--	0.5 J	.8
			Environmental[2]	0.4 J	--	--	.5 J	.8

[18]Data in this table are not in any U.S. Geological Survey database.

[19]Although only one environmental sample was required by the laboratory, extra samples were submitted and analyzed as a result of a misunderstanding regarding the number of environmental samples required.

VOCs detected in well FL12 are listed in table 15. Chloroform, PCE, 1,1,1-TCA, and TCE were detected in all water samples from the sampled intervals in well FL12. The highest chloroform concentration was 9.2 µg/L in the sample from the deepest sampled interval (interval 5 in water-bearing unit 5). The highest PCE concentration was 13 µg/L in the sample from interval 2 (in water-bearing unit 3), and the highest 1,1,1-TCA concentration was 35 µg/L in the field-duplicate sample from interval 2. (The 1,1,1-TCA concentration was qualified as being biased low because the sample holding time was exceeded prior to analysis.) The highest TCE concentration was 60 µg/L in the sample from the deepest sampled interval (interval 5 in water-bearing unit 5); this result was qualified as being biased low because of low recovery.

Degradation products of PCE and TCE also were detected in all samples from well FL12. The highest *cis*-1,2-dichloroethylene (*cis*-1,2-DCE) concentration, 72 µg/L, was found in the sample from the deepest sampled interval (interval 5 in water-bearing unit 5). The highest concentrations of 1,1-dichloroethane (1,1-DCA) and 1,1-dichloroethylene (1,1-DCE) (8.2 and 28 µg/L, respectively) were found in the sample from interval 2 (in water-bearing unit 3); these results were qualified as being biased low because the sample holding time was exceeded prior to analysis.

These seven VOCs detected in samples from well FL12 (chloroform, PCE, 1,1,1-TCA, TCE, *cis*-1,2-DCE, 1,1-DCA, and 1,1-DCE) also were present at Fisher, Sandvik, and Kodak (except that PCE was not present at Kodak (table 11)). On the basis of the distribution of VOCs and the hydraulic connection between well FL12 and the three sites, it is possible that any or all of these sites contribute VOCs to well FL12.

Four additional VOCs were detected in water samples from well FL12. Of these, the compound present at the highest concentration was toluene, with a reported concentration of 65 µg/L in the sample from interval 4. 4-Methyl-2-pentanone was detected in samples from all intervals except the shallowest; the concentration was highest (23 µg/L) in the sample from interval 4 (in water-bearing unit 4). Acetone and 2-butanone were detected in concentrations less than 5 µg/L in some samples.

A markedly different set of VOCs predominates in each water-bearing unit. In water-bearing unit 3, the three VOCs detected at the greatest concentrations were 1,1,1-TCA (35 µg/L), 1,1-DCE (28 µg/L), and PCE (13 µg/L). In water-bearing unit 5, the three VOCs detected at the greatest concentrations were *cis*-1,2-DCE (72 µg/L), TCE (60 µg/L), and chloroform (9.2 µg/L). Similarly, the predominant contaminants differ among the other water-bearing units, indicating that the confining units effectively separate the water-bearing units from one another and that the source of contamination to each water-bearing unit is different. Because the subcrop of each water-bearing unit in well FL12 is beneath at least one of the three potential contaminant source areas (Fisher, Sandvik, and Kodak), it is likely that all of these sites contribute contaminants to this well.

The results of analyses for total metals are listed in table 16. Arsenic was found in the samples from the three lowermost intervals (in water-bearing units 4 and 5), at concentrations ranging from 8.3 to 102 µg/L. Barium, calcium, iron, magnesium, manganese, potassium, and sodium were detected in all sampled intervals. Cobalt, copper, nickel, and zinc were detected in all but the lowermost sampled interval (interval 5). Chromium was detected at a low concentration (2.5 µg/L) in interval 3 and vanadium was detected at low concentrations (less than 8 µg/L) in intervals 3 and 5. Cyanide was detected at low concentrations (less than 6 µg/L) in one sample each from intervals 1, 2, and 4, but was not detected in the other samples from intervals 1 and 2.

Although the primary contaminants of concern in this study are VOCs, the detection of arsenic in well FL12 is an important finding. The concentration of 102 µg/L in the sample from the deepest interval (interval 5 in water-bearing unit 5)

Table 15. Volatile organic compounds detected in samples from packed intervals in well FL12, Fair Lawn, New Jersey[1].

[Concentrations in micrograms per liter; --, not detected; QF, estimated value because of failure of one or more quality-control criteria; QH, holding time exceeded (results considered “biased low” or “minimum values”); QR, low recovery obtained from the matrix spike sample associated with this sample (results considered “biased low” or “minimum values”)]

Packed interval	Depth of interval, in feet below land surface		Water-bearing unit number	Sample type	Acetone	2-Butanone	Chloroform	1,1-Dichloroethane	1,1-Dichloroethylene	cis-1,2-Dichloroethylene	4-Methyl-2-pentanone	Tetrachloroethylene	1,1,1-Trichloroethane	Trichloroethylene	Toluene
	Top	Bottom													
1	35	47.09	2	Environmental	--	--	1.1	1.1	1.9	2.0	--	8.1	4.1	1.7	8.6
2	95	111	3	Environmental	2.2 QF	--	3.7	8.2	28 QH	2.1	1.7	13	34 QH	4.2	3.9
				Field duplicate	1.8 QF	--	3.7	8.0	25 QH	2.1	1.4	12	35 QH	4.1	3.4
3	154	170.49	4	Environmental	--	--	2.1	1.5	3.6	11	2.3	3.8	4.1	9.1	18
4	177	193.49	4	Environmental	4.9 QF	3.1	1.6	1.3	2.8	6.1	23	5.2	4.0	5.3	65
5	223.74	240.23	5	Environmental	--	--	9.2	3.8	15	72 QR	2.3	2.7	3.7	60 QR	11

[20]Data in this table are not in any U.S. Geological Survey database.

Table 16. Metals detected in samples from packed intervals in well FL12, Fair Lawn, New Jersey[1].

[Concentrations in micrograms per liter; --, not detected; B, estimated result (result is less than reporting limit)]

Packed interval	Depth of interval, in feet below land surface		Water-bearing unit number	Sample type	Arsenic	Barium	Calcium	Chromium	Cobalt	Copper	Cyanide	Iron	Magnesium	Manganese	Nickel	Potassium	Sodium	Vanadium	Zinc
	Top	Bottom																	
1	35	47.09	2	Environmental[2]	--	182 B	75,900	--	2.3 B	1.9 B	--	778	13,900	16.3	8.0 B	1,690 B	44,500	--	38.9
				Environmental[2]	--	189 B	77,400	--	2.2 B	2.1 B	2.8 B	741	14,100	15.7	7.6 B	1,750 B	45,700	--	43.5
				Environmental[2]	--	186 B	76,800	--	2.7 B	1.7 B	--	738	14,000	15.7	7.7 B	1,730 B	45,300	--	40.1
2	95	111	3	Environmental[2]	--	200 B	90,900	--	21.8 B	5.0 B	5.4 B	486	22,100	5.3 B	75.3	1,750 B	36,500	--	25.9
				Environmental[2]	--	200 B	91,200	--	21.4 B	5.3 B	4.5 B	522	22,100	6.0 B	75.0	1,740 B	36,900	--	33.7
				Field duplicate	--	200	91,600	--	21.4 B	5.0 B	--	568	22,100	6.3 B	74.1	1,740 B	37,100	--	37.6
3	154	170.49	4	Environmental	17.2	162 B	70,400	2.5 B	3.2 B	4.4 B	--	1,470	14,000	11.8 B	12.8 B	1,600 B	38,900	1.8 B	63.6
4	177	193.49	4	Environmental	8.3 B	171 B	75,100	--	3.8 B	3.6 B	4.0 B	3,950	14,900	56.8	15.0 B	1,700 B	42,200	--	157
5	223.74	240.23	5	Environmental	102	60.7B	40,200	--	--	--	--	570	14,300	6.0 B	--	1,210 B	27,200	7.2 B	--

[21]Data in this table are not in any U.S. Geological Survey database.

[22]Although only one environmental sample was required by the laboratory, extra samples were submitted and analyzed as a result of a misunderstanding regarding the number of environmental samples required.

exceeds both the current USEPA drinking-water standard of 50 µg/L, which has been in effect since 1975 (U.S. Environmental Protection Agency, 2001a), and the 10-µg/L standard, which will take effect in 2006 (U.S. Environmental Protection Agency, 2001b). It is not known whether the arsenic is naturally occurring or anthropogenic. If it is anthropogenic, Fisher, which overlies the subcrop of water-bearing unit 5, is a possible source.

Concentrations of metals varied widely from interval to interval. For example, arsenic was detected only in samples from intervals 3, 4, and 5, at concentrations of 17.2, 8.3, and 102 µg/L, respectively. The concentration of iron ranged from 486 µg/L in interval 2 to 3,950 µg/L in interval 4. Nickel was found in the samples from interval 2 at concentrations of approximately 75 µg/L, but nickel concentrations in samples from the other intervals did not exceed 15 µg/L.

The wide differences in water quality among the water-bearing units present in this well result from their separation by the confining units. Each water-bearing unit has a unique water-quality signature.

Pesticides were detected in all but the lowermost interval in well FL12 (table 17). Alpha-chlordane, dieldrin, gamma-chlordane, and heptachlor epoxide were found in the sample from interval 1. The samples from interval 2 and the sample from interval 3 contained all of these pesticides except heptachlor epoxide. The sample from interval 4 contained alpha-chlordane, gamma-chlordane, and heptachlor epoxide. The only SVOC detected in well FL12 was phenol (at an estimated concentration of 2.5 µg/L in interval 4) (table 17). No PCBs were detected in any sample from well FL12.

The QA/QC blank samples for well FL12 were unremarkable except for the equipment blanks. Sodium was detected in all of the equipment blanks at estimated concentrations ranging from 614 to 846 µg/L (compared to concentrations in the environmental samples ranging from 27,200 to 45,700 µg/L). Although this finding indicates that the concentrations of sodium detected in the environmental samples may be slightly higher or lower than those actually in the sampled zones, the reported concentrations are less than the New Jersey secondary maximum contaminant level (SMLC) of 50,000 µg/L (N.J. Department of Environmental Protection, 2002). Similarly, potassium was detected in all of the equipment blanks at estimated concentrations ranging from 88.8 to 105 µg/L (compared to concentrations detected in environmental samples of 1,210 to 1,750 µg/L). (There is no New Jersey SMLC for potassium.) Neither sodium nor potassium is a contaminant of concern in this study.

Table 17. Pesticides and semivolatile organic compounds (SVOCs) detected in samples from packed intervals in well FL12, Fair Lawn, New Jersey[1].

[Concentrations in micrograms per liter; J, estimated; JN, presumptive evidence for the presence of the material at an estimated value; --, not detected]

Packed interval	Depth of interval, in feet below land surface		Water-bearing unit number	Sample type	Pesticides				SVOC
	Top	Bottom			alpha-Chlordane	gamma-Chlordane	Dieldrin	Hepta-chlor epoxide	Phenol
1	35	47.09	2	Environmental	0.067	0.028 JN	0.023	0.020 JN	--
2	95	111	3	Environmental[2]	.057	.033 JN	.04	--	--
				Environmental[2]	.038 JN	.044 JN	.041	--	--
				Field duplicate	.059 J	.031 JN	.048	--	--
3	154	170.49	4	Environmental	.085	.043 JN	.026 J	--	--
4	177	193.49	4	Environmental	.03 J	.024 JN	--	.021 JN	2.5 J
5	223.74	240.23	5	Environmental	--	--	--	--	--

[23]Data in this table are not in any U.S. Geological Survey database.

[24]Although only one environmental sample was required by the laboratory, extra samples were submitted and analyzed as a result of a misunderstanding regarding the number of environmental samples required.

Two of the equipment blanks contained acetone at concentrations less than 2 µg/L; however, the highest concentration of acetone in the related environmental samples was only slightly higher (2.2 µg/L). Therefore, the detection of acetone in the samples from well FL12 is questionable. The detection of bis (2-ethylhexyl) phthalate in the equipment blank for interval 4 is unremarkable because that compound was not detected in any environmental sample from the well.

Well FL18

Well FL18, in the Memorial well field, is about 7,100 ft south-southwest of Fisher and Sandvik and 5,700 ft south-southwest of Kodak. All four water samples from well FL18, interval 1, contained three VOCs: chloroform, methyl *tert*-butyl ether (MTBE), and toluene (table 18). MTBE was present at the highest concentrations. These compounds commonly are detected in areas contaminated with petroleum products. Because toluene was detected in the field blank at a concentration of 0.9 µg/L, the concentrations of toluene detected in the environmental samples are questionable. One other compound, 2-butanone, was found in the field blank but not in any environmental sample. No VOCs were detected in the other QA/QC blank samples for well FL18.

The sampled interval in well FL18 is in water-bearing unit 2 (fig. 7); therefore, this interval is not hydraulically connected to the Fisher, Sandvik, or Kodak property, and the low concentrations (less than 11 µg/L) of VOCs detected in that interval probably are not related to the contamination at the three industrial sites. Most likely, the contaminants detected in well FL18 originated at sources closer to the well.

Well FL23

Well FL23, in Fair Lawn Industrial Park, is about 1,200 ft south of Fisher and Sandvik and immediately east of Kodak. The sampled intervals in the well (intervals 1, 2, and 6) are in water-bearing units 5 and 7 (fig. 7).

Nine VOCs were detected in the water samples from the three sampled intervals in well FL23 (table 19). TCE was detected in all samples from the sampled intervals, in concentrations up to 120 µg/L. *Cis*-1,2-DCE, a degradation product of TCE, was detected in concentrations up to 140 µg/L in all but one of the samples from well FL23. Two other TCE degradation products, *trans*-1,2-dichloroethylene and 1,1-DCE, were detected in samples from intervals 1 and 2. Two samples from interval 1 and a sample from interval 2 were diluted by the analytical laboratory by factors ranging from 2 to 10, presumably to allow for the measurement of high concentrations of TCE and *cis*-1,2-DCE. The dilution prevented the detection of any compounds that may have been present in these samples at concentrations less than 1, 3, and 5 µg/L for dilution factors of 2, 5, and 10, respectively. The remaining water samples from intervals 1 and 2 were diluted for measurement of only two compounds (*cis*-1,2-DCE and TCE), however, and additional compounds were detected in these samples. The sample from interval 6, the deepest interval in well FL23, contained low concentrations (less than 10 µg/L) of TCE, *cis*-1,2-DCE, and acetone.

Contaminant concentrations generally were much higher in intervals 1 and 2 (in water-bearing unit 5) than in interval 6 (in water-bearing unit 7). Water-bearing unit 5 is directly beneath the overburden at the Fisher property and is less than 100 ft below land surface in the eastern parts of the Sandvik and Kodak properties (figs. 14 and 15, farther on). The subcrop of water-bearing unit 7 is more than 4,500 ft east of all three properties. The VOCs detected in well FL23, like those in

Table 18. Volatile organic compounds detected in samples from a packed interval in well FL18, Fair Lawn, New Jersey[1]

[Concentrations in micrograms per liter]

Packed interval	Depth of interval, in feet below land surface		Water-bearing unit number	Sample type	Chloroform	Methyl *tert*-butyl ether	Toluene
	Top	Bottom					
1	26	39	1	Environmental[2]	5.6	10	1.9
				Environmental[2]	5.2	9.8	1.8
				Field duplicate	5.1	9.4	1.7
				Environmental[2]	5.3	10	1.8

[1] Data in this table are not in any U.S. Geological Survey database.

[2] Although only one environmental sample was required by the laboratory, extra samples were submitted and analyzed as a result of a misunderstanding regarding the number of environmental samples required.

Table 19. Volatile organic compounds detected in samples from packed intervals in well FL23, Fair Lawn, New Jersey[1]

[Concentrations in micrograms per liter; J, estimated; --, not detected; D, sampled was diluted (number following "D" is dilution factor used for analysis); all concentrations in micrograms per liter]

Packed interval	Depth of interval, in feet below land surface		Water-bearing unit number	Sample type	Acetone	Chloroform	1,1-Dichloroethane	1,1-Dichloroethylene	*cis*-1,2-Dichloroethylene	*trans*-1,2-Dichloroethylene	1,1,1-Trichloroethane	Trichloroethylene	Toluene
	Top	Bottom											
1	40.65	52.39	5	Environmental[2]	--	1	2	13	130 D10	0.8	2	120 D10	5
				Environmental[2]	-- D5	-- D5	-- D5	-- D5	61 D5	-- D5	-- D5	37 D5	-- D5
				Environmental[2]	-- D2	1 D2	2 D2	14 D2	120 D10	-- D2	2 D2	120 D10	5 D2
2	59.98	71.72	5	Environmental[2]	9 J	4	2	12	140 D10	1	2	69 D10	2
				Environmental[2]	-- D10	-- D10	-- D10	4 J D10	110 D10	-- D10	-- D10	56 D10	-- D10
				Field duplicate	--	4	2	13	130 D10	0.6	2	63 D10	2
6	349.83	361.57	7	Environmental[2]	5 J	--	--	--	--	--	--	0.4 J	--
				Environmental[2]	8 J	--	--	--	0.4 J	--	--	0.5 J	--

[3] Data in this table are not in any U.S. Geological Survey database.

[4]Although only one environmental sample was required by the laboratory, extra samples were submitted and analyzed as a result of a misunderstanding regarding the number of environmental samples required.

well FL12, were present at one or all of the three sites; consequently, the VOCs detected in well FL23 could be derived from any or all of the sites.

Well FL23, like well FL12, showed a large difference in constituent concentrations in samples from different water-bearing units, indicating effective separation of water-bearing units by confining units. The samples from intervals 1 and 2 in well FL23 (table 19) and the sample from interval 5 in well FL12 (table 15), however, were similar with respect to the concentrations of TCE, *cis*-1,2-DCE, and 1,1-DCE. All three of these intervals are in water-bearing unit 5 (fig. 7).

The QA/QC blank samples for the sampled intervals in well FL23 were unremarkable, with three exceptions. TCE and two of its degradation products (*cis*-1,2-DCE and 1,1-DCE) were found in the trip blank for interval 1 (table 12). The source of these contaminants is unknown. Although the reported concentrations of these compounds in water samples from this interval are questionable as a result, the fact that the reported concentrations were much higher in the environmental samples than in the blank indicates that although these compounds were present in the environmental samples, concentrations may have been lower than those reported. Acetone was found in all three of the QA/QC blanks for interval 6. Acetone also was found in the two environmental samples from interval 6, but its presence in the blanks makes this result questionable. Likewise, the presence of TCE in the field blank for interval 6 makes the presence of TCE in the environmental sample from that interval questionable.

Well FL27

Well FL27, in the Dorothy Street well field, is about 4,300 ft east-southeast of Fisher and Sandvik and 4,500 ft east of Kodak (fig. 8). The sampled intervals in the well (intervals 3 and 6) are in water-bearing units 8 and 9 (fig. 7). It is unlikely that the VOCs detected in this well are related to contamination at the Fisher, Sandvik, or Kodak site because confining units 5, 6, and 7 effectively separate the units open to well FL27 from these sites.

Toluene was the only VOC detected in all water samples from well FL27 (table 20). Xylene was found at a concentration of 0.7 µg/L in a sample from interval 6. These compounds commonly are detected in areas contaminated with petroleum products. Chloroform and PCE were found in all of the sampled intervals, although they were detected in only one of the samples from interval 6. Three additional compounds (*cis*-1,2-DCE, *trans*-1,2-dichloroethylene, and TCE) were detected in samples from interval 6, at concentrations less than 9 µg/L.

Four VOCs (acetone, carbon disulfide, chloromethane, and trichloroethylene) were detected in the QA/QC blank samples for well FL27. None of these compounds was detected in the environmental samples from these intervals, however, and only chloromethane was detected in more than one QA/QC sample—it was found in the equipment blank and trip blank from interval 6.

Well FL29

Well FL29, in the Cadmus well field, is about 7,300 ft south of Fisher and Sandvik and 5,700 ft south of Kodak. The sampled intervals in the well (intervals 2, 3, and 4) are all in water-bearing unit 6. It is unlikely that the VOCs detected in this well are related to contamination at the Fisher, Sandvik, or Kodak site because confining unit 5 effectively separates them from the well.

Table 20. Volatile organic compounds detected in samples from packed intervals in well FL27, Fair Lawn, New Jersey[1]

[Concentrations in micrograms per liter; J, estimated ; --, not detected; D, sample was diluted (number following "D" is dilution factor used for analysis)]

Packed interval	Depth of interval, in feet below land surface		Water-bearing unit number	Sample type	Chloroform	*cis*-1,2-Dichloroethylene	*trans*-1,2-Dichloroethylene	Tetrachloroethylene	Trichloroethylene	Toluene	Xylene
	Top	Bottom									
2	85.06	96.8	8	Environmental	0.3 J	--	--	0.8 J	--	41 J D5	--
3	107.06	118.8	8	Environmental	.5 J	--	--	.5 J	--	12 J	--
6	241.98	253.7	9	Environmental[2]	--	--	--	--	--	0.5	0.7
				Environmental[2]	.5	8	2	.8	2	13	--

[5]Data in this table are not included in any U.S. Geological Survey database.

[6]Although only one environmental sample was required by the laboratory, extra samples were submitted and analyzed as a result of a misunderstanding regarding the number of environmental samples required.

Table 21. Volatile organic compounds detected in samples from packed intervals in well FL29, Fair Lawn, New Jersey[1]

[Concentrations in micrograms per liter; J, estimated; --, not detected]

Packed interval	Depth of interval, in feet below land surface		Water-bearing unit number	Sample type	Methyl *tert*-butyl ether	Methylene chloride	Toluene
	Top	Bottom					
2	81.95	93.69	6	Environmental	0.8	0.3 J	2
3	129.15	140.89	6	Environmental	.6	--	--
4	147.03	158.77	6	Environmental	.6	--	--

[7]Data in this table are not in any U.S. Geological Survey database.

Only MTBE, a gasoline additive, was detected in all three samples from well FL29 (table 21). The concentrations of MTBE in these samples were low, less than 1 µg/L. Toluene, a component of gasoline, was found in the sample from interval 2. The only other compound detected was methylene chloride, a common laboratory contaminant—it was found in the sample from interval 2.

Acetone was found at concentrations of 11 and 13 µg/L in the field blank and trip blank, respectively, for interval 3. The only other compound detected in the QA/QC blanks for sampled intervals in well FL29 was chloromethane, at an estimated concentration of 0.3 µg/L. Neither of these compounds was detected in the environmental samples from this well.

Distribution of Volatile Organic Compounds

Two of the VOCs detected at the highest concentrations in the production wells in the Westmoreland well field are PCE and TCE (table 8). The distribution of these two compounds in production and observation wells in Fair Lawn in 2000-01 is shown in section view in figures 14 and 15, respectively. Also shown schematically in these figures is the highest concentration of these compounds detected in monitor wells at Fisher, Sandvik, and Kodak in November 2002, May 1998, and June 1997, respectively (table 11).

Concentrations of PCE were highest (greater than 500 µg/L) in monitor wells at Sandvik and in Westmoreland well FL10 (fig. 14; tables 8 and 11). Concentrations of TCE were highest at Fisher (2,000 µg/L); moderate concentrations (51-500 µg/L) were detected at Sandvik, in the two shallowest packed intervals in well FL23, and in Westmoreland well FL10. Lower concentrations (1-10 µg/L) were detected at Kodak and in nine other wells, including Westmoreland well FL14 (fig. 15; tables 8 and 11).

Wells in the Westmoreland well field (production wells FL10 and FL14 and observation well FL12) are hydraulically connected to the Fisher, Sandvik, and Kodak sites (figs. 14 and 15). All three wells draw water from water-bearing units 2 through 5; the subcrops of water-bearing units 3 and 4 underlie the Sandvik and Kodak sites, and the subcrops of water-bearing units 4 and 5 underlie the Fisher site.

Simulation of Ground-Water Flow

Four steady-state ground-water scenarios were simulated with the ground-water flow model. In steady-state conditions, water levels and all stresses on the ground-water system are static and the amount of water stored in the system remains constant. Two of the simulations represent ground-water conditions in 1991 and 2000 (hereinafter referred to as the 1991 scenario and the 2000 scenario, respectively). These two years were chosen because pumpage in the Westmoreland well field and Fair Lawn Industrial Park differed substantially between these two years. Because 2000 was a relatively dry year (with 44.45 inches of precipitation at nearby Little Falls, N.J., compared to the 98-year average precipitation of 49.79 inches (National Oceanic and Atmospheric Administration, 2000)), a third scenario (hereinafter referred to as the high-recharge scenario) was developed to represent pumpage in 2000, but with a higher recharge rate. The purpose of this scenario was to determine the effect of an increase in the recharge rate on the contributing areas to wells. The contributing areas to production, industrial, and recovery wells were delineated for the 1991, 2000, and high-recharge scenarios. Contaminant plumes from three potentially contributing sources of ground-water contamination were delineated for the 1991 and 2000 scenarios.

The fourth scenario (hereinafter referred to as the recovery scenario) was used for model calibration purposes only. This scenario represents a period during December 2000 when pumps in Fair Lawn Water Department wells FL2, FL7, and FL28 (fig. 3) were turned off for 0.5, 2, and 20 days, respectively. Data from continuous water-level recorders indicate that water levels in Fair Lawn Water Department wells FL4 and

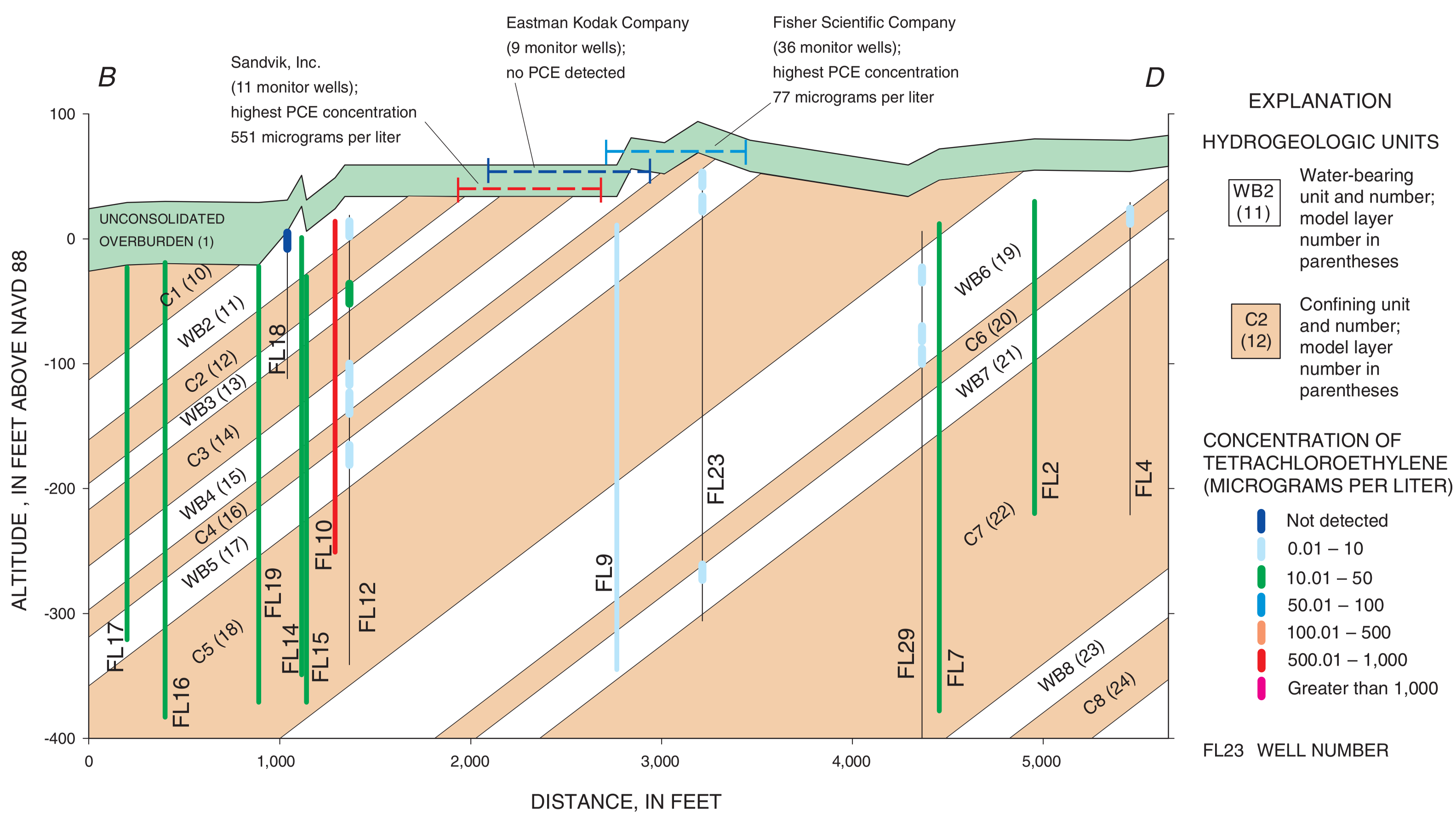


Figure 14. Section B-D along dip of bedding units showing interpreted water-bearing and confining units and concentration of tetrachloroethylene (PCE) in Fair Lawn Water Department production wells, straddle-packer intervals in Fair Lawn Water Department observation wells, and monitor wells at three known contaminated sites, Fair Lawn, New Jersey, 1997-2002. (Location of section shown in figure 8)

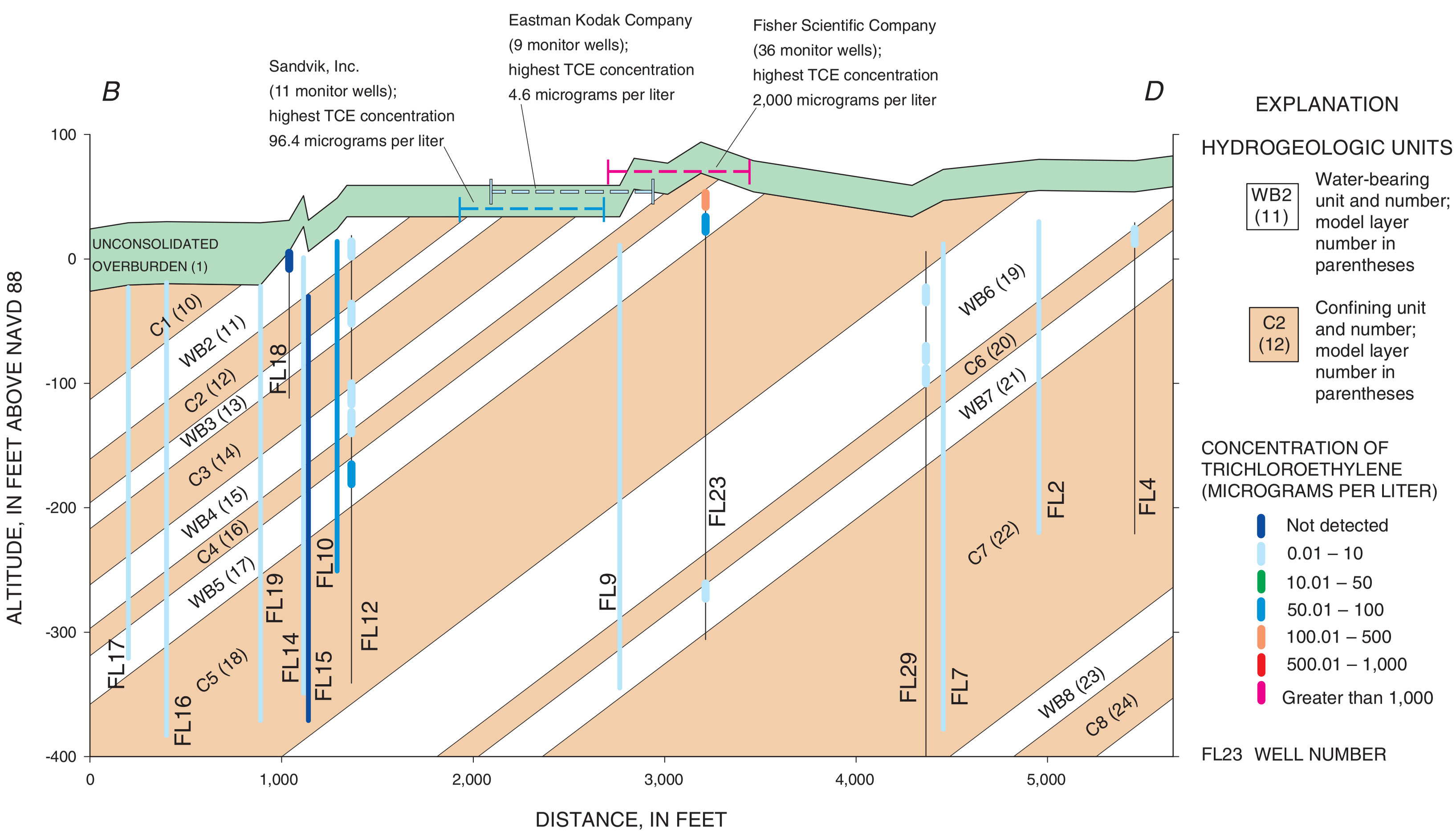


Figure 15. Section B-D along dip of bedding units showing interpreted water-bearing and confining units and concentration of trichloroethylene (TCE) in Fair Lawn Water Department production wells, straddle-packer intervals in Fair Lawn Water Department observation wells, and monitor wells at three known contaminated sites, Fair Lawn, New Jersey, 1997-2002. (Location of section shown in figure 8)

FL29 reached steady-state conditions less than 12 hours after pumps in wells FL2 and FL7 were turned off; similarly, water levels in Fair Lawn Water Department well FL27 reached steady state within 12 hours after the pump in well FL28 was turned off. These water-level changes in wells FL4, FL29, and FL27 were used to calibrate the simulation of the recovery-scenario.

Description of Ground-Water Flow Model

A three-dimensional, finite-difference digital ground-water flow model was used to simulate ground-water flow in and near Fair Lawn. The MODFLOW-2000 code (Harbaugh and others, 2000) was used for the simulation. A particle-tracking post-processor—MODPATH (Pollock, 1994)—was used to compute flowpaths and delineate contributing areas to wells.

Conceptual Model of Ground-Water Flow

The overburden sediments in the study area generally consist of unconsolidated, poorly sorted fluvial, deltaic, and lacustrine sediments overlying hard-packed, fine-grained glacial till. The hydraulic conductivity of the fluvial, deltaic, and lacustrine deposits is greater than that of the till. Precipitation recharging the overburden probably flows short distances (less than 500 ft) horizontally through these sediments before reaching either a nearby stream, where it discharges, or the till. After reaching the till, water probably moves predominantly downward into bedrock.

The Passaic Formation forms a fractured-bedrock aquifer in the study area. Ground-water flow in the Passaic Formation is predominantly through fractures, and flow is controlled primarily by the distribution of fractures in the dipping bedrock. The rocks of the Passaic Formation commonly contain water-bearing fractures along bedding planes in fissile layers separated by massive layers with virtually no bedding-plane partings. Near-vertical fractures perpendicular to bedding planes can transmit water across the massive layers that separate the fissile units (Carleton and others, 1999). The fissile strata comprise water-bearing units, whereas the massive strata comprise confining units.

Anisotropic ground-water flow has been documented at various sites in the Newark Basin (Lewis-Brown and dePaul, 2000; Lacombe, 2000; Carleton and others, 1999; Michalski, 1990). Anisotropy in the Passaic Formation is caused by the interlayering of the dipping water-bearing and confining units. Wells of similar depths aligned along the strike of the bedding intersect the same water-bearing units, but wells of similar depths aligned along the dip of the bedding intersect different water-bearing units. Consequently, wells of similar depths aligned along strike are in greater hydraulic connection than wells aligned along dip.

The predominant direction of ground-water flow in unstressed conditions is in the direction of strike of the bedding units; minor variations from that direction are attributable to topography and flow boundaries (Michalski, 1990). Where a pumped well intersects a water-bearing unit, flow in the nearby parts of that unit generally is toward the well because of the induced gradient.

Grid and Boundary Conditions

The finite-difference model used in this study is discretized into interconnected rectangular cells, each having its own hydrologic characteristics. The cells make up a grid consisting of 329 rows, 248 columns, and 41 layers (fig. 16). The large number of model layers is needed to represent each water-bearing and confining unit individually and to simulate the effects of the anisotropy caused by these dipping, heterogeneous units. The model grid is oriented along the strike of the bedding units. Cells within the area containing the Westmoreland well field and Fair Lawn Industrial Park are 25 ft × 25 ft. Elsewhere, the cells are larger, with a maximum size of 500 ft × 500 ft near the model boundaries

The size of cells in the Westmoreland well field and Fair Lawn Industrial Park areas was set at 25 ft × 25 ft in order to simulate accurately the hydrogeologic framework of the area. When fractured-rock aquifers are simulated as a porous medium, the net effect of many fractures is simulated rather than the effect of each individual fracture. Instead of simulating the actual contorted path of the water through all the fractures within an individual cell, only a straight-line path is simulated from the point where water enters a cell to the point where it leaves the cell. Consequently, the volume of rock represented by a single model cell must contain a sufficient number of fractures so that the net cell-to-cell flow is simulated correctly. Houghton (1990) suggests that the Passaic Formation contains approximately 15 to 30 fractures across each 25- × 25-ft area. Therefore, the large number of fractures represented by each cell helps to ensure that the net effect of all of the fractures in a cell is simulated.

The vertical structure of the model is shown in figure 17. Model layer 1 represents the unconsolidated overburden materials overlying bedrock. These materials range in thickness from 10 to 100 ft. Water-bearing units 2 through 9 and confining units 2 through 9 (fig. 7) are represented in the model as layers 11 through 26 (fig. 17). Because the model extends beyond the Fair Lawn area, hypothetical layers 2 through 10 and 27 through 41 were added downdip and updip from the layers identified during this study. Water-bearing and confining units represented by these additional layers were assigned the mean thicknesses of the defined water-bearing and confining units, respectively. Model layer 1 was simulated as unconfined; all other model layers were simulated as confined units.

Representation of bedding units as model layers is complicated by the dip of the units. Each model layer must be present over the full model area even though the bedding units they represent may not be. Each bedding unit terminates updip at the

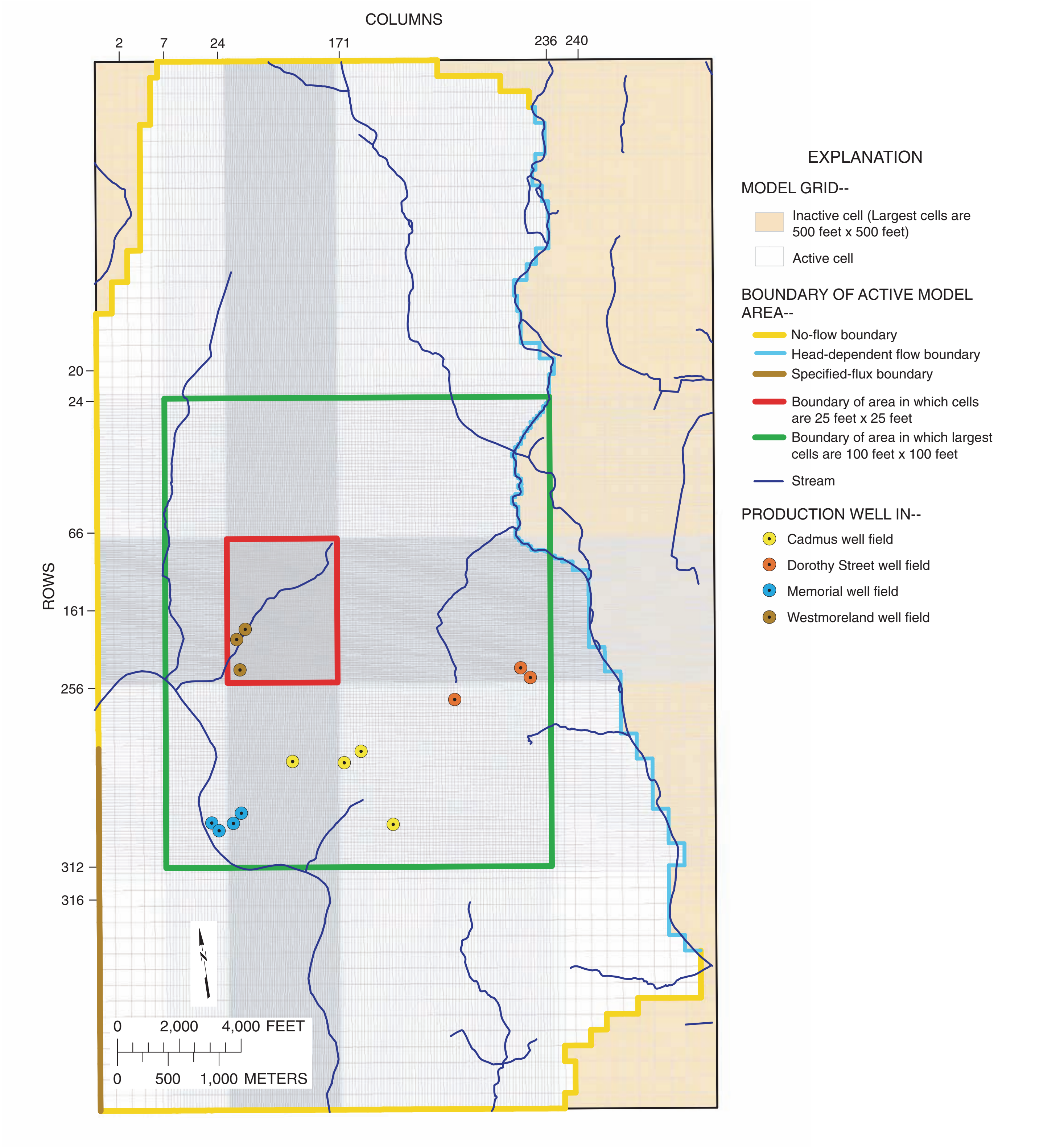


Figure 16. Finite-difference grid for the ground-water flow model of Fair Lawn, New Jersey, and vicinity. (Location shown in figure 1)

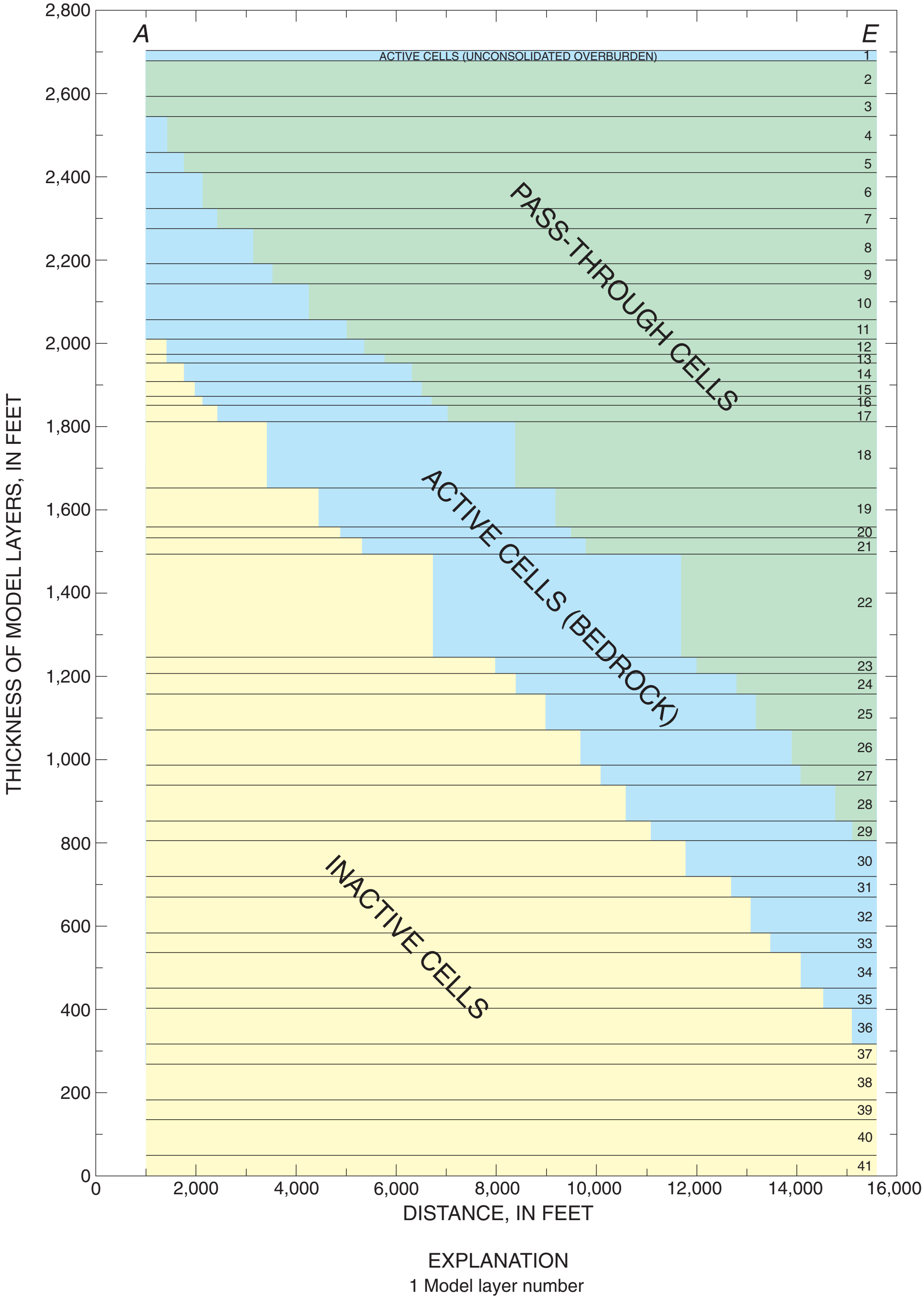


Figure 17. Section showing vertical discretization of the ground-water flow model along section A-E, Fair Lawn, New Jersey (Location of section shown in figure 8)

base of the overburden deposits. Although each bedding unit probably extends thousands of feet downdip, ground-water flow was assumed to be negligible at depths greater than 500 ft below land surface, as explained in the Horizontal Hydraulic Conductivity and Transmissivity section of this report. In order to represent these changes in the character of each bedding unit, each model layer is made up of three zones. The most downdip of these zones is inactive, representing the part of the bedding unit deeper than 500 ft. The middle zone is active, representing the part of the bedding unit between the unconsolidated overburden and a depth of 500 ft below land surface. The most updip zone is a pass-through zone that represents the extension of the bedding unit beyond its outcrop area and above land surface. This zone is composed of pass-through cells that allow water to flow vertically from the unconsolidated overburden (model layer 1) to the bedding unit that actually lies directly beneath the overburden (fig. 17).

The model extends as far as 3.5 mi beyond Fair Lawn. The hydrogeologic framework outside Fair Lawn was assumed to be the same as in Fair Lawn. No hydrogeologic data were collected outside Fair Lawn during this study; however, Houghton (1990), in his description of the geology of the Newark Basin, did not note any variation in the framework within the model area.

The model boundaries (fig. 16) were chosen to ensure that the entire flowpath of any water that passes through Fair Lawn is included in the model. Most of the model boundaries are no-flow boundaries. Criteria for delineating the boundary of the active model, in order of importance, were

- Any ground-water sources and sinks (rivers and wells) in Fair Lawn must be in the active area.
- No-flow boundaries are far enough from the area of interest (Westmoreland well field and Fair Lawn Industrial Park) so that any flow that actually occurs across the boundaries will have no effect on the area of interest. Because the ground-water system is anisotropic, with flow predominantly in the strike (NNE-SSW) direction, the model was extended farther beyond the area of interest in the strike direction than in the dip direction. The boundary is 9,000 ft SSW and 14,000 ft NNE beyond the area of interest. The model was extended at least far enough in the dip direction so that any model layers that include pumped wells are wholly within the active model area. These two criteria ensure that any ground-water flow into, out of, or through the area of interest is represented accurately in the model.
- Where feasible, entire surface-water drainage basins were included in the active area so that simulated ground-water budgets could be calculated for each basin. The entire basins of Diamond Brook, Henderson Brook, Jordan Brook, Beaver Dam Brook, Pehle Brook, and Lyncrest Brook (fig. 2) were included in the active model area. The basins of the Passaic River, Saddle River, Fleischer Brook, and Hohokus Brook extend too far from the area of interest to be included in the active model area in their entirety.

The model boundaries, based on these criteria, are as follows:

- The eastern part of the southern boundary (fig. 16) is formed by the boundary of the Pehle Brook drainage basin (fig. 2). The western part of the southern boundary is a line beginning at the southernmost point of the Pehle Brook drainage basin and extending westward to the western boundary of the model area. The entire southern boundary is a no-flow boundary.
- The entire eastern boundary is formed by the Saddle River (figs. 2 and 14) and is represented by a head-dependent flux boundary.
- The eastern part of the northern boundary (fig. 16) is the line separating drainage to the Saddle River above and below USGS streamflow-gaging station 01390500 at Ridgewood, N.J. (fig. 1). The western part of the northern boundary is a line through the northernmost point in the Diamond Brook drainage basin and parallel to the dip direction of the bedding planes (fig. 2). This boundary is 14,000 ft from the area of interest. The entire northern boundary is a no-flow boundary.
- The western boundary is composed of three segments. The northernmost segment (fig. 16) is formed by the boundary of the Diamond Brook drainage basin (fig. 2) and is a no-flow boundary. The central segment, also a no-flow boundary, is a line beginning at the westernmost point of the Diamond Brook drainage basin and extending southward to the southernmost segment. The southernmost segment is a specified-flux boundary. Flux was applied because the contributing area to wells in the Memorial well field impinges on the western model boundary, indicating that the contributing area actually extends beyond the boundary and that water flows across the model boundary.

To determine the amount of water that flows across the specified-flux boundary, the final, calibrated model was extended temporarily beyond the boundary by increasing the width of the three westernmost model columns. The widths of columns 1, 2, and 3 were changed temporarily from 500, 500, and 420 ft to 25, 3,800, and 1,420 ft, respectively. In the temporary model, the width of column 3 equals the sum of the widths of columns 1, 2, and 3 in the final model. Therefore, the amount of water flowing from column 2 to column 3 in the temporary model is equal to the amount flowing across the western boundary of the final model. In the temporary model, column 2 was widened incrementally until it encompassed the western edge of the contributing area to the Memorial well field (that is, until column 1 was not included in the contributing area). Column 1 was made narrow (25 ft) so that the temporary model would not include the reach of the Passaic River west of the final model area (fig. 1). The amount of water flowing from column 2 to column 3 in the temporary model (135,680 ft^3/d) was applied to column 1 in the final model as a specified-flux boundary.

About half of the flow into the model area at the flux boundary is induced by pumping from wells in the Fair Lawn Water Department Memorial well field (wells FL15, FL16, FL17, and FL19) and wells owned by Marcal Paper Mills (wells MP1, MP2, MP3, MP4, MP5, and MP6) (fig. 3). In the final, calibrated model, about 45 percent (60,800 ft^3/d) of the flux entering the model at this border discharges at the Memorial well field, where the total pumpage in 2000 was 121,500 ft^3/d. About 7 percent (9,500 ft^3/d) discharges at wells owned by Marcal Paper Mills near the southern border of the model area. Pumpage from those wells totaled 68,720 ft^3/d in 2000.

Although the change in column widths is large near the western boundary of the temporary model, the accuracy of the contributing areas and pathlines simulated by the final model in the area of interest (the Westmoreland well field and Fair Lawn Industrial Park) is not reduced. The large change in column widths may affect slightly the configuration of the contributing area to the Memorial well field, which is not part of the defined USEPA Superfund site and, therefore, is outside the area of interest of this study.

Hydrologic Parameters

Hydrologic parameters used in the model for this study were based on field measurements made in Fair Lawn. Parameters that cannot be measured directly were estimated initially on the basis of values used in digital ground-water flow models of hydrologically similar areas. During model calibration in this study (discussed in the Calibration section of this report), all of the parameters were adjusted within reasonable ranges.

Horizontal Hydraulic Conductivity of the Unconsolidated Overburden

The horizontal hydraulic conductivity of the unconsolidated overburden has been measured in monitor wells at two industrial sites in Fair Lawn using slug tests and aquifer tests (Roy F. Weston, Inc., 1984 and 1985; Golder Associates, Inc., 2000), and estimated by calibration of a previous digital model (Geotrans, Inc., 1985) (table 22). Fluvial and lacustrine sediments overlie till at both of these sites. The thickness of the overburden at these two sites generally is on the order of 25 ft, and the screens in wells completed in the overburden generally are from 10 to 20 ft long. Consequently, the wells used in the slug and aquifer tests probably are open to more than one, and possibly all, of these sediment types; therefore, the measurements probably represent the composite conductivity of the entire overburden.

The horizontal hydraulic conductivities of the other types of unconsolidated overburden sediments (deltaic, lacustrine fan, ice-contact, alluvium) found elsewhere in the model area have not been measured. Hydraulic conductivity values reported by Heath (1983) for these sediment types and the conductivities used in the calibrated ground-water flow model are listed in table 23.

Transmissivity of the Bedrock

The approximate transmissivity of water-bearing and confining units in the bedrock at Fair Lawn was determined from the results of slug tests conducted during straddle-packer testing at six observation wells. The measurements are listed in table 4 and summarized in table 24. In cases where slug tests were conducted in more than one interval in the same hydrogeologic unit and in the same well, the measured transmissivity values were added to obtain the total transmissivity of that unit at that well. For example, in well FL23, intervals 1 and 2 are both in water-bearing unit 5 (fig. 7). The transmissivities in the zones adjacent to the two intervals, 850 and 500 ft^2/d, respectively, were added to obtain a total transmissivity of 1,350 ft^2/d for water-bearing unit 5 at well FL23.

Some of the packed intervals were assigned qualitative "high," "medium," or "near-zero" transmissivity on the basis of slug-test results, as discussed in the Straddle-Packer Testing section of this report. High transmissivity was assumed to represent transmissivity greater than 100 ft^2/d, and medium transmissivity, a range from 10 to 100 ft^2/d. To estimate the transmissivity of each hydrogeologic unit, these qualitative results were assigned an estimated quantitative value. "High" transmissivity was assigned a value of 860 ft^2/d, which is the median of the 15 transmissivity values quantitatively determined to exceed 100 ft^2/d (table 4). "Medium" transmissivity was assigned a value of 50 ft^2/d, which is the median of the three transmissivity values quantitatively determined to be from 10 to 100 ft^2/d.

The thickness of each hydrogeologic unit is constant throughout most of the model area. In the shallowest part of the bedrock, however, each unit pinches out in the updip direction, and in the deepest part, each unit pinches out in the downdip direction (fig. 7). In order to represent accurately the diminishing transmissivity of the units in these shallow and deep areas, the transmissivity of each unit was converted into hydraulic conductivity, and the hydraulic conductivity was multiplied by the unique thickness of each model cell to obtain the transmissivity of each model cell. The transmissivity was converted into hydraulic conductivity by dividing the total transmissivity of the unit by the total thickness of the layer (table 24). The final values of hydraulic conductivity used in the calibrated model are equal or nearly equal to these calculated conductivities.

In the model, conductivities used for water-bearing units in which no measurements were made initially were set at 38 ft/d, the median measured conductivity of water-bearing units in which measurements were made. Similarly, the hydraulic conductivity of confining units in which no measurements were made initially was set at 0.13 ft/d, the median hydraulic conductivity of confining units in which measurements were made. In the final, calibrated model, hydraulic conductivities of 44 and 0.60 ft/d were assigned to these water-bearing and confining units, respectively.

In the fractured-rock aquifer composed of rocks in the Passaic Formation, transmissivity decreases with depth because the density of fractures decreases with depth (Lewis-Brown and

Table 22. Summary of published values of horizontal hydraulic conductivity of fluvial sediments, lacustrine sediments, and till in Fair Lawn, New Jersey.

[--, not applicable]

Location	Reference	Number of wells	Testing method	Analysis method	Horizontal hydraulic conductivity (feet per day)	
					Range	Median
Cole Engineering, Inc.	Golder Associates, Inc., 2000	9	Slug tests	Hvorslev (1951)	0.01 – 8.82	0.93
Cole Engineering, Inc.	Golder Associates, Inc., 2000	4	Aquifer tests	Theis (1935)	.13 – 2.29	.34
			Aquifer tests	Jacob (1950)	.11 – 1.11	.42
			Aquifer tests	Theis (1935)	.08 – 9.93	.36
Fisher Scientific Company	Roy F. Weston, Inc., 1984	3	Slug tests	Not reported	.6 – 1.4	1.3
Fisher Scientific Company	Geotrans, Inc., 1985	--	--	Calibration of digital model	--	5.07
Fisher Scientific Company	Roy F. Weston, Inc., 1985	2	Aquifer test	Jacob (1950)	4.2	4.2
				Theis (1935)	4.8	
				Theis (1935)	.42	

Table 23. Hydraulic conductivity and thickness of unconsolidated overburden sediments in and near Fair Lawn, New Jersey.

[<, less than; na, no data available]

Geologic unit (Stanford and others, 1990) (fig. 4)	Generalized description of sediments (Stone and others, 1995)	Thickness (feet)	Generalized horizontal hydraulic conductivity of sediment type (Heath, 1983) (feet per day)	Hydraulic conductivity used in calibrated ground-water flow model (feet per day)	
				Horizontal	Vertical
Continuous till	Sandy to clayey till; compact, firm to hard consistency	10 – 30	$10^{-6} – 10^{0}$	30	0.1
Deltaic and lacustrine-fan deposits	Deltaic and esker deposits	< 50	na	30	.1
Fluvial deposits	Fluvial sand, silt, and gravel	<20	$1 – 10^{4}$	5	.1
Fluvial over lacustrine deposits	Fluvial sand, silt, and gravel overlying lake-bottom silt, fine sand, and clay	< 50	$1 – 10^{4}$ (fluvial) $10^{-6} – 10$ (lake-bottom)	5	.1
Ice-contact deposits	Sand and gravel	<50	$1 – 10^{4}$	30	.1
Alluvium in flood plains of Passaic River	Laminated and thinly bedded silt, clay, and poorly sorted sand overlying poorly sorted gravel and sand	50 – 100	$10^{-6} – 10$ $1 – 10^{4}$	30	.1
Alluvium in tributaries to Passaic River	Poorly sorted sand and gravel	< 15	$1 – 10^{4}$	30	.1

Table 24. Summary of transmissivity measured in bedrock hydrogeologic units in Fair Lawn, New Jersey.

[WB, water-bearing unit; CU, confining unit; ft, feet; ft^2/d, feet squared per day; ft/d, feet per day]

Hydro-geologic unit	Model layer	Layer thickness (ft)	Measurement site		Transmissivity determined from slug testing (ft^2/d)			Horizontal hydraulic conductivity (ft/d)	
			Well	Packed interval	This test	Total transmissivity of this unit at this well	Median transmissivity of this unit at all wells	Initial value (Median measured transmissivity divided by layer thickness)	Final calibrated value (at 25 ft below land surface)
WB2	11	48	FL18	1	2,000	2,000	1,400	29.0	57.0
			FL12	1	860	860			
CU2	12	35				(No tests in this unit)			.6
WB3	13	21	FL18	2	1,400	1,400	5,200	250	67.0
			FL12	2	8,900	8,900			
CU3	14	45							.6
WB4	15	35	FL12	3	1,000	2,700	2,700	77.0	79.0
			FL12	4	1,700				
	16	22							.6
WB5	17	39	FL12	5	2,000	2,000	1,900	49.0	51.0
			FL23	1	850	1,700			
			FL23	2	860				
	18	159		6		11	11		.6
				7					
WB6	19	95	FL23	3	860	2,600	3,100	33.0	37.0
			FL23	4	860				
			FL23	5	860				
			FL29	1	780	3,600			
			FL29	2	780				
			FL29	3	590				
			FL29	4	1,400				
	20	25		1		52	52		2.0
				2					
WB7	21	39	FL23	6	860	850	850	22	22
			FL29	5	840				
	22	248		6		50	71		.35
				7					
				3					
				4		130			
				5					
				1		29			
WB8	23	39	FL27	2	860	1,300	1,300	33	23
			FL27	3	400				
	24	50							.6
WB9	25	85	FL27	5	860	1,500	1,500	18	14
			FL27	6	670				
	26	86		7		0	0		.12
				8					

DePaul, 2000). Therefore, horizontal hydraulic conductivity values used in the model were set to decrease as a function of depth. The model conductivity values listed in table 24 represent the conductivity at a depth of 25 ft below land surface. Below 25 ft, the conductivity decreases linearly; at the base of the active model, 500 ft below land surface, the conductivity is 1/10 the conductivity at 25 ft below land surface.

Vertical Hydraulic Conductivity

Vertical hydraulic conductivity cannot readily be measured in the field, especially in fractured rock; therefore, this parameter was determined by model calibration. The best model calibration was achieved when the vertical hydraulic conductivity of the overburden was set at 0.10 ft/d. This low conductivity reflects the presence of the dense, clayey Rahway till at the base of the overburden. In confined bedrock water-bearing units, vertical hydraulic conductivity is assumed to be lower than horizontal hydraulic conductivity because the number of horizontal fractures per unit volume of aquifer is greater than the number of vertical fractures; the horizontal fractures also are more continuous. Vertical conductivity in the bedrock was set at 4.4 ft/d for the water-bearing units and 0.12 ft/d for the confining units. Vertical leakance, the parameter actually used in the model, was calculated with a computer program (not part of the model) by dividing the vertical hydraulic conductivity at each cell by the thickness of the unit represented by the cell.

Cells in the pass-through zone were assigned a vertical leakance of 100 ft/d to ensure nearly instantaneous movement of water through these cells from the overburden to the model layer that represents the bedding unit directly beneath the overburden.

The rate of flow between a stream and the adjacent aquifer is affected primarily by the vertical hydraulic conductivity and thickness of the streambed material. Because the vertical hydraulic conductivity of a streambed is difficult to measure in the field, this parameter was determined by model calibration. The best model calibration was achieved when the vertical hydraulic conductivity and thickness of all streambed material were set at 1 ft/d and 1 ft, respectively.

Areal Recharge

The effective areal recharge rate used in the model is 20 in/yr. A range of reasonable effective areal recharge rates was determined to be from 16.9 to 22 in/yr. The high end of this range, 22 in/yr, is based on reported recharge to a valley-fill glacial aquifer system in the New Jersey Highlands area (Nicholson and others, 1996). Because the Fair Lawn area is more developed than the Highlands area, it has a greater percentage of impervious surface area and, consequently, probably less ground-water recharge than the Highlands.

The low end of the range is estimated on the basis of streamflow measurements, ground-water pumpage, and ground-water evapotranspiration (table 25). Streamflow measurements were made at base-flow conditions in five tributaries to the Passaic and Saddle Rivers in Fair Lawn (fig. 2) by USGS personnel. The actual effective areal recharge rate for the area encompassing the drainage basins of these five tributaries is the sum of (1) base flow measured at the mouth of each stream minus any industrial discharges to the stream at the time of measurement, (2) ground water pumped from each basin, (3) ground-water evapotranspiration, (4) underflow (precipitation that falls on the tributary basins but discharges to other streams), and (5) change in ground-water storage. Base flow, industrial discharges to the streams, and ground-water pumpage were measured directly. Ground-water evapotranspiration from similar rocks in southeastern Pennsylvania was estimated at 2 in/yr by Sloto and Schreffler (1994). Underflow and change in ground-water storage cannot be measured directly, and estimates of these processes are associated with a large degree of uncertainty. Consequently, the recharge estimate of 16.9 in/yr shown in table 25 is considered to be low because it does not include underflow. The change in ground-water storage, which also is omitted from the estimate, may cause the estimate to be either high or low, depending on whether storage increases or decreases.

Simulation of Discharge Features

Features in the model area that allow ground water to discharge—streams and pumped wells—were included in the model by use of the “River” and “Wells” modules of MODFLOW-2000 (Harbaugh and others, 2000).

Streams

Streams in the model area are the Passaic and Saddle Rivers and Lyncrest, Henderson, Diamond, Hohokus, Jordan, Beaver Dam, Pehle, and Fleischer Brooks (fig. 2). The position of these streams relative to the model grid was determined by overlaying the model grid on topographic maps by means of a geographic information system.

Stream data were obtained from three sources. Stream locations, lengths, widths, and altitudes of the tops of streambeds were derived from reports of the Federal Emergency Management Agency (FEMA) (1976, 1981, 1991) for Beaver Dam Brook, Diamond Brook, Henderson Brook, Jordan Brook, the Passaic River, the southernmost mile of Hohokus Brook, and the southernmost 3.2 mi of the Saddle River. The location, length, and stage of Fleischer Brook and the remaining reaches of Hohokus Brook and the Saddle River were obtained from USGS topographic maps. Widths of these streams were derived from discharge-measurement records on file at the USGS office in West Trenton, N.J. For each of these streams, the average width reported for all measurements made during base-flow conditions from October 2000 through March 2002 was used. For all streams, the depth of water (difference between stream stage and altitude of the top of the streambed) was derived from the same base-flow discharge-measurement records. For each stream, an average depth computed from these measurements was used in the model.

Table 25. Ground-water recharge in and near Fair Lawn, New Jersey, 2000-2001, estimated from base flow, ground-water pumpage, industrial discharge to streams, and ground-water evapotranspiration.

[mi^2, square miles; ft^3/s, cubic feet per second; in/yr, inches per year; nm, not measured; na, not applicable]

Streamflow gaging station number (fig. 2)	Location of streamflow-gaging station	Estimate based on September 2000 conditions				Estimate based on June 2001 conditions			
		Drainage area (mi^2)	Base flow, 9/7/2000 (ft^3/s)	Mean daily ground-water pumpage, 9/2000 (ft^3/s)	Mean daily industrial discharge to stream, 9/2000 (ft^3/s)	Drainage area (mi^2)	Base flow, 6/20/2001 (ft^3/s)	Mean daily ground-water pumpage, 6/2001 (ft^3/s)	Mean daily industrial discharge to stream, 6/2001 (ft^3/s)
01389860	Diamond Brook at Bindary Entrance Road	na	nm	na	0	3.19	2.87	1.626	0
01389865	Henderson Brook at River Road	1.25	1.61	.567	.257	1.25	.861	.745	.487
01389873	Lyncrest Brook at River Road	.45	.078	.437	0	.45	.113	.479	0
01391109	Jordan Brook at Saddle River Road	1.05	.382	.265	0	1.05	.717	.324	0
01391250	Beaver Dam Brook at Saddle River Road	.74	.107	.405	0	.74	.192	.313	0
Total:		3.49	2.177	1.674	0.257	6.68	4.753	3.487	0.487
Base flow plus pumpage minus industrial discharge (ft^3/s)		3.594				7.753			
Base flow plus pumpage minus industrial discharge (in/yr)		14.0				15.8			
Estimated ground-water evapotranspiration (in/yr) [1]		2.0				2.0			
Estimated ground-water recharge (in/yr)		16.0				17.8			
Mean estimated ground-water recharge (in/yr)		**16.9**							

[8]Sloto and Schreffler, 1994.

The streams were simulated with the "River" module of MODFLOW-2000. This module treats streams as head-dependent flux boundaries. McDonald and Harbaugh (1988) define the flow between a stream and the adjacent aquifer in a given model cell according to the equation

$$Q = \frac{K_s L W}{m_s}(h_{riv} - h_{aq}) \qquad (1)$$

where

Q is the flux between the stream and the aquifer, taken as positive if it is directed into the aquifer, in cubic feet per day;

K_s is the vertical hydraulic conductivity of the streambed material, in feet per day;

L is the length of the reach within the given model cell, in feet;

W is the width of the stream, in feet;

m_s is the thickness of the streambed, in feet;

h_{riv} is the hydraulic head in the stream, in feet;

and

h_{aq} is the hydraulic head in the aquifer, in feet.

Pumped Wells

All of the model simulations made as a part of this study included well pumpage. Most of the pumped wells are open to more than one model layer. Pumpage from these wells was apportioned among the model layers on the basis of the ratio of the final calibrated transmissivity of each layer to the total transmissivity of all model layers intersected by the well opening.

Calibration

Three of the four scenario simulations were used in model calibration. The 2000 scenario was used in the most rigorous calibration because far more measured data were available for calibration purposes than for the other three scenarios. Most of the measurements made for this study were made during 2000. Water levels in 70 wells, water levels in 15 intervals isolated by straddle packers in deep observation wells, and base flow in five streams were used in calibrating the 2000 model. The initial estimates of hydrologic parameters described in previous sections were adjusted within reasonable limits until 75 percent of simulated water levels were within 10 ft of measured water levels and simulated base flow at the five measurement sites was within 8 percent of the mean measured base flow.

The rise in water levels in response to increased recharge was used to calibrate the simulation of the high-recharge scenario. The rise in water levels in response to cessation of pumping in production wells was used to calibrate the recovery scenario. Data and methods used to calibrate these scenarios are described in the following sections.

Static Ground-Water Levels

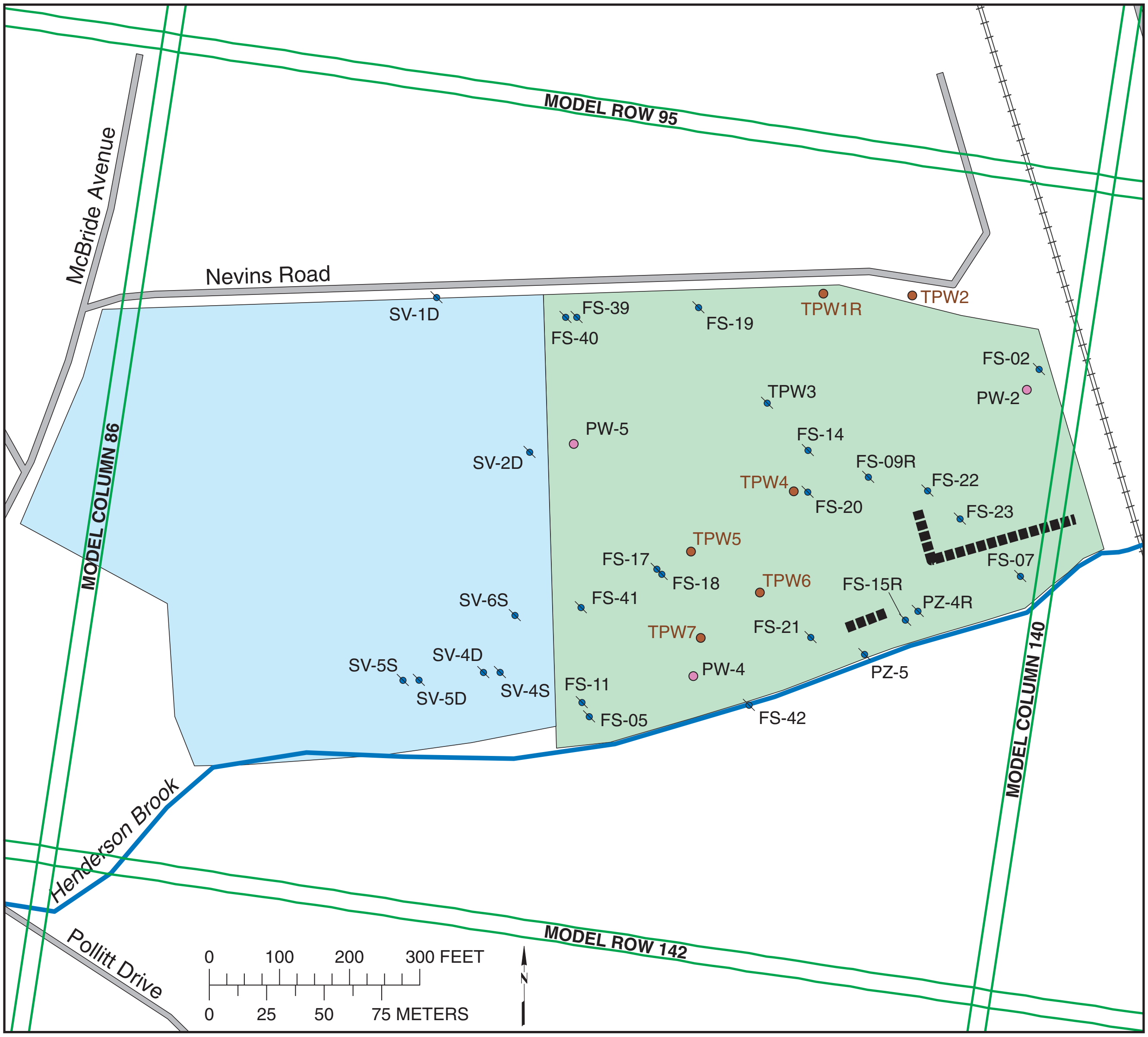
Water levels in 70 wells were used in model calibration. Sixty-eight of the wells are located at five industrial sites—Fisher Scientific Company and Sandvik, Inc. (fig. 18); Einson, Freeman and deTroy (fig. 19); and Cole Engineering, Inc., and Archery Plaza (fig. 20). The other two wells are owned by the Fair Lawn Water Department; these are FLS-1 and FLP-1 (USGS well numbers 030618 and 030620, respectively) (fig. 3, table 1).

Water-level measurements at the five industrial sites were made at various times by various contractors. At each of the sites, various sets of measurements were made over the years. In choosing the sets of measurements to use for calibration purposes, an attempt was made to choose sets that were made under similar, static hydrologic stress conditions. One tool used to assess the similarity of stress conditions was streamflow at the USGS gaging station in the Saddle River at Lodi (station 01391500, fig. 1). All water-level measurements were made on days when the mean daily flow at that gaging station was between 30 and 60 ft^3/s. For comparison, the overall range in streamflow at that station over the period of record (1924-2000) is 4.9 to 2,970 ft^3/s.

Precipitation recorded at Little Falls, N.J., about 5 mi southwest of Fair Lawn, also was used to assess whether measurements were made under static stress conditions. Because at least 3 days had passed since the last recorded precipitation (table 26), conditions were assumed to be static with respect to ground-water recharge. It is unknown whether the water-level measurements were made under static stress conditions with respect to ground-water pumping because daily pumpage records for some nearby pumped wells are not available; however, pumpage from production wells was constant during the 3-day period prior to the dates when the selected sets of water-level measurements were made.

Fair Lawn Water Department observation wells FLP-1 and FLS-1, screened in the unconsolidated overburden, also were used in model calibration. These wells were equipped with continuous water-level recorders. The mean water-level altitude recorded on September 12, 2000, was used for calibration for four reasons: (1) this date falls during the same time period as most of the packer testing; (2) no precipitation fell during the 9-day period preceding this date; (3) no known changes in pumpage at nearby wells occurred during the 3 days preceding this date; and (4) streamflow in the Saddle River at Lodi on that day was 59 ft^3/s, which falls within the 30- to 60-ft^3/s range mentioned above.

Water levels measured in isolated intervals of five of the deep Fair Lawn Water Department observation wells during packer testing also were used for model calibration. These measurements include 11 made in wells FL4, FL23, FL27, and FL29 from August 16 to October 26, 2000, and 4 made in well FL12 from October 23 to October 30, 2001. These measurements were made when ground-water levels were static; measurements made during non-static conditions were not used for model calibration. Measured and simulated water levels in wells and packer-test intervals used for calibration are listed in table 27.



EXPLANATION

INDUSTRIAL SITE--

Fisher Scientific Company

Sandvik, Inc.

Shallow-recovery trench

Model grid line

Railroad

FS-17 Observation well and well number

TPW6 Shallow recovery well and well number

PW-4 Deep recovery well and well number

Figure 18. Location of observation and recovery wells at Fisher Scientific Company and Sandvik, Inc., Fair Lawn, New Jersey. (Location shown in figure 3; model grid shown in figure 16)

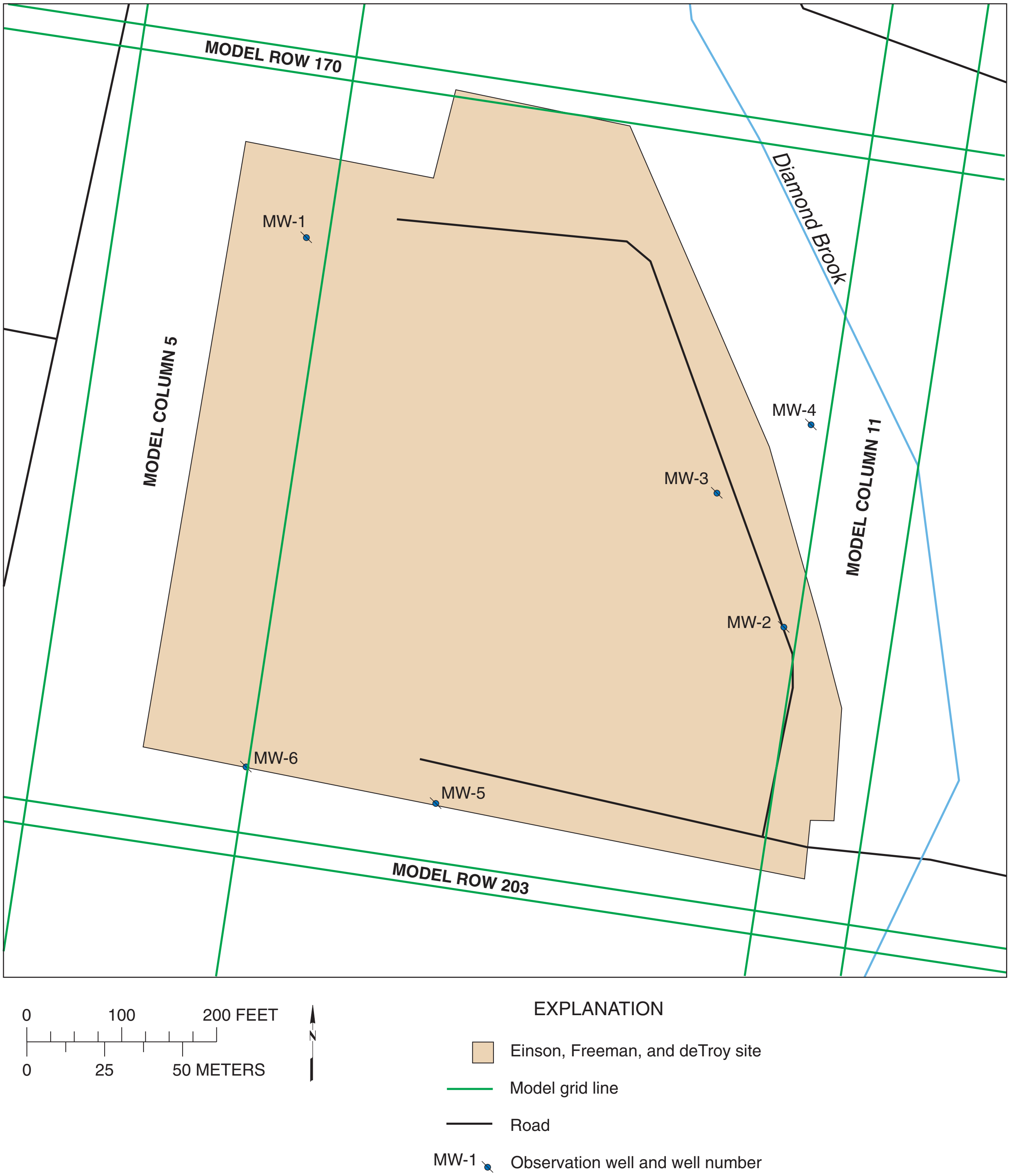


Figure 19. Location of observation wells at Einson, Freeman, and deTroy industrial site, Fair Lawn, New Jersey. (Location shown in figure 3; model grid shown in figure 16)

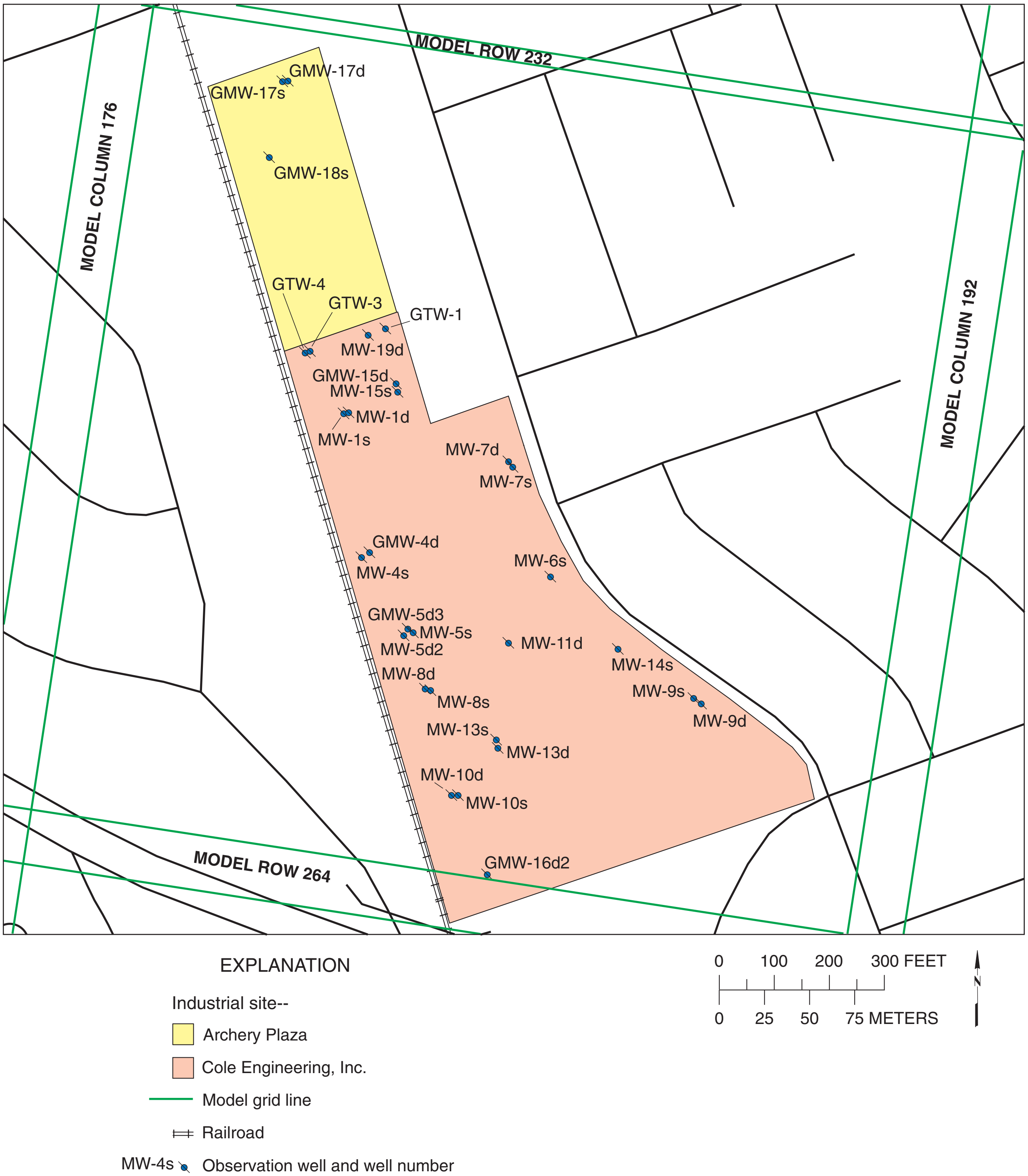


Figure 20. Location of observation wells at the Cole Engineering, Inc., and Archery Plaza industrial sites, Fair Lawn, New Jersey. (Location shown in figure 3; model grid shown in figure 16)

Table 26. Sources of water-level data at four industries in Fair Lawn, New Jersey, measurement dates, mean daily streamflow at a nearby gaging station, and number of days since precipitation.

[NJDEP, New Jersey Department of Environmental Protection; ft^3/s, cubic feet per second]

Industrial site	Source of water-level data	Date of measurement	Mean daily streamflow at gaging station 01391500 (ft^3/s)	Number of days preceding measurement when no precipitation was reported at Little Falls, New Jersey
Fisher Scientific Company	Jacqueline Bobko, NJDEP, written commun., 2002	06/05/2000	60	3
Sandvik, Inc.	James De Noble, NJDEP, written commun., 2001	12/07/2000	33	8
Einson, Freeman and deTroy	EnviroSciences, Inc., 1991	08/30/1991	34	6
Cole Engineering, Inc., and Archery Plaza	Ann Wolf, NJDEP, written commun., 2001	11/1/2000	30	5

Base Flow to Streams

Streamflow was measured under base-flow conditions at or near the most downstream point of Diamond, Henderson, Lyncrest, Jordan, and Beaver Dam Brooks (fig. 2) in Fair Lawn. Two measurements were made at each site except Diamond Brook, where only one measurement was made. The measured and simulated base flow in each of these five streams are listed in table 28. Simulated ground-water discharge to streams was calculated by use of the computer program ZONEBUDGET (Harbaugh, 1990). All simulated base flows are within 8 percent of the mean measured base flow. The uncertainty in these base-flow measurements is 10 percent; therefore, the model calibration is considered to be acceptable with respect to simulated base flow to streams.

Water-Level Rise Resulting from Increased Recharge

The accuracy of the model output for the high-recharge (22 in/yr) scenario was evaluated by comparing measured and simulated rises in base flow and ground-water levels as a result of the increased recharge. Base flow at the USGS gaging station in the Saddle River at Lodi (station 01391500, fig. 1) was used for this analysis. Ground-water levels at Cole Engineering, Inc., were used because that site is farther from pumping stresses than the other three sites for which large sets of measurements are available. The steps used to evaluate the high-recharge scenario simulation results are described below:

1. Base flow to the Saddle River simulated with the digital model in the high-recharge scenario was compared to simulated base flow in the 2000 scenario. The high-recharge scenario resulted in a 10-percent increase in base flow to the Saddle River.
2. Streamflow records for the Saddle River at Lodi indicate that base flow at the gaging station was 30 ft^3/s on November 1, 2000 (the date of the water-level measurements at Cole Engineering, Inc., used to calibrate the 2000 model).
3. Streamflow records for the Saddle River at Lodi for all other dates when water levels were measured at Cole Engineering, Inc., were examined. (There were 18 sets of measurements from 1995 to 2001.) Any date when the river was not at base-flow conditions was discarded. From the remaining dates, the one on which streamflow was closest to 110 percent of 30 ft^3/s (33 ft^3/s) was chosen to represent the high-recharge scenario. This date was July 22, 1998, when measured streamflow was 32 ft^3/s. Precipitation records from the Little Falls, New Jersey, weather station (fig. 1) were examined to ensure that recharge, rather than an unknown stress, caused the increased streamflow and higher ground-water levels on July 22, 1998. During the 12 months preceding July 22, 1998, total precipitation was 55.46 in.; during the 12 months preceding November 11, 2000, total precipitation was 44.64 in.
4. Water levels measured at Cole Engineering, Inc., on July 22, 1998, were compared to water levels measured on November 1, 2000. The measured difference in water levels was compared to the difference in water levels between the 2000 simulation and the high-recharge simulation.

Measured and simulated increases in water levels in 23 wells resulting from the increased recharge are listed in table 29. The simulated water-level rise is within 2 ft of the measured rise at 68 percent of the sites.

Table 27. Measured and simulated ground-water levels, Fair Lawn, New Jersey.

[FLWD, Fair Lawn Water Department; --, no data; na, not applicable; OB, unconsolidated overburden; WB, water-bearing unit; CU, confining unit; Hayward, Hayward Industries, Inc. (the owner of the property where the Cole Engineering, Inc., site is located); Sandvik, Sandvik, Inc.; FS, Fisher Scientific Company, EFD, Einson Freeman and deTroy]

Well owner	Well name (figs. 3, 18-20)	Packed-interval number	Model-layer number	Hydro-geologic unit	Water-level measurement date	Water-level altitude (feet above NAVD 88)		
						Measured	Simulated	Difference (simulated minus measured)
EFD	MW-1	na	1	OB	08-30-1991	37.11	47.35	10.24
EFD	MW-2	na	1	OB	08-30-1991	40.77	40.11	-0.66
EFD	MW-3	na	1	OB	08-30-1991	39.91	41.28	1.37
EFD	MW-4	na	1	OB	08-30-1991	40.27	39.90	-0.37
EFD	MW-5	na	1	OB	08-30-1991	39.12	39.71	0.59
EFD	MW-6	na	1	OB	08-30-1991	40.60	40.50	-0.10
FLWD	FLP-1	na	1	OB	09-12-2000	41.79	51.54	9.75
FLWD	FLS-1	na	1	OB	09-12-2000	18.46	27.99	9.53
FS	FS-02	na	1	OB	06-05-2000	76.07	67.66	-8.41
FS	FS-07	na	1	OB	06-05-2000	74.21	67.42	-6.79
FS	FS-20	na	1	OB	06-05-2000	72.53	65.06	-7.47
FS	FS-21	na	1	OB	06-05-2000	70.16	65.27	-4.89
FS	FS-22	na	1	OB	06-05-2000	75.98	65.43	-10.55
FS	FS-23	na	1	OB	06-05-2000	75.68	65.06	-11.62
FS	PZ-4R	na	1	OB	06-05-2000	74.03	66.16	-7.87
FS	PZ-5	na	1	OB	06-05-2000	72.39	65.60	-6.79
Hayward	MW-1s	na	1	OB	11-01-2000	66.36	61.88	-4.48
Hayward	MW-4s	na	1	OB	11-01-2000	61.99	60.97	-1.02
Hayward	MW-5s	na	1	OB	11-01-2000	61.85	60.92	-0.93
Hayward	MW-6s	na	1	OB	11-01-2000	58.13	62.04	3.91
Hayward	MW-7s	na	1	OB	11-01-2000	60.92	62.58	1.66
Hayward	MW-8s	na	1	OB	11-01-2000	60.35	60.26	-0.09
Hayward	MW-9s	na	1	OB	11-01-2000	57.47	62.29	4.82
Hayward	MW-10s	na	1	OB	11-01-2000	59.79	59.92	0.13
Hayward	MW-13s	na	1	OB	11-01-2000	58.37	60.81	2.44
Hayward	MW-14s	na	1	OB	11-01-2000	57.47	61.94	4.47
Hayward	MW-15s	na	1	OB	11-01-2000	66.64	62.21	-4.43
Hayward	GMW-17s	na	1	OB	11-01-2000	73.59	63.25	-10.34
Hayward	GMW-18s	na	1	OB	11-01-2000	71.74	62.92	-8.82
Hayward	GTW-4	na	1	OB	11-01-2000	67.34	62.11	-5.23
FLWD	FL12	1	11	WB2	10-23-2001	44.80	48.37	3.57
FLWD	FL12	2	13	WB3	10-24-2001	39.21	49.98	10.77
FLWD	FL12	3	14	CU3	10-25-2001	38.93	51.07	12.14
Sandvik	SV-5s	na	14	CU3	12-07-2000	58.07	60.99	2.92
FS	FS-05	na	15	WB4	06-05-2000	67.23	61.37	-5.86

Table 27. Measured and simulated ground-water levels, Fair Lawn, New Jersey.—Continued

[FLWD, Fair Lawn Water Department; --, no data; na, not applicable; OB, unconsolidated overburden; WB, water-bearing unit; CU, confining unit; Hayward, Hayward Industries, Inc. (the owner of the property where the Cole Engineering, Inc., site is located); Sandvik, Sandvik, Inc.; FS, Fisher Scientific Company, EFD, Einson Freeman and deTroy]

Well owner	Well name (figs. 3, 18-20)	Packed-interval number	Model-layer number	Hydro-geologic unit	Water-level measurement date	Water-level altitude (feet above NAVD 88)		
						Measured	Simulated	Difference (simulated minus measured)
FS	FS-39	na	15	WB4	06-05-2000	60.02	63.56	3.54
FS	FS-17	na	15	WB4	06-05-2000	64.33	62.36	-1.97
Sandvik	SV-4s	na	15	WB4	12-07-2000	60.16	61.10	0.94
Sandvik	SV-6s	na	15	WB4	12-07-2000	59.64	61.62	1.98
Sandvik	SV-1D	na	16	CU4	12-07-2000	55.94	63.42	7.48
FLWD	FL12	5	17	WB5	10-30-2001	45.22	51.47	6.25
FLWD	FL23	2	17	WB5	09-25-2000	63.76	58.76	-5.00
FS	FS-11	na	17	WB5	06-05-2000	52.00	62.11	10.11
FS	FS-14	na	17	WB5	06-05-2000	70.67	64.26	-6.41
FS	FS-15R	na	17	WB5	06-05-2000	73.59	63.82	-9.77
FS	FS-18	na	17	WB5	06-05-2000	51.67	62.99	11.32
FS	FS-19	na	17	WB5	06-05-2000	51.12	64.46	13.34
FS	FS-40	na	17	WB5	06-05-2000	56.50	63.91	7.41
FS	FS-41	na	17	WB5	06-05-2000	51.30	62.44	11.14
Sandvik	SV-2D	na	17	WB5	12-07-2000	52.03	62.84	10.81
Sandvik	SV-4D	na	17	WB5	12-07-2000	53.24	61.75	8.51
Sandvik	SV-5D	na	17	WB5	12-07-2000	53.69	61.60	7.91
FS	FS-9R	na	18	CU5	06-05-2000	58.66	64.98	6.32
FS	FS-42	na	18	CU5	06-05-2000	45.56	63.51	17.95
FLWD	FL23	5	19	WB6	10-02-2000	52.44	61.98	9.54
FLWD	FL29	3	19	WB6	08-21-2000	29.67	44.91	15.24
Hayward	MW-1d	na	19	WB6	11-01-2000	59.13	60.70	1.57
Hayward	GMW-4d	na	19	WB6	11-01-2000	57.82	59.75	1.93
Hayward	GMW-15d	na	19	WB6	11-01-2000	57.75	61.04	3.29
Hayward	GMW-17d	na	19	WB6	11-01-2000	71.84	62.11	-9.73
Hayward	GTW-1	na	19	WB6	11-01-2000	64.76	61.32	-3.44
Hayward	GTW-3	na	19	WB6	11-01-2000	65.18	60.92	-4.26
FLWD	FL4	1	20	CU6	10-16-2000	32.35	53.10	20.75
Hayward	MW-7d	na	20	CU6	11-01-2000	60.76	61.58	0.82
Hayward	MW-8d	na	20	CU6	11-01-2000	58.51	59.11	0.60
Hayward	MW-10d	na	20	CU6	11-01-2000	53.54	58.73	5.19
FLWD	FL23	6	21	WB7	10-04-2000	53.41	62.07	8.66
FLWD	FL29	5	21	WB7	08-22-2000	24.84	44.86	20.02
Hayward	MW-5d2	na	21	WB7	11-01-2000	53.33	59.98	6.65

Table 27. Measured and simulated ground-water levels, Fair Lawn, New Jersey.—Continued

[FLWD, Fair Lawn Water Department; --, no data; na, not applicable; OB, unconsolidated overburden; WB, water-bearing unit; CU, confining unit; Hayward, Hayward Industries, Inc. (the owner of the property where the Cole Engineering, Inc., site is located); Sandvik, Sandvik, Inc.; FS, Fisher Scientific Company, EFD, Einson Freeman and deTroy]

Well owner	Well name (figs. 3, 18-20)	Packed-interval number	Model-layer number	Hydro-geologic unit	Water-level measurement date	Water-level altitude (feet above NAVD 88)		
						Measured	Simulated	Difference (simulated minus measured)
Hayward	MW-11d	na	21	WB7	11-01-2000	57.02	60.13	3.11
Hayward	MW-13d	na	21	WB7	11-01-2000	53.78	59.57	5.79
FLWD	FL4	4	22	CU7	10-16-2000	32.93	54.60	21.67
FLWD	FL27	1	22	CU7	09-11-2000	49.58	56.22	6.64
Hayward	GMW-5d3	na	22	CU7	11-01-2000	53.34	59.89	6.55
Hayward	MW-9d	na	22	CU7	11-01-2000	56.83	61.12	4.29
Hayward	GMW-16d2	na	22	CU7	11-01-2000	46.79	59.31	12.52
Hayward	MW-19d	na	22	CU7	11-01-2000	55.10	61.00	5.90
FLWD	FL27	3	23	WB8	09-14-2000	49.55	57.53	7.98
FLWD	FL27	5	25	WB9	09-18-2000	47.16	57.39	10.23
FLWD	FL27	8	26	CU9	09-22-2000	49.93	56.86	6.93

Table 28. Measured and simulated base flow to streams, Fair Lawn, New Jersey.

[ft^3/s, cubic feet per second; nm, not measured]

Measure-ment site	Stream	Mea-sured stream-flow, 9/7/2000 (ft^3/s)	Indus-trial dis-charges, 9/2000 (ft^3/s)	Base flow (stream-flow minus industrial dis-charges), 9/2000 (ft^3/s)	Mea-sured stream-flow, 6/20/2001 (ft^3/s)	Indus-trial dis-charges, 6/2001 (ft^3/s)	Base flow (stream-flow minus industrial dis-charges), 6/2001 (ft^3/s)	Mean base flow (ft^3/s)	Simu-lated base flow (ft^3/s)	Percent difference between measured and simulated base flow
01389860	Diamond Brook	nm	0	nm	2.87	0	2.87	2.87	2.80	2.4
01389865	Henderson Brook	1.61	.257	1.353	.861	.487	.374	.864	.862	.2
01389873	Lyncrest Brook	.078	0	.078	.113	0	.113	.0955	.103	7.9
01391109	Jordan Brook	.382	0	.382	.717	0	.717	.550	.585	6.4
01391250	Beaver Dam Brook	.107	0	.107	.192	0	.192	.150	.148	1.3

Table 29. Measured and simulated water-level rise resulting from increased recharge, Fair Lawn, New Jersey.

[Hayward, Hayward Industries, Inc., (the owner of the property where the Cole Engineering, Inc., site is located); OB, overburden; WB, water-bearing unit; CU, confining unit]

Well owner	Well name (fig. 20)	Model layer number	Hydrogeologic unit	Rise in water level (feet)		
				Measured	Simulated	Difference (simulated minus measured)
Hayward	MW-1s	1	OB	2.33	2.97	0.64
Hayward	MW-4s	1	OB	4.56	2.98	-1.58
Hayward	MW-6s	1	OB	4.96	2.94	-2.02
Hayward	MW-7s	1	OB	5.70	2.93	-2.77
Hayward	MW-8s	1	OB	7.56	2.98	-4.58
Hayward	MW-9s	1	OB	2.70	2.93	.23
Hayward	MW-13s	1	OB	4.56	2.93	-1.63
Hayward	MW-14s	1	OB	3.09	2.95	- .14
Hayward	MW-15s	1	OB	0.62	2.99	2.37
Hayward	GMW-17s	1	OB	1.53	2.97	1.44
Hayward	GMW-18s	1	OB	1.44	2.97	1.53
Hayward	MW-1d	19	WB6	2.37	2.84	.47
Hayward	GMW-4d	19	WB6	3.27	2.84	- .43
Hayward	GMW-15d	19	WB6	2.69	2.85	.16
Hayward	GMW-17d	19	WB6	2.11	2.82	.71
Hayward	MW-7d	20	CU6	5.59	2.84	-2.75
Hayward	MW-8d	20	CU6	4.90	2.83	-2.07
Hayward	MW-11d	21	WB7	5.45	2.85	-2.60
Hayward	MW-13d	21	WB7	1.89	2.83	.94
Hayward	MW-9d	22	CU7	2.70	2.72	.02
Hayward	GMW-16d2	22	CU7	1.48	2.72	1.24
Hayward	MW-19d	22	CU7	2.53	2.68	.15

Water-Level Rise During Shutdown of Pumped Wells

Continuous water-level recorders were used to measure rises in water levels in observation wells in response to shutdown of pumps in production wells. Water levels in the recovery-scenario simulation were compared to water levels in the 2000 scenario simulation to determine the simulated water-level rise in Fair Lawn Water Department observation wells FL4 and FL29 when the pumps in Fair Lawn Water Department wells FL2 and FL7 were turned off and in well FL27 when the pump in well FL28 was turned off. Measured and simulated water-level rises in these observation wells are listed in table 30.

Sensitivity Analysis

The purpose of a sensitivity analysis is to quantify the uncertainty in the calibrated model. In the model used in this study, uncertainty is created, in part, by estimation of horizontal and vertical hydraulic conductivity and recharge rates. A sensitivity analysis was performed by systematically changing the values of these parameters within hydrologically reasonable ranges. Although the simulation results also may be sensitive to boundary conditions, grid discretization, and spatial and temporal variations in parameter values, sensitivity testing of these factors is impractical. Results of the sensitivity analysis are reported as the effects of changes in parameter values on the simulated water levels and base flow to streams.

Table 30. Measured and simulated water-level rise in observation wells during shutdown of nearby production wells, Fair Lawn, New Jersey.

[--, not applicable]

Pumped well	Duration of shutdown of pumped well	Water-level rise in well FL4 (feet)		Water-level rise in well FL29 (feet)		Water-level rise in well FL27 (feet)	
		Measured	Simulated	Measured	Simulated	Measured	Simulated
FL2 and FL7	12 hours	9.78	4.79	5.15	2.64	--	--
FL28	20 days	--	--	--	--	4.11	1.18

The calibrated 2000 model was used for sensitivity analysis. Variation in water levels and base flow to streams as a result of variations in hydraulic-conductance properties (horizontal hydraulic conductivity, transmissivity, vertical leakance, and streambed conductance) are shown in figures 21 and 22, respectively. The change in base flow is given as the ratio of base flow to tributaries to the Passaic and Saddle Rivers to the total base flow to tributaries and rivers. This ratio is an indicator of changes in the proportion of recharge to tributary basins that eventually discharges to the tributary as opposed to flowing under the tributary and discharging to the more distant river. Changes in hydraulic properties were applied equally to all model cells. Conductivity was varied over a range of five orders of magnitude. Variations in hydraulic head and base flow as a result of variations in recharge are shown in figure 23. Changes in recharge were applied equally to all active cells in layer 1 (representing the overburden) (or the uppermost active layer at cells where layer 1 was dry). Recharge was varied over a range of 8 in/yr. The model was most sensitive to changes in transmissivity (layers 2-41, representing the bedrock) and horizontal hydraulic conductivity (layer 1, representing the overburden) and least sensitive to changes in vertical hydraulic leakance.

Simulated Water Budgets

Simulated water budgets for the drainage basins of streams in the study area are listed in table 31. These budgets represent ground-water conditions in 2000. The budgets were calculated with the computer program ZONEBUDGET (Harbaugh, 1990).

The budgets indicate a great deal of interbasin transfer of ground water. For example, in the Henderson Brook drainage basin, approximately 136,000 ft^3/d of water flows into the basin from neighboring basins, and approximately 175,000 ft^3/d flows out of the basin to neighboring basins. To put these amounts in perspective, recharge to the basin from precipitation is approximately 159,000 ft^3/d.

Most (66 percent) of the water that enters the unconsolidated overburden (model layer 1) flows downward into the bedrock layers (model layers 2-41). The other 34 percent remains in layer 1 and discharges to nearby streams and to recovery wells and trenches at Fisher. About 72 percent of the water that enters the bedrock layers eventually flows back into layer 1 and discharges to streams. The remainder flows to pumped wells.

Model Limitations

Ground-water flow in fractured rocks is too complex to be simulated succinctly with a digital model. By making certain necessary simplifying assumptions, however, a model can be constructed that is capable of approximating flow through the fractured-rock units.

An important assumption incorporated into the model is that ground-water flow at depths greater than 500 ft is negligible. If this assumption is false, then some of the simulated flowpaths—especially those beginning in deep bedrock units—could be shallower than the actual flowpaths, and their discharge points could be simulated inaccurately.

All of the data used to calibrate the model were collected in Fair Lawn; therefore, the model cannot be used to obtain detailed simulations of ground-water conditions outside Fair Lawn. This limitation has no effect on the primary intended uses of this model, which are to delineate contributing areas to the Westmoreland well field, delineate contaminant plumes from Fisher, Sandvik, and Kodak, and estimate the effect of pumping at the Westmoreland well field and Fisher on flowpaths of contaminated water.

The model represents a porous medium, and the pores in this hydrogeologic setting consist of a network of fractures in three orientations that generally are at right angles to and interconnected with each other. Each model cell represents a volume of space that contains many fractures. The model calculates the flowpath from one cell to the next by simulating the net effect of all of the fractures in that interval. Therefore, flowpaths on a scale smaller than the cell size cannot be simulated. In the area encompassing Fair Lawn Industrial Park and the Westmoreland well field, this limitation means that flowpaths within areas smaller than a 25-ft-by-25-ft square cannot be simulated.

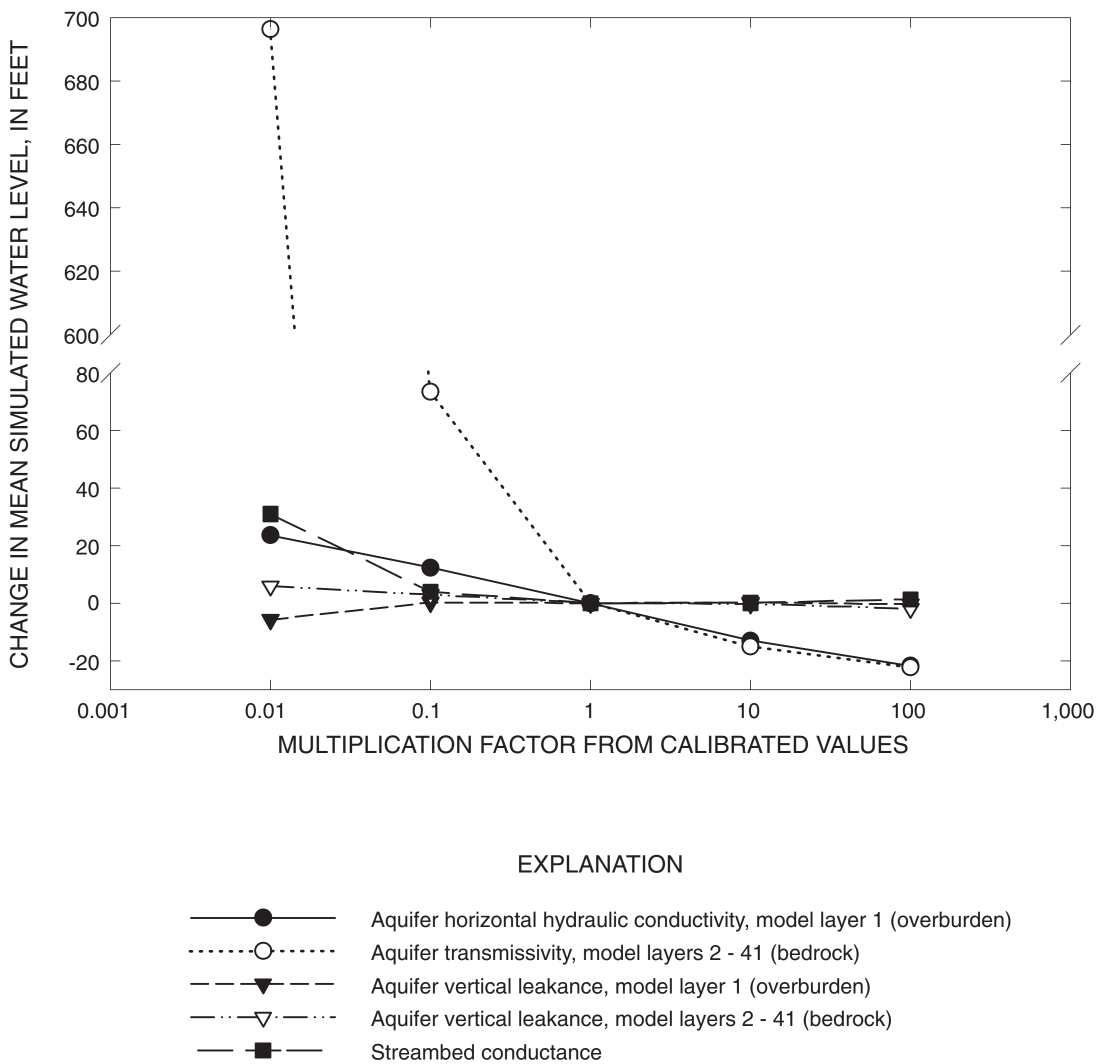


Figure 21. Sensitivity of simulated water levels to variations in the values of hydrologic parameters, Fair Lawn, New Jersey, and vicinity.

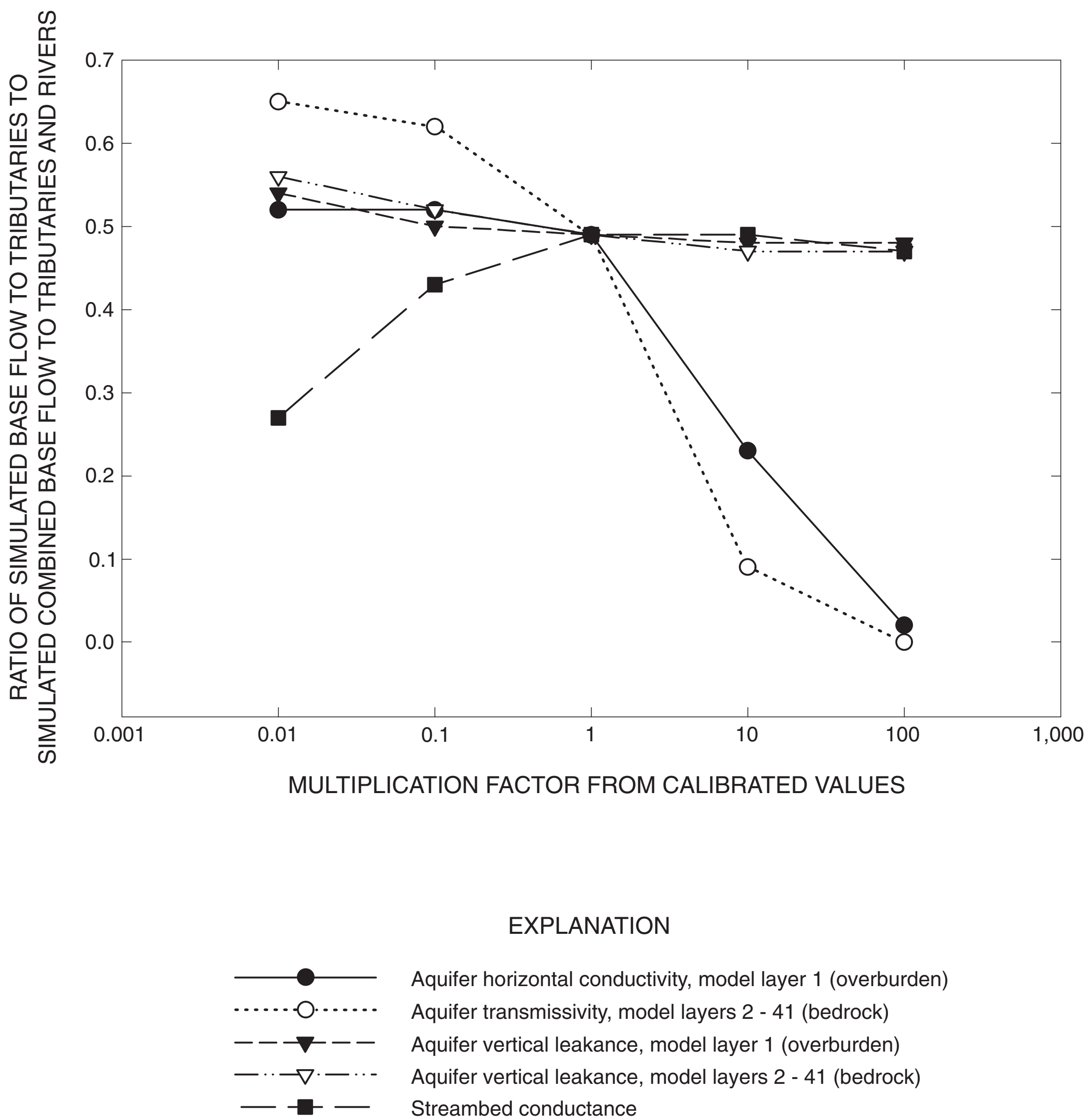
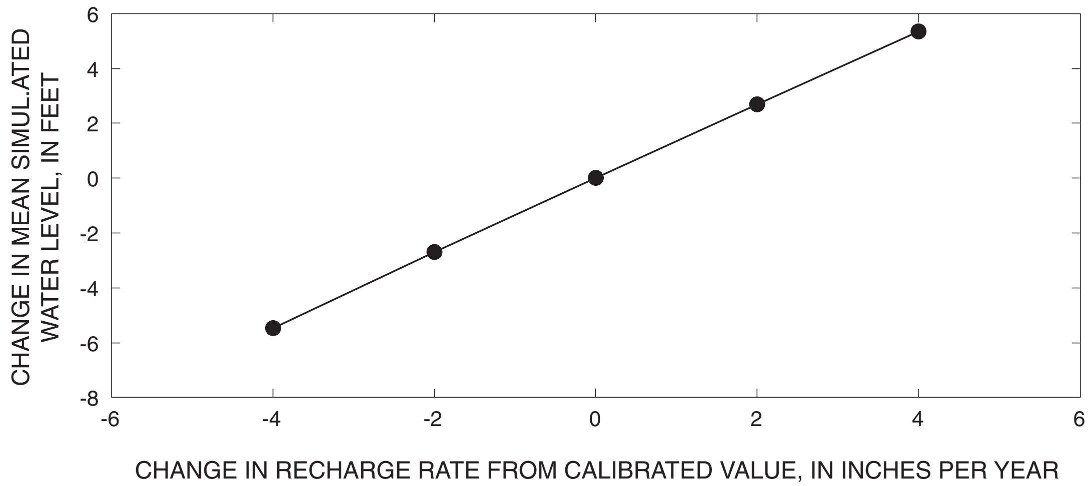


Figure 22. Sensitivity of simulated stream base flow to variations in the values of hydrologic parameters, Fair Lawn, New Jersey, and vicinity.



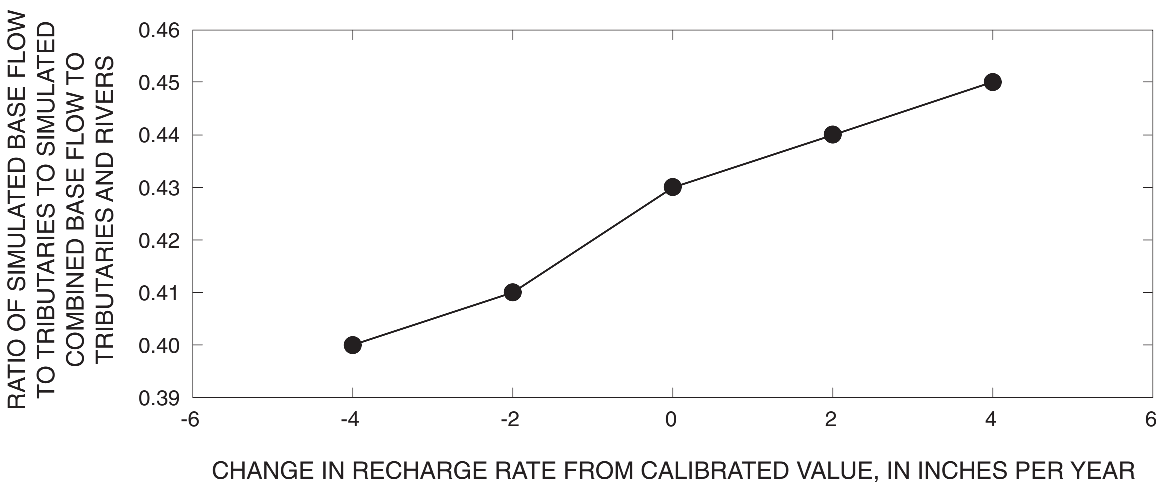


Figure 23. Sensitivity of simulated water levels and stream base flow to variations in the areal recharge rate, Fair Lawn, New Jersey, and vicinity.

Table 31. Simulated water budgets in surface-water drainage basins in and near Fair Lawn, New Jersey, 2000.

[na, not applicable; all values represent flow, in cubic feet per day]

Water entering ground-water system as:	Beaver Dam Brook	Diamond Brook	Fleischer Brook	Henderson Brook	Hohokus Brook[1]	Jordan Brook	Lyncrest Brook	Passaic River[1]	Pehle Brook	Saddle River[1]
Recharge	94,579	407,420	178,390	159,050	336,150	136,010	55,937	579,900	91,519	259,340
Inflow from streams	3,709	6,302	0	2,839	0	651	1,777	3,457	503	10,140
Inflow from flux boundary	0	0	0	0	0	0	0	135,680	0	0
Inflow from Beaver Dam Brook Basin	na	0	39	0	0	9,078	2,786	0	0	62,825
Inflow from Diamond Brook Basin	0	na	0	83,679	36,543	0	0	62,925	0	0
Inflow from Fleisher Brook Basin	1,959	0	na	0	0	0	12,182	49,729	12,462	245
Inflow from Henderson Brook Basin	0	69,695	0	na	4,170	33,805	0	66,947	0	0
Inflow from Hohokus Brook Basin	0	35,607	0	10,889	na	5,521	0	0	0	49,203
Inflow from Jordan Brook Basin	13,608	0	0	17,705	1,454	na	2,108	45,399	0	37,059
Inflow from Lyncrest Brook Basin	1,980	0	6,968	0	0	45	na	56,797	0	0
Inflow from Passaic River Basin	0	15,881	2,629	23,464	0	503	41,159	na	0	0
Inflow from Pehle Brook Basin	0	0	15,831	0	0	0	0	0	na	46,779
Inflow from Saddle River Basin	10,521	0	0	0	62,456	4,062	0	0	6,121	na
Total entering ground-water system in drainage basin	126,356	534,905	203,857	297,627	440,773	189,675	115,949	1,000,834	110,606	465,591
Water leaving ground-water system as:										
Base flow to streams	16,489	248,090	127,280	77,283	232,480	51,169	10,656	715,090	47,997	362,230
Flow to pumped wells	35,159	104,630	0	47,824	107,260	21,392	39,519	202,330	0	20,219
Outflow to Beaver Dam Brook Basin	na	0	1,959	0	0	13,608	1,980	0	0	10,521
Outflow to Diamond Brook Basin	0	na	0	69,695	35,607	0	0	15,881	0	0
Outflow to Fleisher Brook Basin	39	0	na	0	0	0	6,968	2,629	15,831	0
Outflow to Henderson Brook Basin	0	83,679	0	na	10,889	17,705	0	23,464	0	0
Outflow to Hohokus Brook Basin	0	36,543	0	4,170	na	1,454	0	0	0	62,456
Outflow to Jordan Brook Basin	9,078	0	0	33,805	5,521	na	45	503	0	4,062
Outflow to Lyncrest Brook Basin	2,786	0	12,182	0	0	2,108	na	41,159	0	0
Outflow to Passaic River Basin	0	62,925	49,729	66,947	0	45,399	56,797	na	0	0
Outflow to Pehle Brook Basin	0	0	12,463	0	0	0	0	0	na	6,121
Outflow to Saddle River Basin	62,825	0	245	0	49,203	37,053	0	0	46,779	na
Total leaving ground-water system in drainage basin	126,376	535,867	203,858	299,724	440,960	189,888	115,965	1,001,056	110,607	465,609

[9]Part of the drainage basin of this stream is outside the active model area.

Only advective movement of contaminants can be simulated with the model. Non-advective processes (density-driven movement, dispersion, diffusion, dilution, and biological and chemical degradation of contaminants) cannot be simulated with the model. The effects of density-driven movement, dispersion, diffusion, and dilution widen contaminant flowpaths, whereas the effects of degradation shorten and narrow flowpaths. In the bedrock of the Newark Basin, however, advection is by far the primary mechanism of contaminant movement. The low porosity of the Passaic Formation (0.0014 or less as determined by Carleton and others (1999)) results in high ground-water velocities. Where ground-water velocities are high, the effects of the much slower non-advective processes of contaminant transport are diminished. Non-advective processes probably are more important in the unconsolidated overburden, however.

Simulated Ground-Water Flowpaths

Ground-water flowpaths were computed on the basis of the digital model described in this report using the post-processor MODPATH (Pollock, 1994). Flowpaths were computed for the 1991, 2000, and high-recharge scenarios. The 1991 and 2000 scenarios are different in two important ways: (1) at Fisher, seven shallow (less than 19 ft deep) recovery wells and two interceptor trenches, with a total pumpage of 5.5 Mgal in 2000, were installed in the overburden during the intervening period; and (2) pumpage from the Westmoreland well field decreased from 130 Mgal in 1991 to 49 Mgal in 2000.

Simulated Contributing Areas

The contributing area to a pumped well is defined as the surface area on the three-dimensional boundary of the ground-water system where the water that eventually discharges at the well enters the ground-water system (modified from Reilly and Pollock, 1993). Because only advective flow is simulated with the model, the effects of density, dispersion, diffusion, dilution, and degradation of contaminants are not accounted for in the simulated contributing areas. The contributing areas to wells in the model area include some of the contaminated sites in and near Fair Lawn that have been identified by the New Jersey Department of Environmental Protection (2001). All of the contaminated sites identified by the NJDEP are listed in table 32 and shown in figure 24 and in subsequent figures depicting contributing areas.

1991 Scenario

The simulated contributing areas to Fair Lawn Water Department well fields (Cadmus, Dorothy Street, Memorial, and Westmoreland) in 1991 are shown in figure 25; the contributing area to the Westmoreland well field is shown in more detail in figure 26. In 1991, when 130 Mgal of water was pumped from the Westmoreland well field, the contributing area to that well field encompassed about one-fourth of Fair Lawn Industrial Park and included nearly all of the Fisher property, a small part (less than 1 percent) of the Sandvik property, and about three-fourths of the Kodak property (fig. 26). The contributing area extended about 2.5 mi north of Fair Lawn. This area includes or is less than 200 ft from two other known contaminated sites (an Exxon service station and a Hess service station (table 32)). The ground-water contaminants at the service stations, however, probably are gasoline byproducts unrelated to the contamination at the Westmoreland well field. Consequently, the contributing-area analysis indicates that Fisher, Sandvik, and Kodak all are potential sources of the VOCs at the Westmoreland well field and that no other potential sources are known.

In 1991, the contributing area to the Memorial wells was northeast of the wells and south and east of the Fisher, Sandvik, and Kodak properties. It did not include any known contaminated sites but was less than 500 ft from three sites: the site known as 12-59 12th Street, Topps Cleaners and Launderers, and an Exxon service station (table 32).

In 1991, the contributing area to the Cadmus wells encompassed an area generally northeast of the wells and included five known contaminated sites: the site known as 12-59 12th Street, Topps Cleaners and Launderers, an Exxon service station, Borden Chemical Printing Ink Division, and Cole Engineering, Inc. (table 32). Another Exxon service station was less than 500 ft from this contributing area.

In 1991, the contributing area to the Dorothy Street wells included two known contaminated sites and was less than 500 ft from another site; however, no contamination has been detected in water samples from the Dorothy Street wells.

2000 Scenario

The simulated contributing areas to Fair Lawn Water Department well fields in 2000 are shown in figure 27; the contributing area to the Westmoreland well field is shown in more detail in figure 28. In 2000, the contributing area to the Westmoreland well field was much smaller than in 1991 because pumpage from the Westmoreland well field had decreased from about 130 Mgal in 1991 to about 49 Mgal in 2000. The configuration of the contributing area to the Westmoreland well field also changed substantially from 1991 to 2000, primarily as a result of the installation of the shallow recovery system at Fisher (seven shallow wells and two trenches with a total pumpage of 2,025 ft^3/d). In contrast to the 1991 contributing area, the 2000 contributing area included only a small part of the Fisher property.

In 2000, the contributing area to the Westmoreland well field also included a small part of the Kodak property but none of the Sandvik property. The area remained less than 200 ft from a Hess service station (table 32) and still extended about 2 mi north of Fair Lawn. The contributing-area analysis indicates that Fisher and Kodak both are potential sources of the VOC contamination in the Westmoreland well field and that no other potential sources are known.

Table 32. Known contaminated sites, Fair Lawn and Glen Rock, New Jersey.

[Source: New Jersey Department of Environmental Protection, 2001]

Map number in figure 24	Name	Address	Municipality
1	1-33 36th Street	1-33 36th Street	Fair Lawn Borough
2	1-38 Cyril Avenue	1-38 Cyril Avenue	Fair Lawn Borough
3	12-59 12th Street	12-59 12th Street	Fair Lawn Borough
4	14-23 Third Street	14-23 Third Street	Fair Lawn Borough
5	17-17 to 17-71 River Road	17-17 to 17-71 River Road	Fair Lawn Borough
6	27-11 Kipp Street	27-11 Kipp Street	Fair Lawn Borough
7	30-13 High Street	30-13 High Street	Fair Lawn Borough
8	Amtech, Incorporated	20-21 Wargaraw Road	Fair Lawn Borough
9	Auto Sumser, Incorporated	7-06 Saddle River Road	Fair Lawn Borough
10	Berdan Holding Company	11-12 River Road	Fair Lawn Borough
11	Biocraft Labs, Incorporated	18-01 River Road	Fair Lawn Borough
12	Borden Chemical Printing Ink Division	8-10 22nd Street	Fair Lawn Borough
13	Citgo Station Fair Lawn	12-32 Maple Drive	Fair Lawn Borough
14	Cole Engineering, Incorporated	13-00 Plaza Road	Fair Lawn Borough
15	Eastman Kodak Company	16-31 Route 208	Fair Lawn Borough
16	Einson Freeman & deTroy Corporation	20-10 Maple Avenue	Fair Lawn Borough
17	Engine Reguilders	18-02 River Road	Fair Lawn Borough
18	Exxon Service Station Fair Lawn Borough	Plaza Road & Morlot Avenue	Fair Lawn Borough
19	Exxon Service Station Fair Lawn Borough	20-22 Plaza Road & Fairlawn Avenue	Fair Lawn Borough
20	Fair Lawn Borough Board of Education	5-01 Bergen Avenue	Fair Lawn Borough
21	Fair Lawn Self Storage	16-01 McBride Avenue	Fair Lawn Borough
22	Fisher Scientific Company	1 Reagent Avenue	Fair Lawn Borough
23	Getty Service Station Fair Lawn Borough	22-02 Broadway	Fair Lawn Borough
24	Kem Manufacturing Company, Inc.	18-35 River Road	Fair Lawn Borough
25	Parkway Friendly Service, Incorporated	30-09 Broadway	Fair Lawn Borough
26	Sandoz Chemical Corporation	Fair Lawn Avenue & 3rd Street	Fair Lawn Borough
27	Sandvik, Incorporated	17-02 Nevins Road	Fair Lawn Borough
28	Sealed Air Corporation	19-01 Route 208	Fair Lawn Borough
29	State Tire Automotive Discount Center	15-10 River Road	Fair Lawn Borough
30	Steam Leasing Associates	20-21 Wargaraw Road	Fair Lawn Borough
31	Topps Cleaners & Launderers	22-02 Fairlawn Avenue	Fair Lawn Borough
32	TSS Realty, Inc.	24-28 Maple Avenue	Fair Lawn Borough
33	Zero Twenty Four Service Station	40-10 Route 4 East	Fair Lawn Borough
34	64 Highland Road	64 Highland Road	Glen Rock Borough
35	Exxon Service Station Glen Rock Borough	650 Maple Avenue	Glen Rock Borough
36	FSI Company	175 Rock Road	Glen Rock Borough
37	Glen Rock Borough Department of Public Works	473 Doremus Avenue	Glen Rock Borough
38	Glen Rock Park	Allen Street	Glen Rock Borough
39	Hess Service Station Glen Rock Borough	390 Maple Avenue	Glen Rock Borough
40	Manhattan Industries	25 deBoer Drive	Glen Rock Borough
41	Ridgewood Police Firing Range	561 Prospect Street	Glen Rock Borough
42	Saddle River County Park	Prospect Avenue	Glen Rock Borough
43	Texaco Service Station Glen Rock Borough	531 Prospect Street	Glen Rock Borough

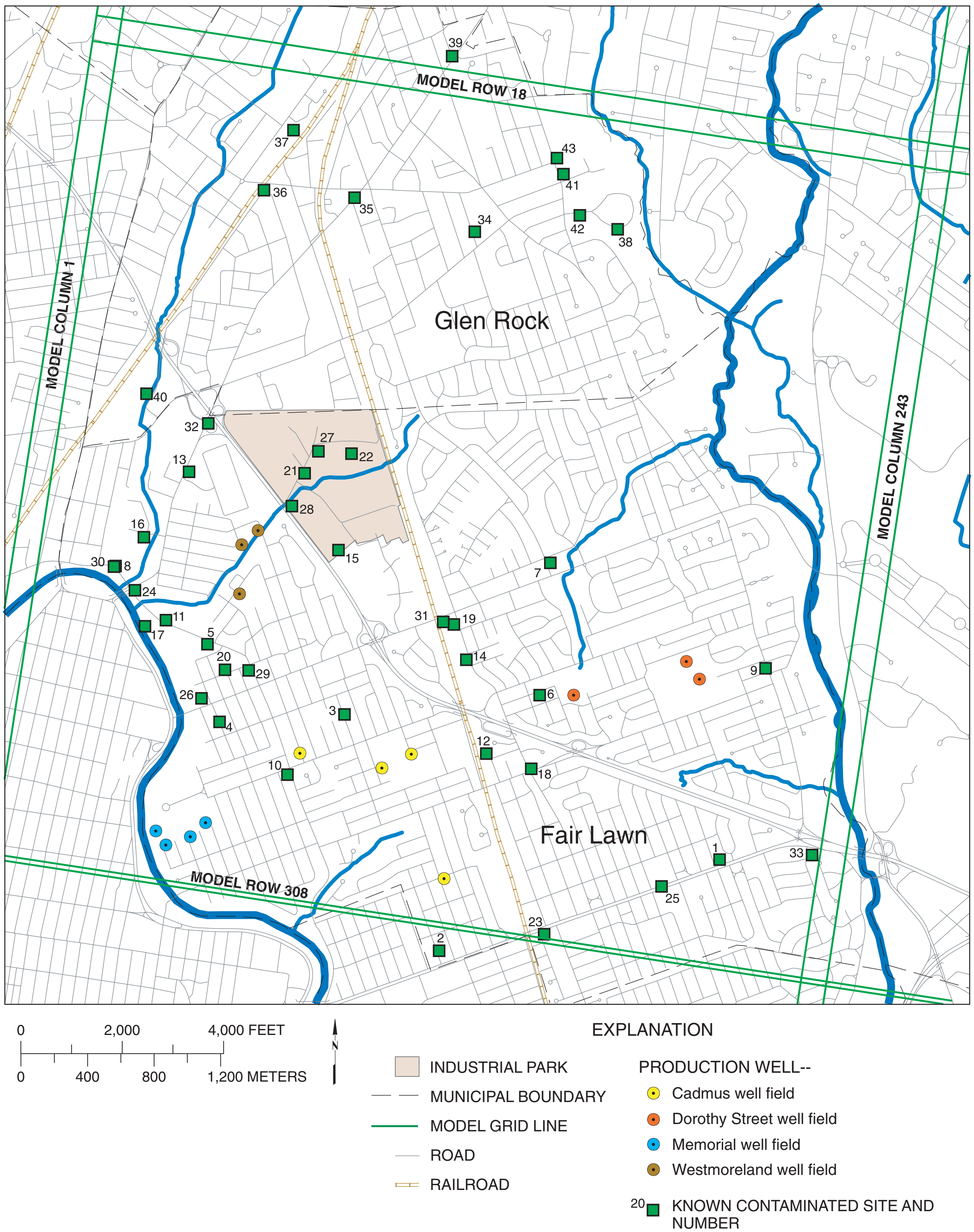


Figure 24. Location of known contaminated sites, Fair Lawn and Glen Rock, New Jersey. (Model grid shown in figure 16; contaminated sites from N.J. Department of Environmental Protection, 2001)

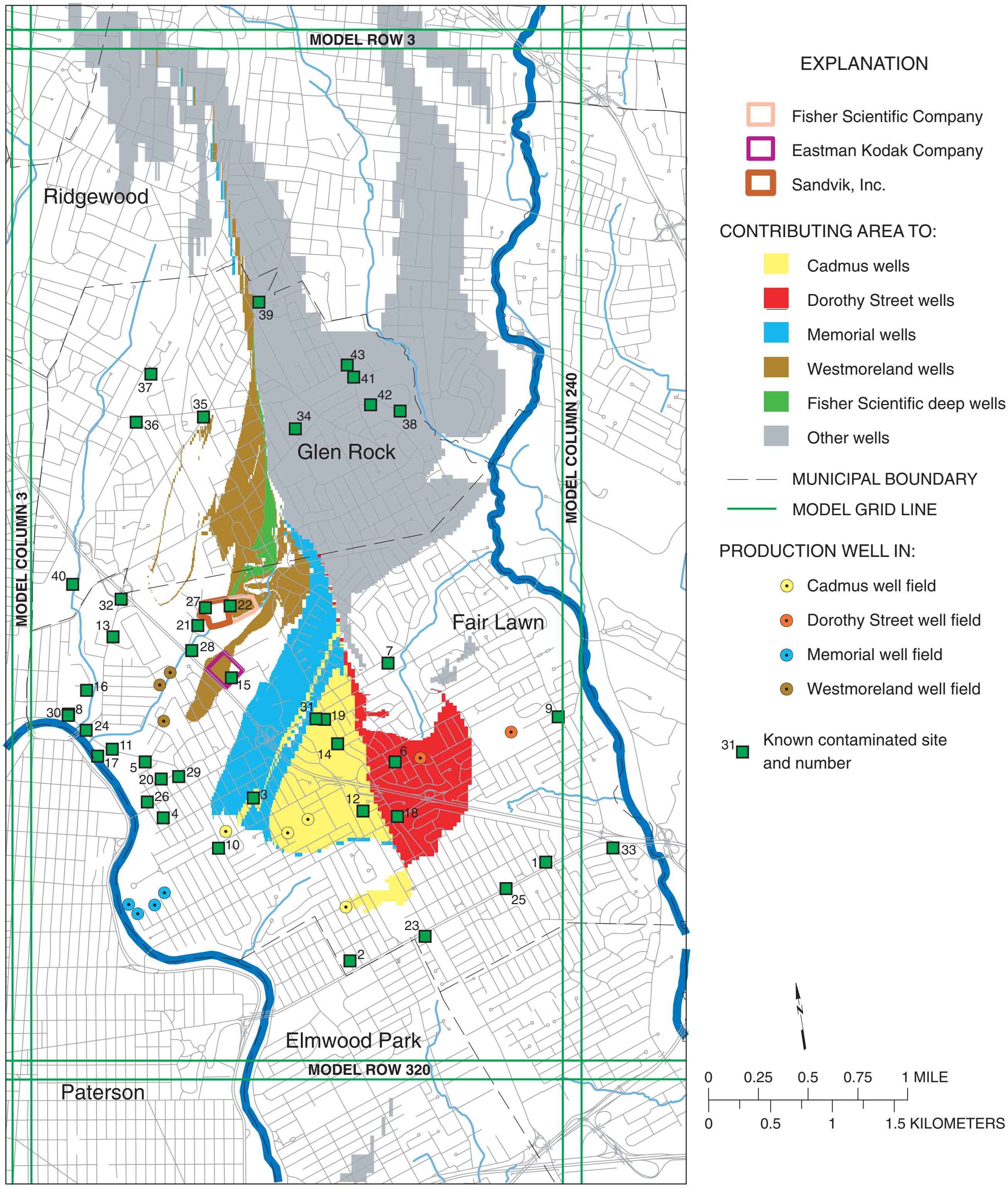


Figure 25. Simulated contributing areas to wells in and near Fair Lawn, New Jersey, for 1991 conditions. (Model grid shown in figure 16; contaminated sites from N.J. Department of Environmental Protection, 2001)

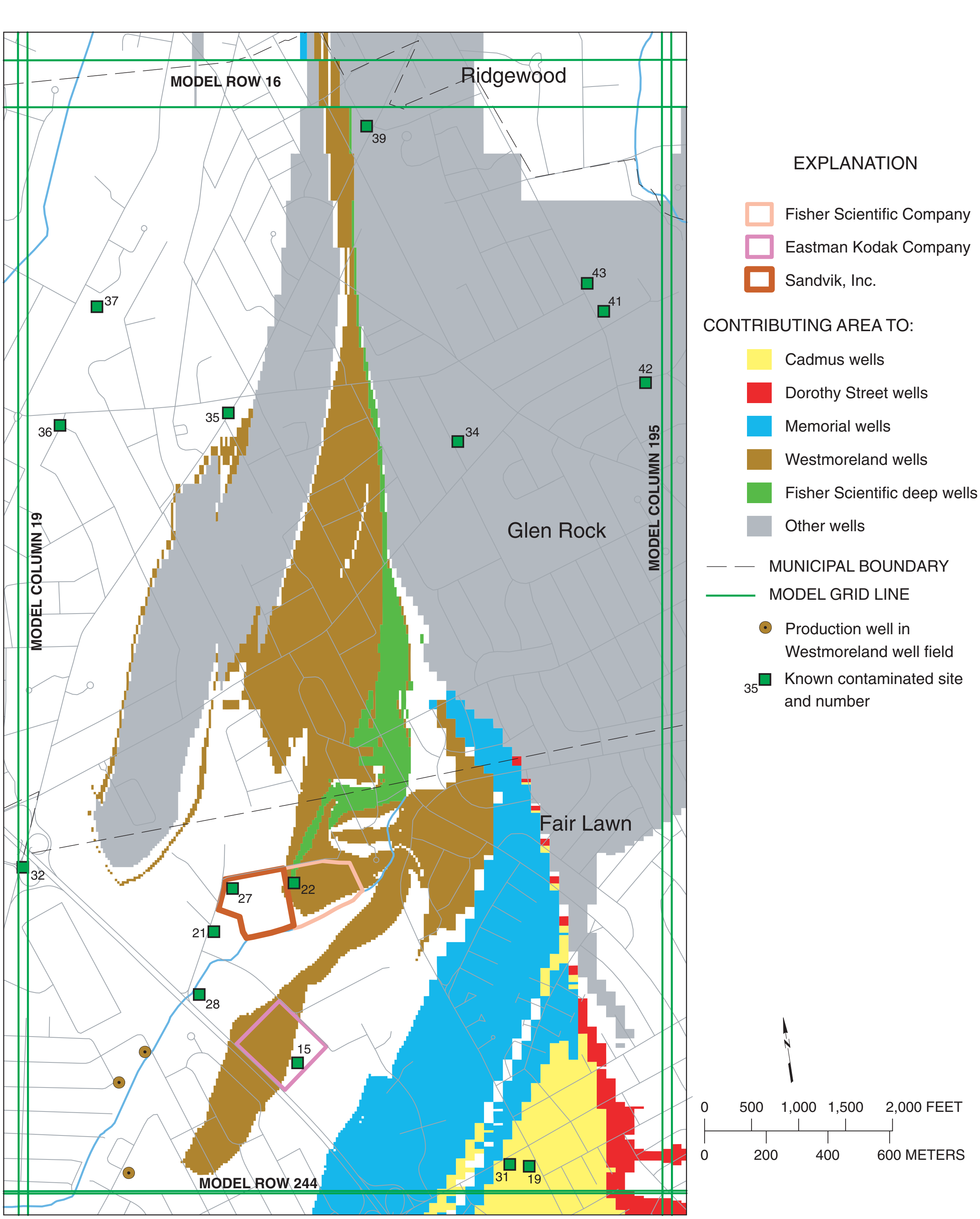


Figure 26. Simulated contributing areas to production wells in the Westmoreland well field and other wells in and near Fair Lawn, New Jersey, for 1991 conditions. (Model grid shown in figure 16; contaminated sites from N.J. Department of Environmental Protection, 2001)

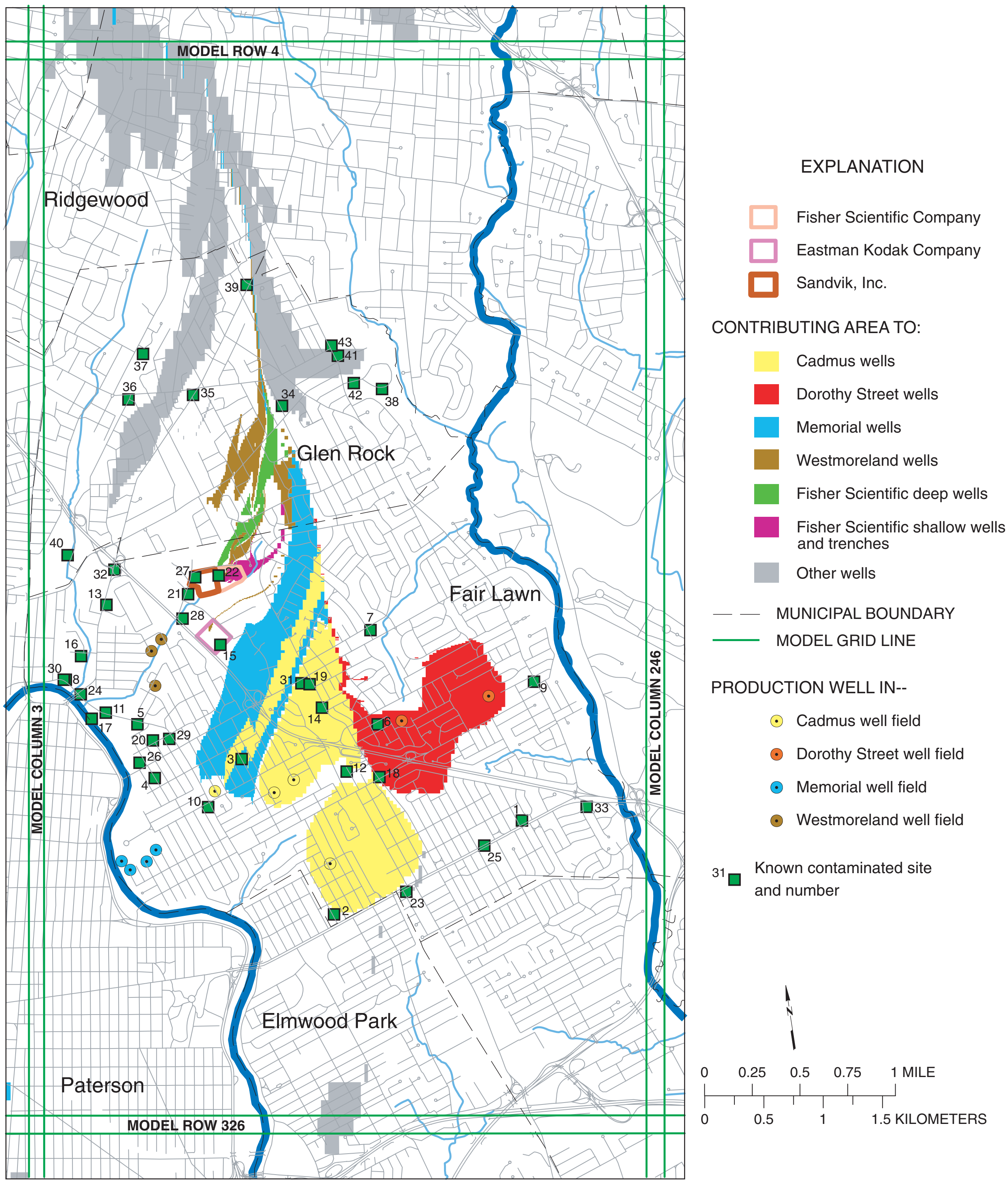


Figure 27. Simulated contributing areas to wells in and near Fair Lawn, New Jersey, for 2000 conditions. (Model grid shown in figure 16; contaminated sites from N.J. Department of Environmental Protection, 2001)

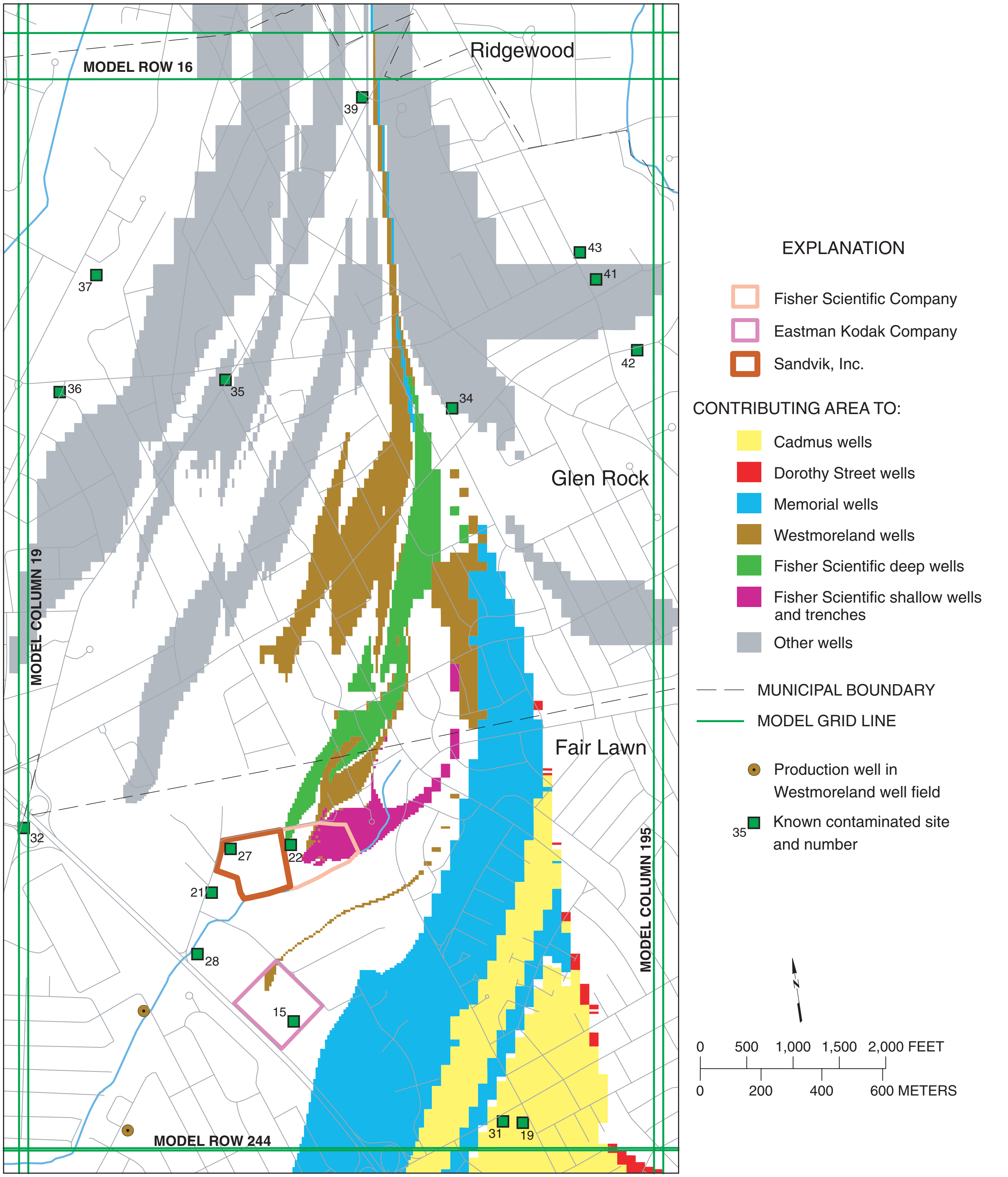


Figure 28. Simulated contributing areas to production wells in the Westmoreland well field and other wells in and near Fair Lawn, New Jersey, for 2000 conditions. (Model grid shown in figure 16; contaminated sites from N.J. Department of Environmental Protection, 2001)

In 2000, the contributing area to the Memorial well field was nearly identical to the area in 1991, probably because pumpage had changed only minimally (from about 351 Mgal in 1991 to 332 Mgal in 2000).

The contributing area to the Cadmus wells was larger in 2000 than in 1991 and added an area of about 0.3 mi^2 around well FL8. This additional area reflects the increase in pumpage from 17 Mgal in 1991 to 108 Mgal in 2000. The 2000 contributing area to all of the Cadmus wells included or was less than 300 ft from eight known contaminated sites (1-38 Cyril Avenue; 12-59 12th Street; Borden Chemical Printing Ink Division; Cole Engineering, Inc.; two Exxon service stations; a Getty service station; and Topps Cleaners and Launderers (table 32)).

The configuration of the contributing area to the Dorothy Street wells changed substantially from 1991 to 2000 because of changes in the distribution in pumpage among the three wells. The 2000 contributing area includes two known contaminated sites, 20-11 Kipp Street and an Exxon service station (table 32).

High-Recharge Scenario

In the high-recharge scenario, the simulated contributing area to each well field is smaller than the contributing area in the 2000 scenario because the higher recharge rates enable wells to draw the same amount of water from smaller areas. The contributing areas to Fair Lawn Water Department well fields in the high-recharge scenario are shown in figure 29; the contributing area to the Westmoreland well field is shown in more detail in figure 30. The contributing area to the Westmoreland well field is small; none of the Fisher or Sandvik property and only a small part of the Kodak property is included in the contributing area (fig. 30). The contributing areas to other well fields all are similar to but smaller than the contributing areas in the 2000 scenario.

Simulated Contaminant Plumes

A simulated contaminant plume is defined as the three-dimensional area containing flowpaths from a contaminated source area to their point of discharge at a stream or a pumped well. As previously noted, because only advective flow is simulated with the model, the effects of density, dispersion, diffusion, dilution, and degradation of contaminants are not accounted for in the plumes. Plumes were tracked from the three industrial sites (Fisher, Sandvik, and Kodak).

The starting area of each plume was determined from water-quality data from the three sites. Paths were started in all model cells that represent areas known to be contaminated at each site. One starting particle was placed at the center of each model cell in the starting area. Although ground water in the starting area of each plume is known to contain VOCs, it is not known whether VOCs are present along the entire path of the plumes, except at points where the plumes pass through wells known to be contaminated with VOCs.

Monitor wells are located over nearly all of the Fisher property except the southeastern part, and water samples from all of them have contained VOCs at concentrations in excess of drinking-water standards at some time in the past 2 decades (Jacqueline Bobko, N.J. Department of Environmental Protection, written commun., 2004). The wells are 16 to 125 ft deep. Some are screened in the overburden (model layer 1); others are screened in or open to the bedrock (model layers 15, 16, 17, and 18). The starting points of the contaminant plume from Fisher encompass nearly all of the company’s property in the overburden and the upper part of the bedrock (model layers 1, 15, 16, 17, and 18).

Far fewer monitor wells are located at the Sandvik property than at the Fisher property. Eleven monitor wells encompass about the southeastern two-thirds of the property, and water samples from all of them have contained VOCs at concentrations higher than drinking-water standards at some time in the past 2 decades (James DeNoble, N.J. Department of Environmental Protection, written commun., 2004). These wells are from 40 to 104 ft deep and are screened in or open to bedrock layers 14 through 17. No monitor wells are present in the overburden at Sandvik; however, soil samples from the site were found to contain VOCs (Metcalf & Eddy, Inc., 1994). The starting points of the contaminant plume from Sandvik encompass the southeastern two-thirds of the company’s property in model layers 1, 14, 15, 16, and 17.

Eleven monitor wells are distributed over the Kodak property. All 11 are described as being open to shallow bedrock (Quest Environmental and Engineering Services, Inc., 2002). Water samples were collected from nine of the wells in 1997, and samples from eight of them contained VOCs at concentrations in excess of drinking-water standards (Jamie MacBlane, N.J. Department of Environmental Protection, written commun., 2004). The starting points of the contaminant plume from Kodak encompass the half of the property known to contain contaminated ground water in the shallow bedrock (model layers 14, 15, 16, and 17). Although VOCs have been detected in the soil at Kodak, no particles were started in the overburden (model layer 1) because simulation results indicate that the overburden at Kodak is unsaturated.

Map and section views of the plumes from the three industrial sites were generated for the 1991 and 2000 scenarios and are presented below. The map views show actual computed pathlines of water, but the section views are generalized, showing a two-dimensional representation of the area containing the same pathlines along a representative plane through the plume.

The volumes of water originating at or passing through each of the three industrial sites and discharging to each discharge point (stream or well) also are presented below. These volumes were computed using two USGS computer programs. The discharge point of water starting in each model cell representing a contaminated point at each site was determined using MODPATH (Pollock, 1994). After the starting model cells were grouped by discharge point, ZONEBUDGET (Harbaugh, 1990) was used to compute and compile the volume of water leaving each group of model cells.

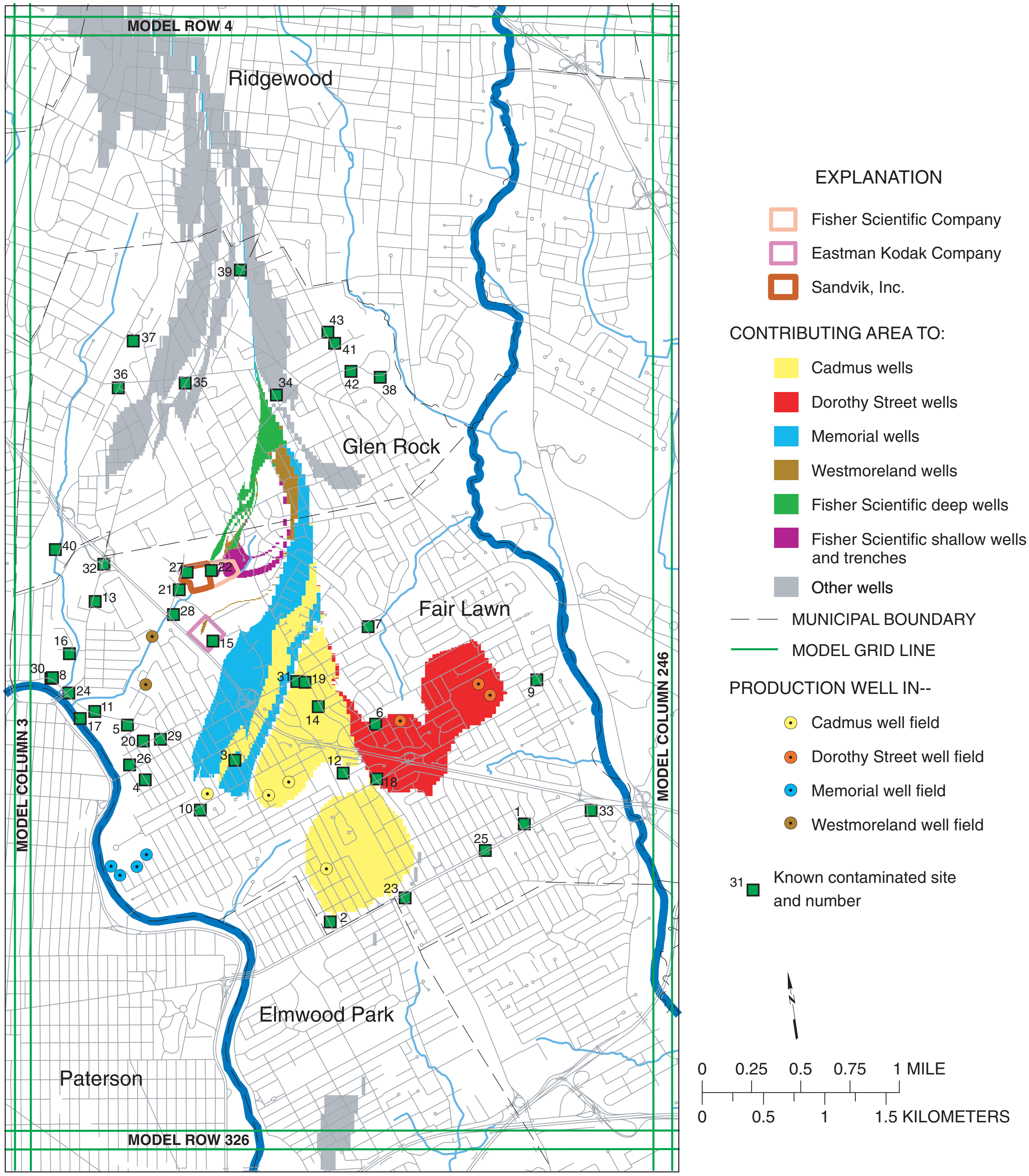


Figure 29. Simulated contributing areas to wells in and near Fair Lawn, New Jersey, for the high-recharge scenario for 2000 conditions. (Model grid shown in figure 16; contaminated sites from N.J. Department of Environmental Protection, 2001)

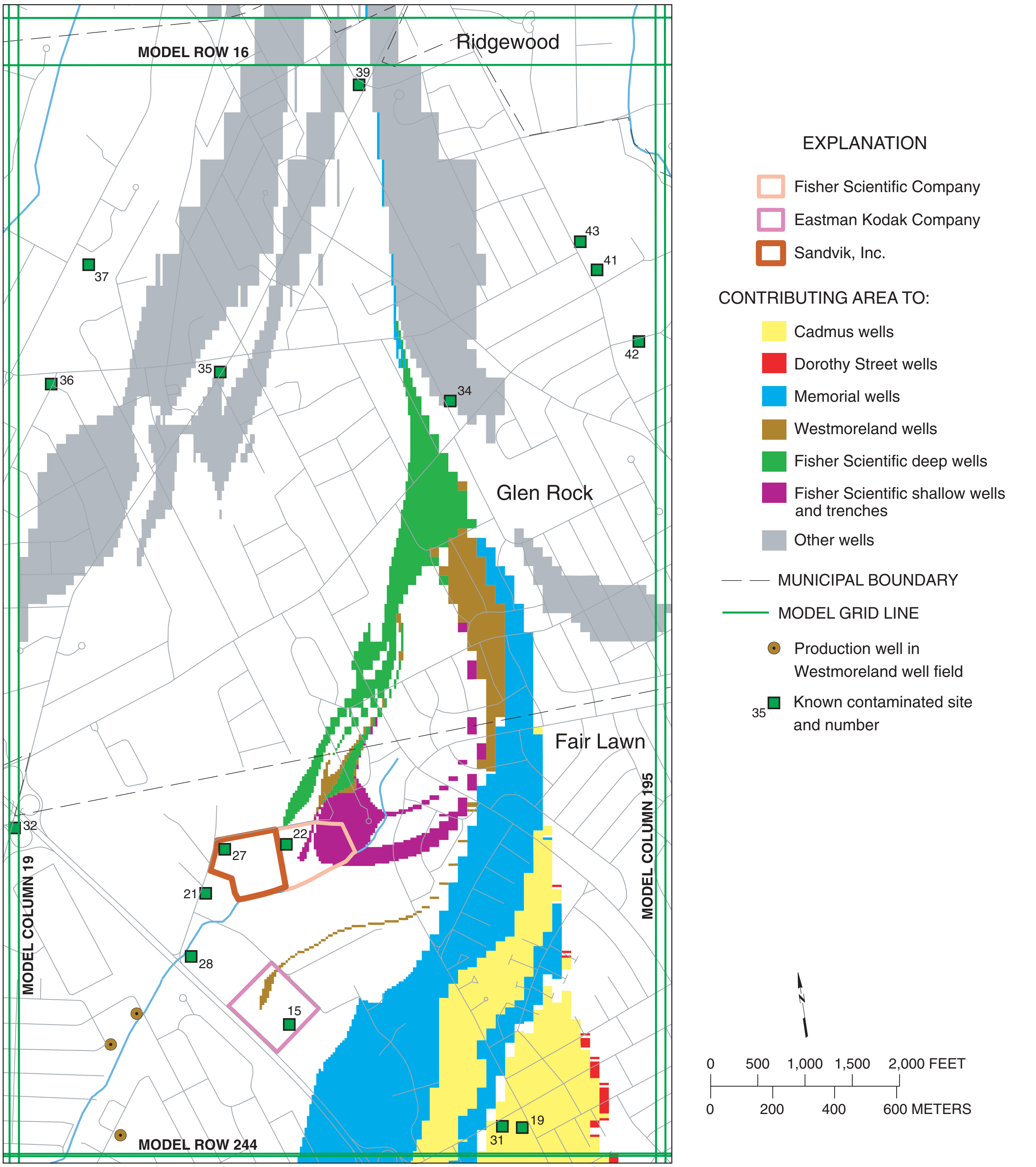


Figure 30. Simulated contributing areas to production wells in the Westmoreland well field and other wells in and near Fair Lawn, New Jersey, for the high-recharge scenario for 2000 conditions. (Model grid shown in figure 16; contaminated sites from N.J. Department of Environmental Protection, 2001)

1991 Scenario

The simulated plumes from the three industrial sites in the 1991 scenario are described below. These plumes represent conditions during a year when 130 Mgal of water was pumped from the Westmoreland well field and the shallow recovery system at Fisher was not yet operating.

Fisher Scientific Company

The simulated plume from the overburden at Fisher in 1991 is shown in figures 31 and 32; the plume from the bedrock is shown in figures 33 and 34. The plume extends from Fisher generally southwest to the Westmoreland well field, Henderson Brook, and the Passaic River. Part of the plume passes through the southeastern part of the Sandvik property and the northwestern corner of the Kodak property (figs. 31 and 33). Part of the plume originating in the overburden flows through bedrock water-bearing units 2, 3, and 4 and reaches a maximum depth of about 200 ft below land surface (fig. 32). The plume from the bedrock flows through bedrock water-bearing units 1 through 5 and reaches a maximum depth of about 260 ft below land surface (fig. 34).

In the 1991 scenario, Westmoreland well FL14 captured 94 percent of the water from the overburden and 31 percent of the water from the bedrock at Fisher. Well FL11, also in the Westmoreland well field, captured 16 percent of the water from the bedrock. Water originating at or passing through the Fisher overburden contributed 11 percent of the water pumped by well FL14, whereas water from the bedrock contributed 20 percent of the water pumped by well FL14 and 14 percent of the water pumped by well FL11 (table 33). The plume from the bedrock at Fisher does not reach well FL10, but it does pass within 150 ft of it. Because the plume does not include the effects of diffusion or dispersion, the possibility that some of the water from the Fisher property discharged to well FL10 in 1991 cannot be ruled out.

In 1991, the deep recovery wells at Fisher (PW2, PW4, and PW5) captured 3 percent of the water originating in or passing through the overburden and 49 percent of the water from the bedrock at Fisher (table 33). In 1991, 3 percent of the water from the overburden and 4 percent of the water from the bedrock at Fisher was not captured by any well; rather, it discharged to Henderson Brook (table 33).

Sandvik, Inc.

The simulated plume from the overburden at Sandvik in 1991 is shown in figures 35 and 36; the plume from the bedrock is shown in figures 37 and 38. The plume extends generally southwest to the Westmoreland well field, Henderson Brook, and the Passaic River (figs. 35 and 37). Part of the plume originating in the overburden flows into bedrock water-bearing units 2, 3, and 4 and reaches a maximum depth of about 110 ft below land surface (fig. 36). The plume from the bedrock flows through bedrock water-bearing units 1 through 5 and reaches a maximum depth of about 200 ft below land surface (fig. 38).

In the 1991 scenario, Westmoreland well FL14 captured 3 percent of the water from the overburden and 24 percent of the water from the bedrock at Sandvik. Westmoreland well FL10 captured 27 percent of the water from the bedrock and well FL11 captured 42 percent. Water originating at or passing through the Sandvik overburden contributed less than 1 percent of the water pumped by wells in the Westmoreland well field. Water from the Sandvik bedrock contributed 24 percent of the water pumped by well FL10, 38 percent of the water pumped by well FL11, and 16 percent of the water pumped by well FL14 (table 33).

In the 1991 scenario, 97 percent of the water from the overburden and 7 percent of the water from the bedrock at Sandvik was not captured by any well; rather, the water discharged to Henderson Brook (table 33).

Eastman Kodak Company

The simulated plume from the bedrock at Kodak in 1991 is shown in map view in figure 39 and in section view in figure 40. (A plume from the overburden was not simulated because the model simulations indicate that the overburden at Kodak is unsaturated.) The plume extends from Kodak generally southwest to the Westmoreland well field, Henderson Brook, and the Passaic River (fig. 39). The plume flows through bedrock water-bearing units 1 through 5 and reaches a maximum depth of about 260 ft below land surface (fig. 40).

In the 1991 scenario, well FL14 in the Westmoreland well field captured 73 percent of the water from the bedrock at Kodak. None of the water from Kodak was captured by well FL10 or FL11 in the same well field. Water from the bedrock at Kodak contributed 49 percent of the water pumped from well FL14 (table 33). Under 1991 conditions, 26 percent of the water from Kodak was not captured by any well; rather, the water discharged to the Passaic River (table 33).

2000 Scenario

The simulated plumes from the three industrial sites in the 2000 scenario are described below. These plumes represent conditions during a year when 49 Mgal of water was pumped from the Westmoreland well field and the shallow recovery system at Fisher was operating.

Fisher Scientific Company

The simulated plume from the overburden at Fisher in 2000 is shown in figures 41 and 42; the plume from the bedrock is shown figures 43 and 44. The plume extends from Fisher generally southwest to the Westmoreland well field, Henderson Brook, and the Passaic River. Part of the plume from Fisher passes through the southeastern part of the Sandvik property and the northwestern corner of the Kodak property (figs. 41 and 43). Part of the plume originating in the overburden flows in bedrock water-bearing units 1 through 4 and reaches a maximum depth of about 130 ft below land surface (fig. 42). The plume from the bedrock flows through bedrock water-bearing units 1 through 5 and reaches a maximum depth of about 260 ft below land surface (fig. 44).

In the 2000 scenario, Westmoreland well FL14 captured 6 percent of the water from the overburden and 34 percent of the water from the bedrock at Fisher (table 34). Although the plume from the bedrock at Fisher does not reach Westmoreland well FL10, it does pass within 300 ft of it. Because the plume does not include the effects of diffusion or dispersion, the possibility that well FL10 captured some of the water from the bedrock at Fisher in 2000 cannot be ruled out. Westmoreland well FL11 was not pumped in 2000. Water originating at or passing through the Fisher overburden contributed only 1 percent of the water pumped from well FL14, whereas water originating in or passing through the Fisher bedrock contributed 45 percent of the water pumped from well FL14 (table 34).

In 2000, the shallow recovery system at Fisher, consisting of seven wells and two trenches, captured 55 percent of the water originating in or passing through the overburden at Fisher. This system had begun operating in 1998. The deep recovery wells at Fisher (PW2, PW4, and PW5) captured 4 percent of the water from the overburden and 58 percent of the water from the bedrock at Fisher (table 34).

In 2000, 35 percent of the water from the overburden and 9 percent of the water from the bedrock at Fisher was not captured by any well; rather, it discharged to Henderson Brook and the Passaic River (table 34).

Sandvik, Inc.

The simulated plume from the overburden at Sandvik in 2000 is shown in figures 45 and 46; the plume from the bedrock is shown in figures 47 and 48. The plume from the overburden is nearly entirely contained on the Sandvik property (fig. 45); the plume from the bedrock extends from Sandvik generally southwest to the Westmoreland well field, Henderson Brook, and the Passaic River (fig. 47). Part of the plume from the overburden flows downward into bedrock water-bearing units 2, 3, and 4 and reaches a maximum depth of about 100 ft below land surface before flowing back up into the overburden and into Henderson Brook (fig. 46). The plume originating in the bedrock flows through bedrock water-bearing units 1 through 5 and reaches a maximum depth of about 260 ft below land surface (fig. 48).

In 2000, none of the water originating in or passing through the overburden at Sandvik was captured by any well; all of the water discharged to Henderson Brook, and most of that water discharged in the reach of the brook on the Sandvik property (fig. 45). Of the water originating in or passing through the bedrock at Sandvik, 54 percent discharged to Henderson Brook and 20 percent discharged to the Passaic River (table 34).

In 2000, Westmoreland well FL10 captured 3 percent of the water from the bedrock at Sandvik; well FL14 captured 20 percent. (Westmoreland well FL11 was not pumped in 2000.) Water originating at or passing through the Sandvik bedrock contributed 15 percent of the water pumped from wells in the Westmoreland well field (table 34).

Eastman Kodak Company

The simulated plume from the bedrock at Kodak in 2000 is shown in map view in figure 49 and in section view in figure 50. (A plume from the overburden was not simulated because the model simulations indicate that the overburden at Kodak is unsaturated.) The plume extends from Kodak generally to the southwest to the Westmoreland well field, Henderson Brook, and the Passaic River (fig. 49). The plume flows through bedrock water-bearing units 1 through 5 and reaches a maximum depth of about 260 ft below land surface (fig. 50).

In 2000, Westmoreland well FL14 captured 9 percent of the water from the bedrock at Kodak. None of the water from Kodak was captured by Westmoreland well FL10; Westmoreland well FL11 was not pumped in 2000. Water from the bedrock at Kodak contributed 12 percent of the water pumped from well FL14 (table 34). In 2000, 91 percent of the water from Kodak was not captured by any well; rather, the water discharged to the Passaic River and Henderson Brook (table 34).

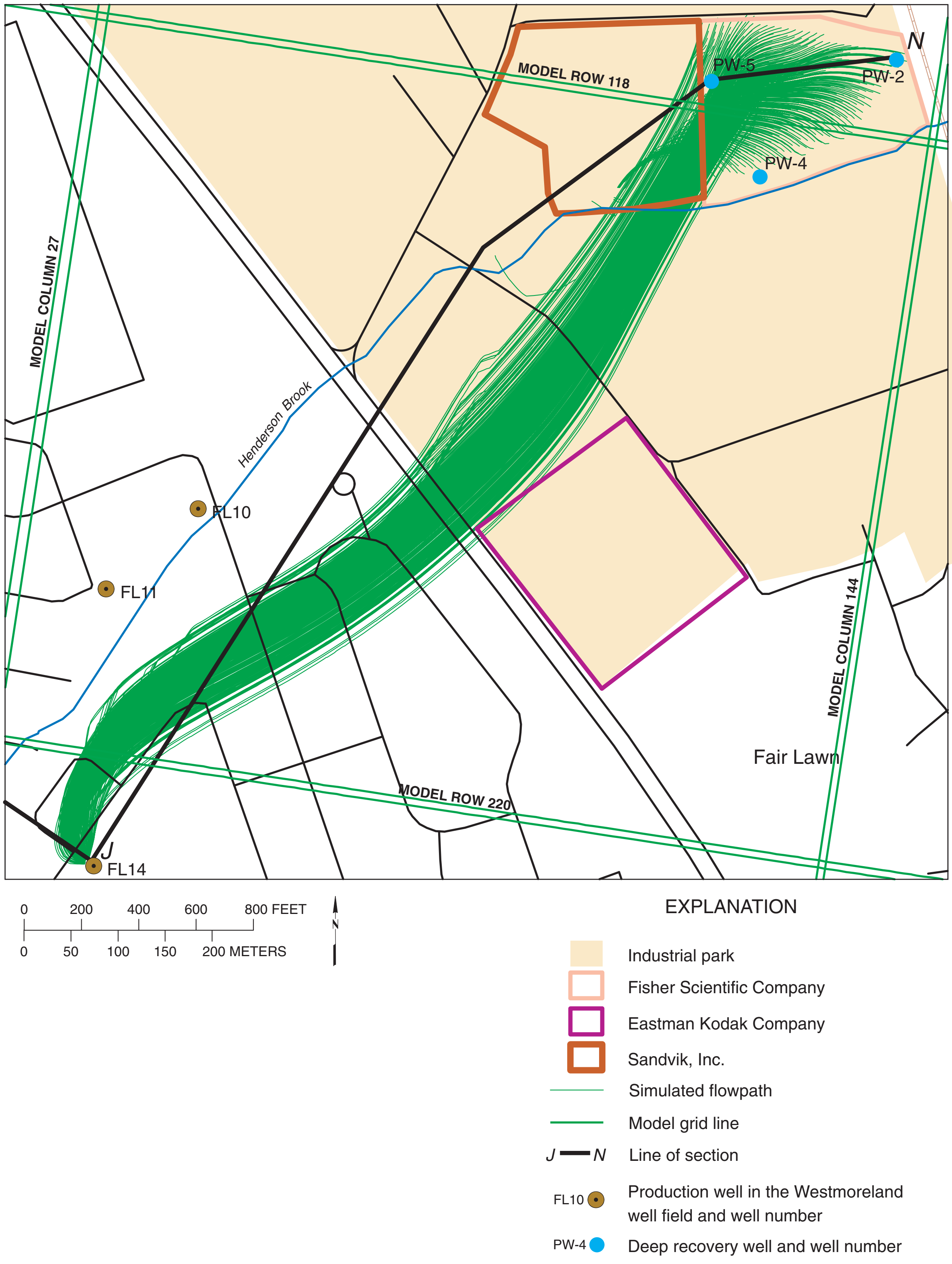


Figure 31. Map view of simulated plume of ground water originating in the overburden at Fisher Scientific Company for 1991 conditions, and line of section, Fair Lawn, New Jersey. (Model grid shown in figure 16)

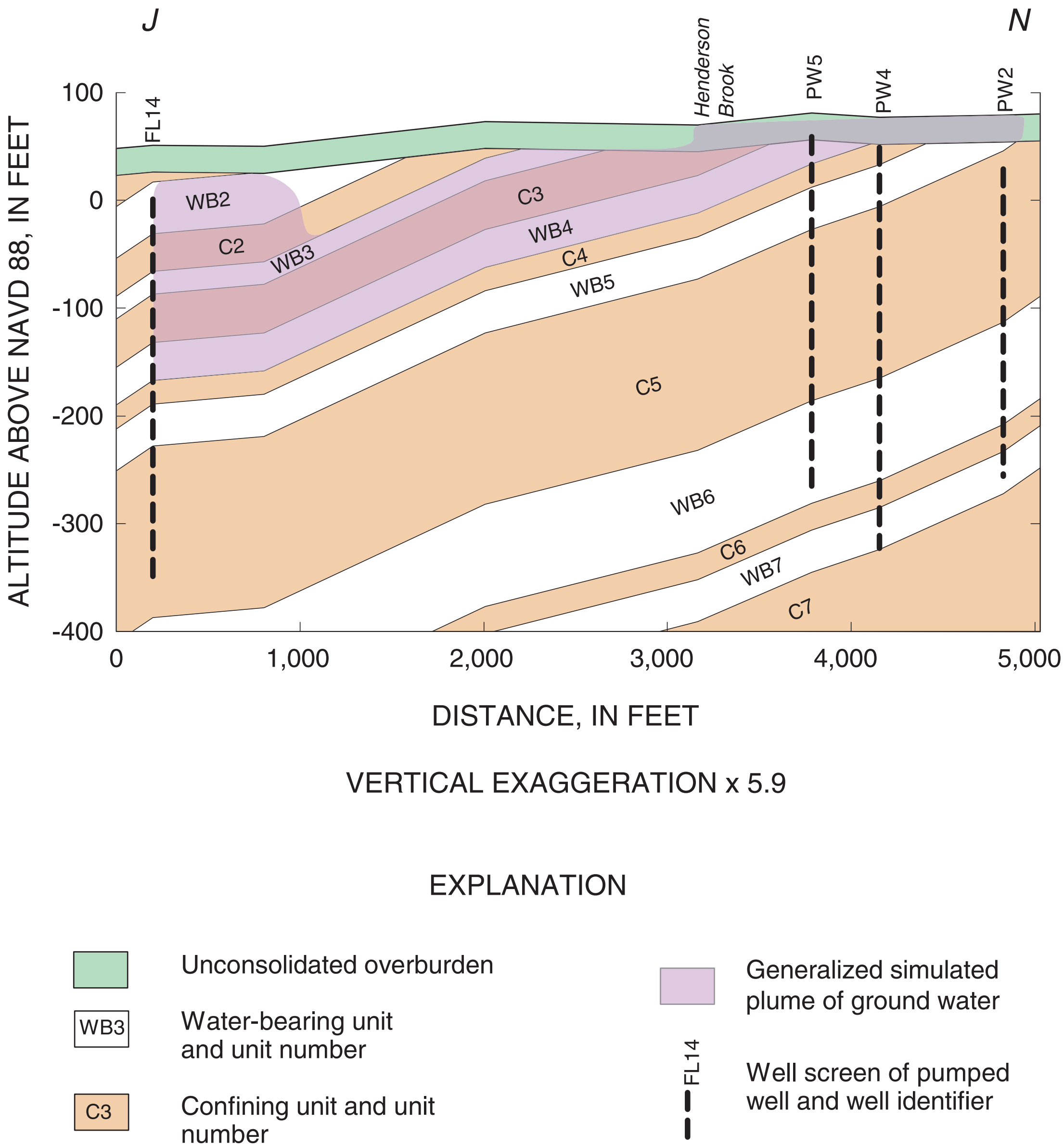


Figure 32. Generalized view along section J-N of simulated plume of ground water originating in the overburden at Fisher Scientific Company for 1991 conditions, Fair Lawn, New Jersey. (Line of section shown in figure 31)

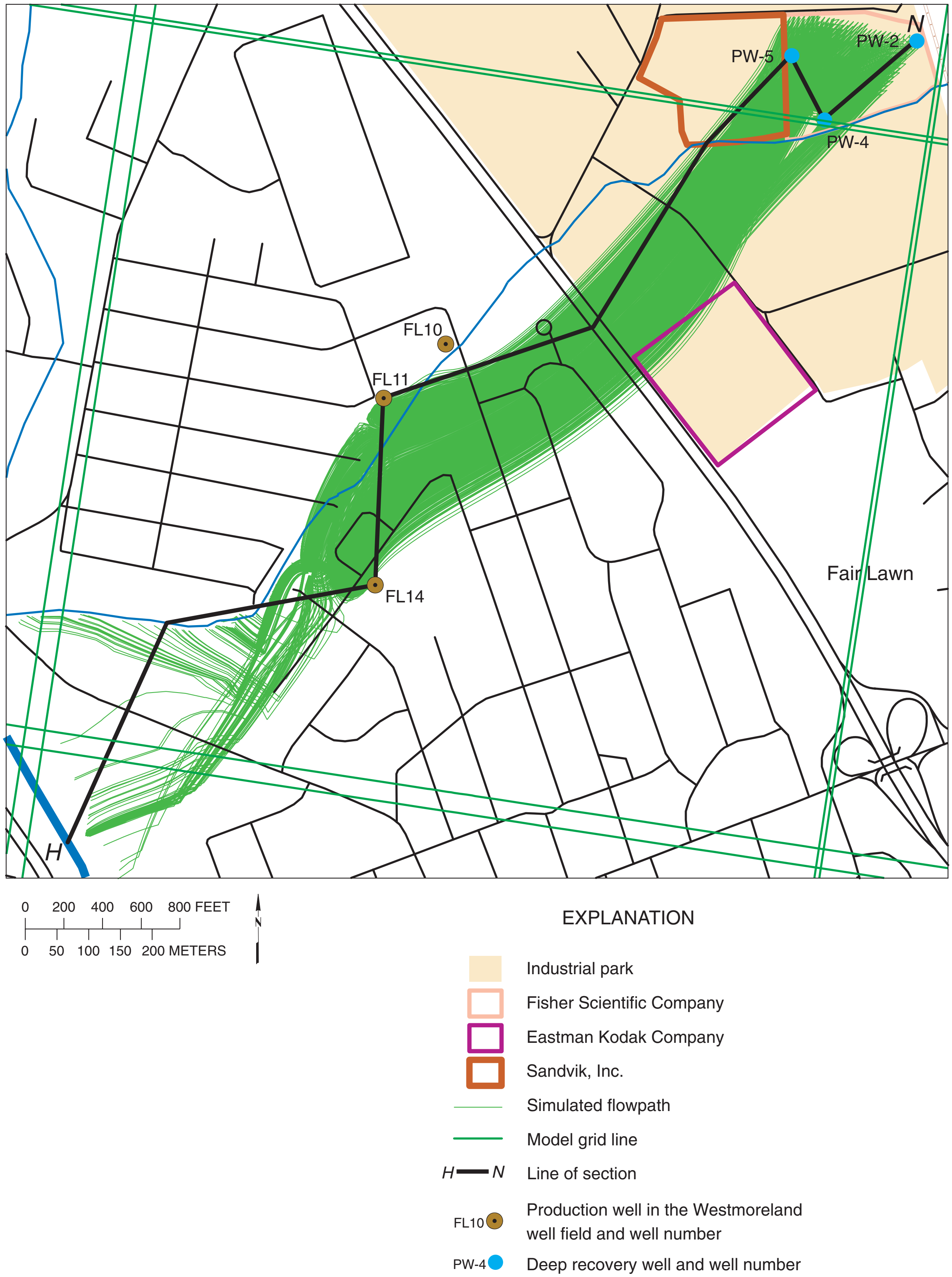


Figure 33. Map view of simulated plume of ground water originating in the bedrock at Fisher Scientific Company for 1991 conditions, and line of section, Fair Lawn, New Jersey. (Model grid shown in figure 16)

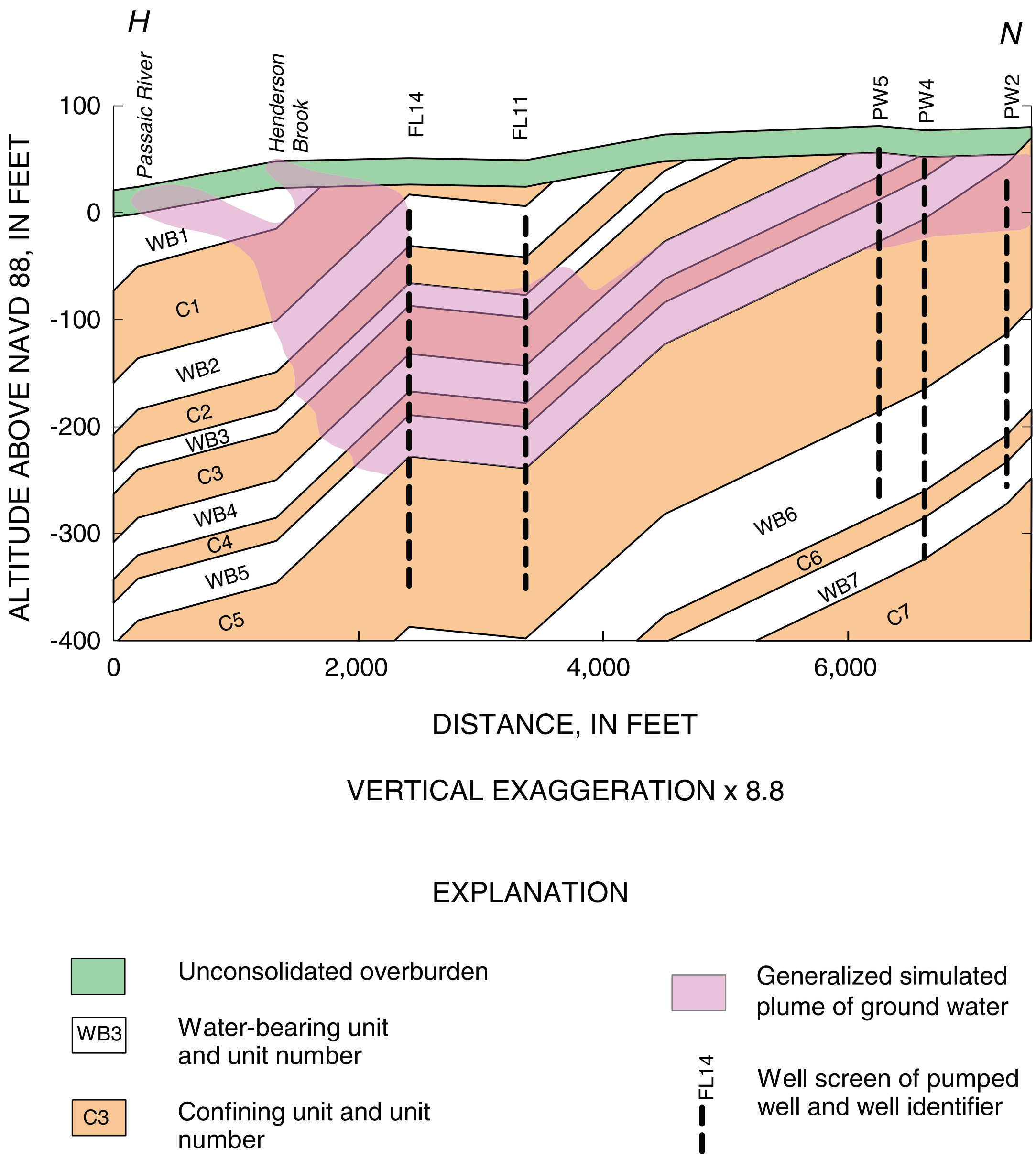


Figure 34. Generalized view along section H-N of simulated plume of ground water originating in the bedrock at Fisher Scientific Company for 1991 conditions, Fair Lawn, New Jersey. (Line of section shown in figure 33)

Table 33. Simulated flux of ground water originating at or passing through Fisher Scientific Company, Sandvik, Inc., and Eastman Kodak Company and discharging to wells and streams, Fair Lawn, New Jersey, 1991.

[All fluxes shown in cubic feet per day; na, not applicable]

Discharge point	Total flux pumped from well	Ground water originating at or passing through Fisher Scientific Company site						Ground water originating at or passing through Sandvik, Inc., site						Ground water originating at or passing through Eastman Kodak Company site		
		From overburden			From bedrock			From overburden			From bedrock			From bedrock		
		Flux	Percent of total flux from site dischar-ging at well or stream	Percent of total pumpage from well origin-ating at or passing through site	Flux	Percent of total flux from site dischar-ging at well or stream	Percent of total pumpage from well origin-ating at or passing through site	Flux	Percent of total flux from site dischar-ging at well or stream	Percent of total pumpage from well origin-ating at or passing through site	Flux	Percent of total flux from site dischar-ging at well or stream	Percent of total pumpage from well origin-ating at or passing through site	Flux	Percent of total flux from site dischar-ging at well or stream	Percent of total pumpage from well origin-ating at or passing through site
Henderson Brook	na	75	3	na	485	4	na	1,308	97	na	963	7	na	38	0	na
Passaic River	na	0	0	na	59	0	na	0	0	na	3	0	na	3,368	26	na
Well FL10	14,299	0	0	0	0	0	0	0	0	0	3,456	27	24	0	0	0
Well FL11	14,299	0	0	0	1,962	16	14	0	0	0	5,407	42	38	0	0	0
Well FL14	19,066	2,034	94	11	3,779	31	20	46	3	0	3,062	24	16	9,333	73	49
Shallow recovery wells and trenches, Fisher Scientific Company	Not pumped in 1991															
Well PW2	2,694	0	0	0	223	2	8	0	0	0	0	0	0	0	0	0
Well PW4	5,652	0	0	0	1,973	16	35	0	0	0	0	0	0	0	0	0
Well PW5	4,549	61	3	1	3,867	31	85	0	0	0	0	0	0	0	0	0

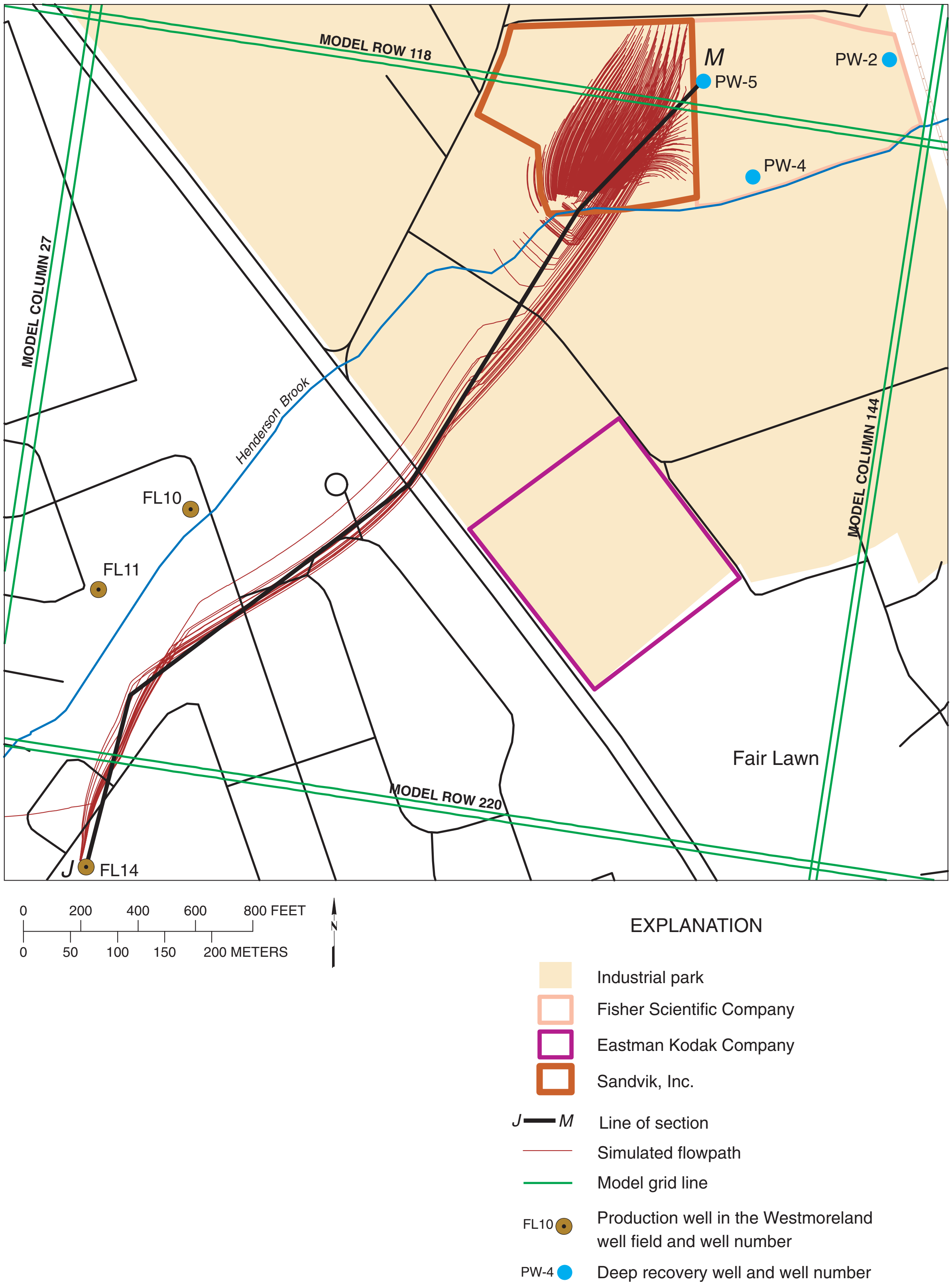


Figure 35. Map view of simulated plume of ground water originating in the overburden at Sandvik, Inc., for 1991 conditions, and line of section, Fair Lawn, New Jersey. (Model grid shown in figure 16)

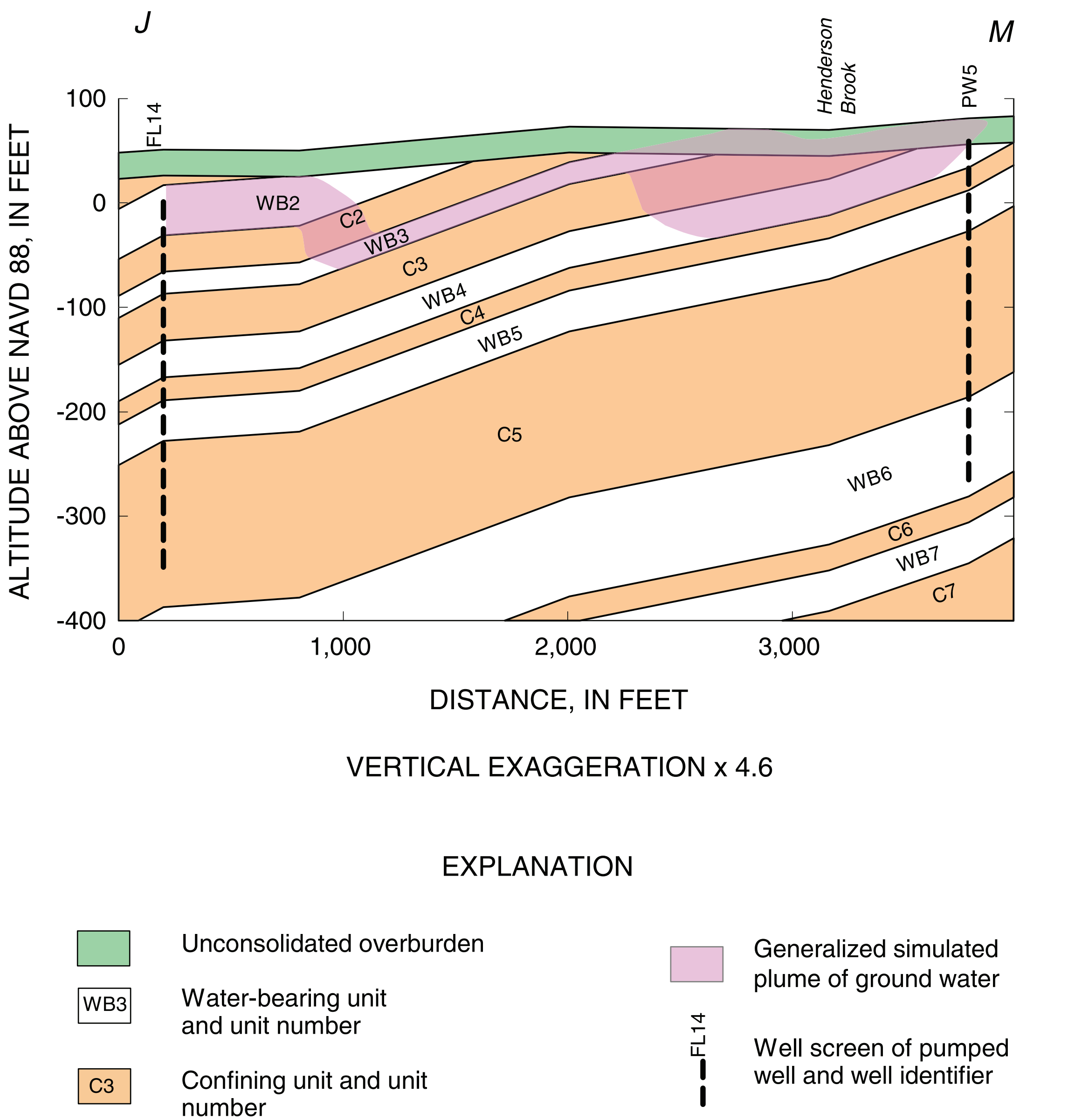


Figure 36. Generalized view along section J-M of simulated plume of ground water originating in the overburden at Sandvik, Inc., for 1991 conditions, Fair Lawn, New Jersey. (Line of section shown in figure 35)

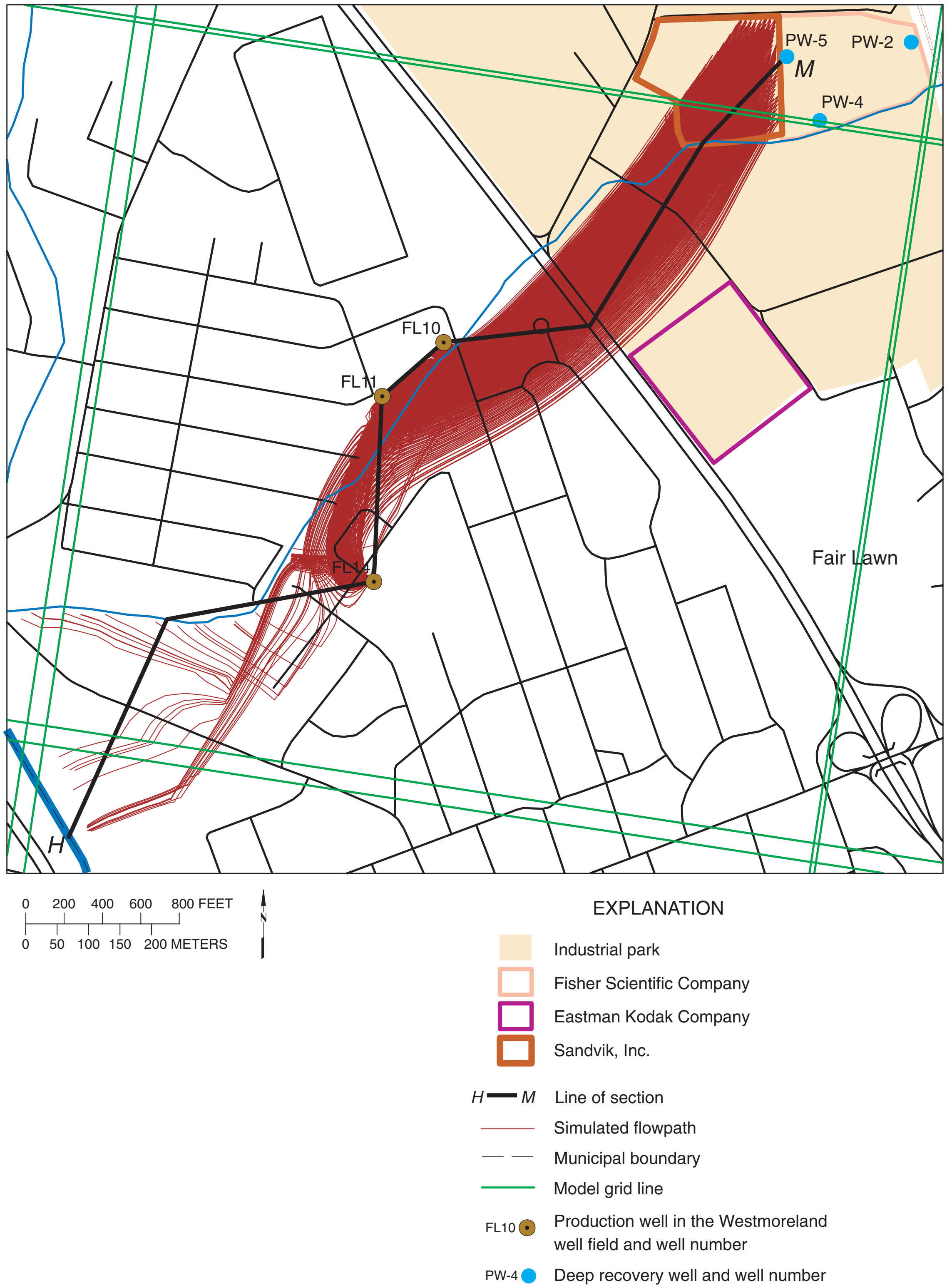


Figure 37. Map view of simulated plume of ground water originating in the bedrock at Sandvik, Inc., for 1991 conditions, and line of section, Fair Lawn, New Jersey. (Model grid shown in figure 16)

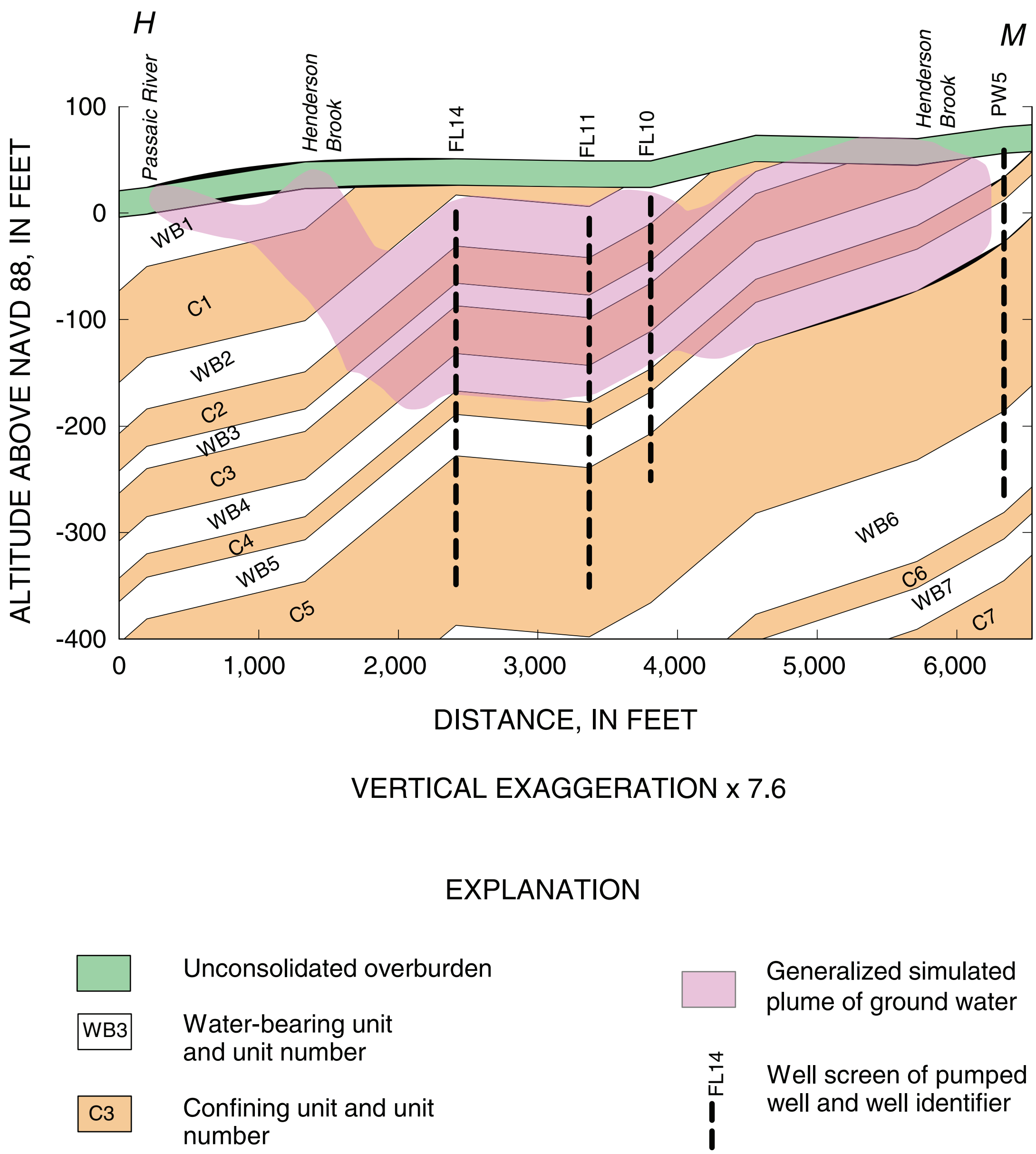


Figure 38. Generalized view along section H-M of simulated plume of ground water originating in the bedrock at Sandvik, Inc., for 1991 conditions, Fair Lawn, New Jersey. (Line of section shown in figure 37)

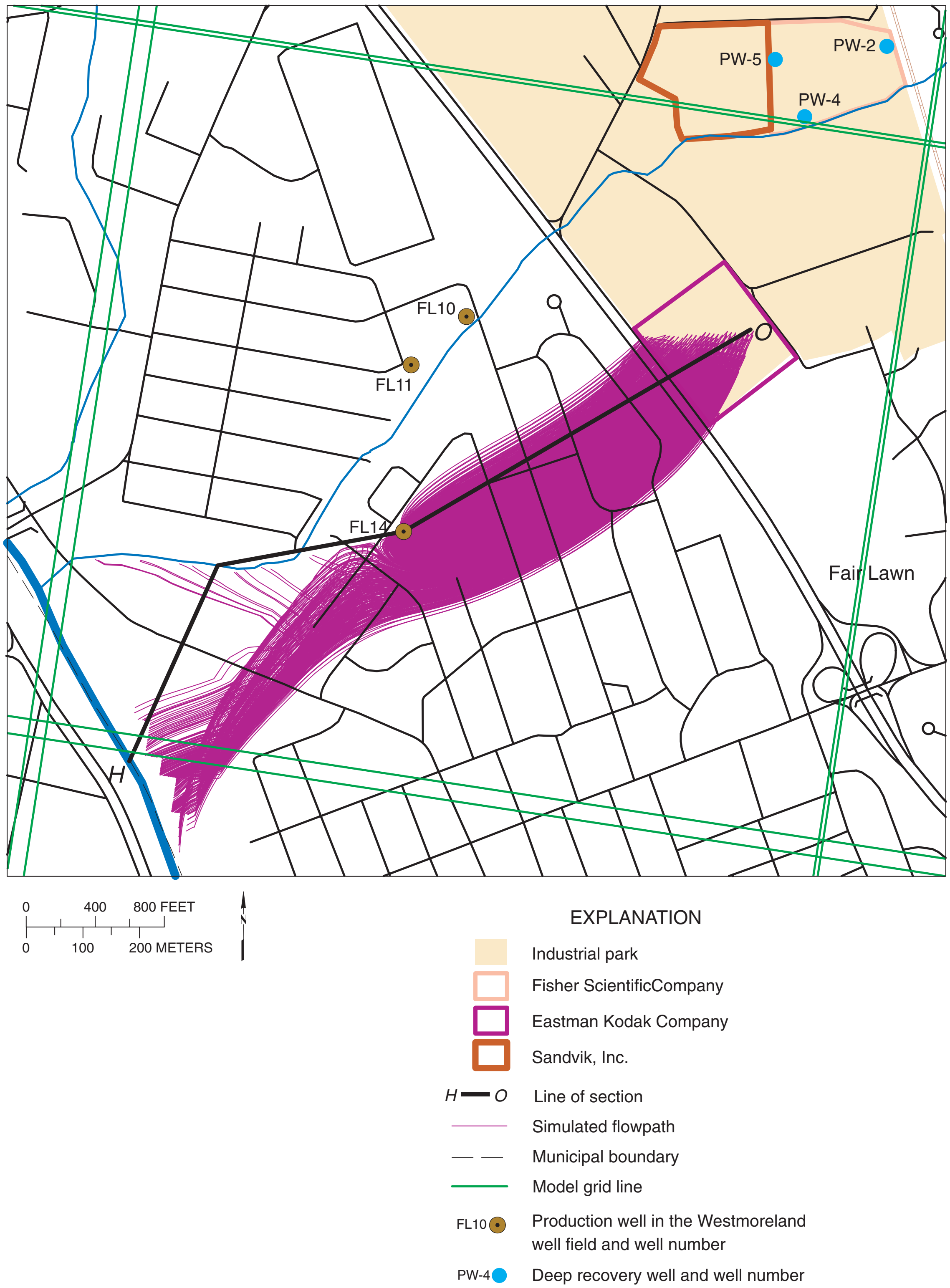


Figure 39. Map view of simulated plume of ground water originating in the bedrock at Eastman Kodak Company for 1991 conditions, and line of section, Fair Lawn, New Jersey. (Model grid shown in figure 16)

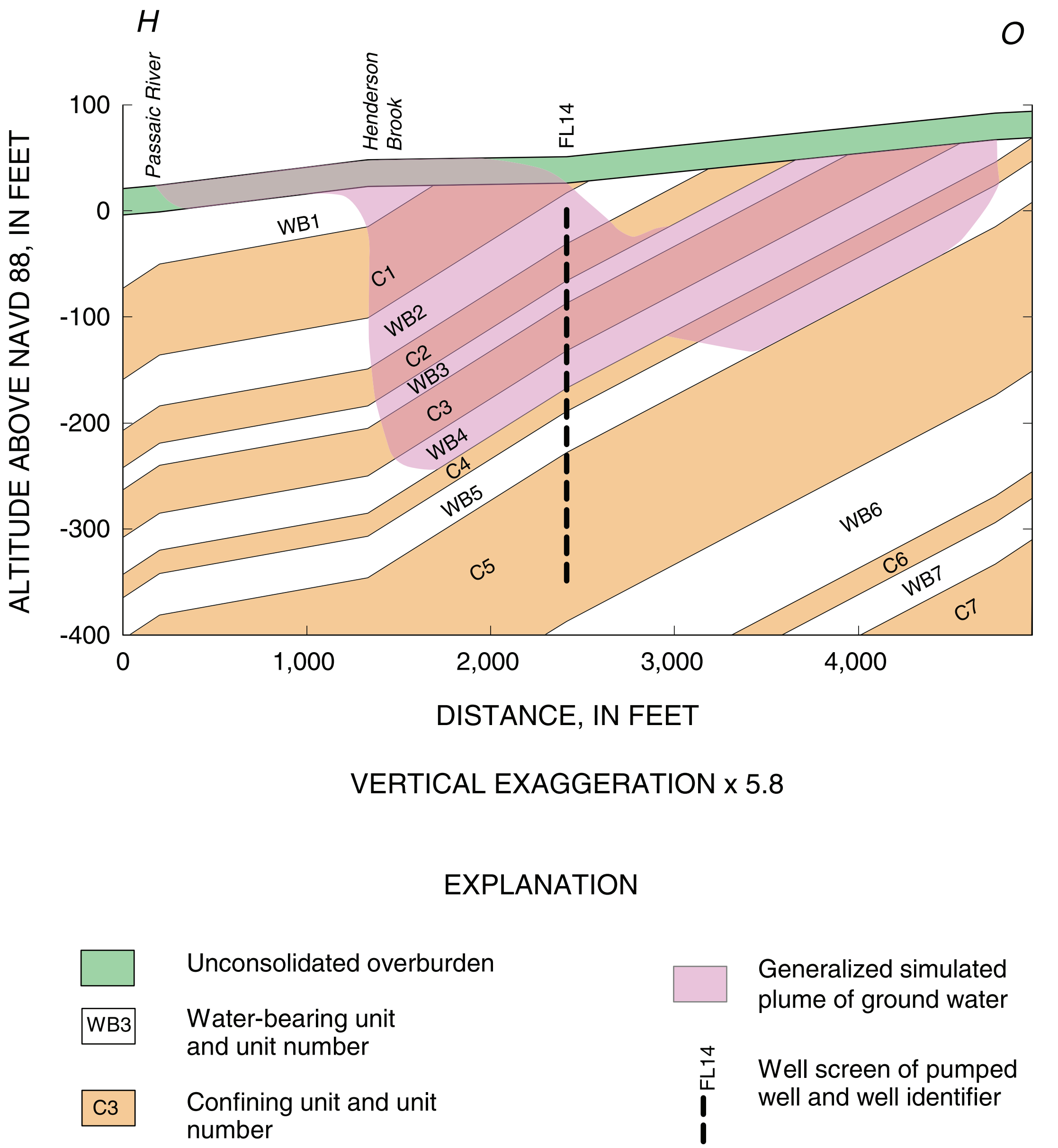


Figure 40. Generalized view along section H-O of simulated plume of ground water originating in the bedrock at Eastman Kodak Company for 1991 conditions, Fair Lawn, New Jersey. (Line of section shown in figure 39)

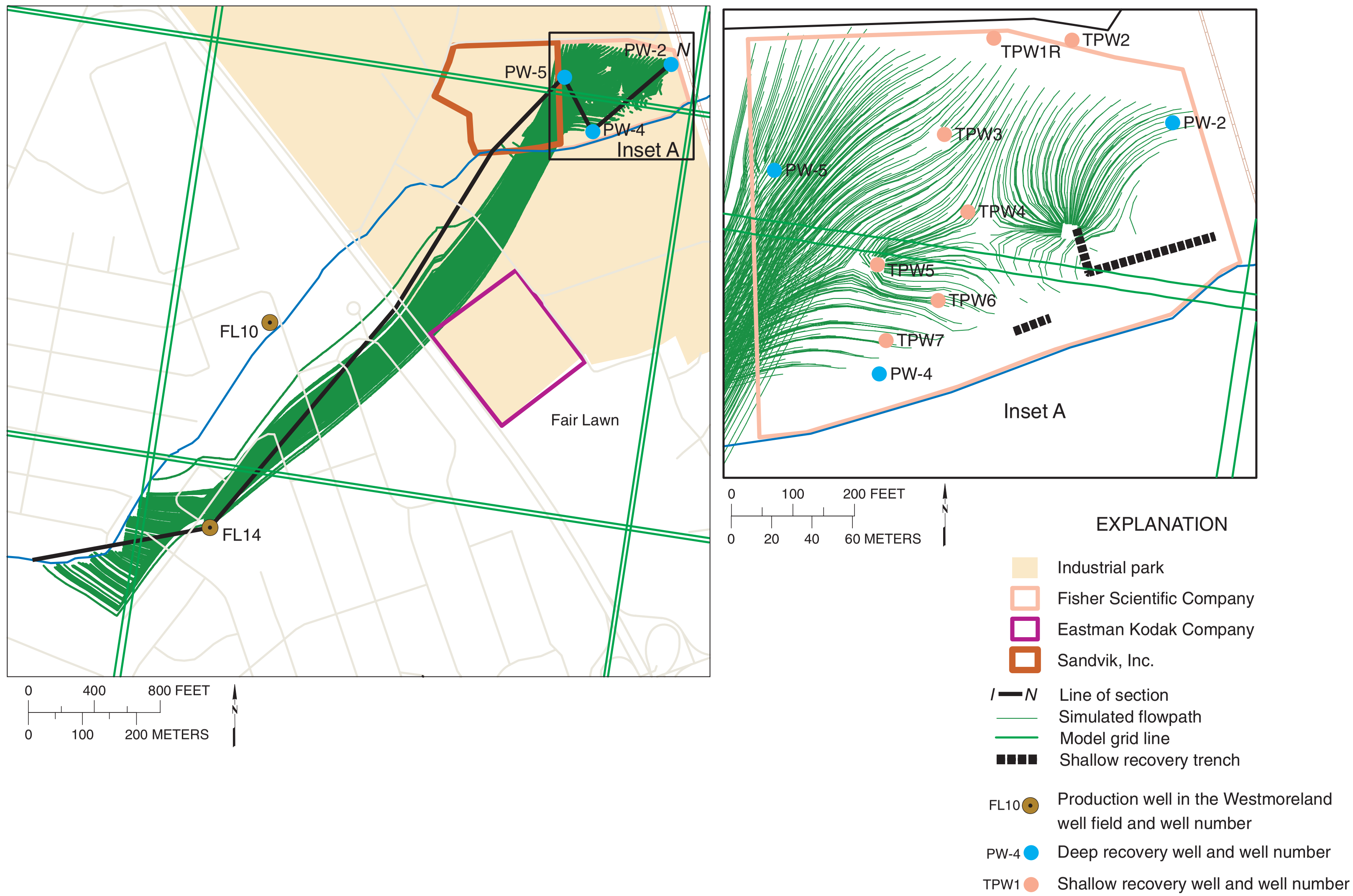


Figure 41. Map view of simulated plume of ground water originating in the overburden at Fisher Scientific Company for 2000 conditions, and line of section, Fair Lawn, New Jersey. (Model grid shown in figure 16)

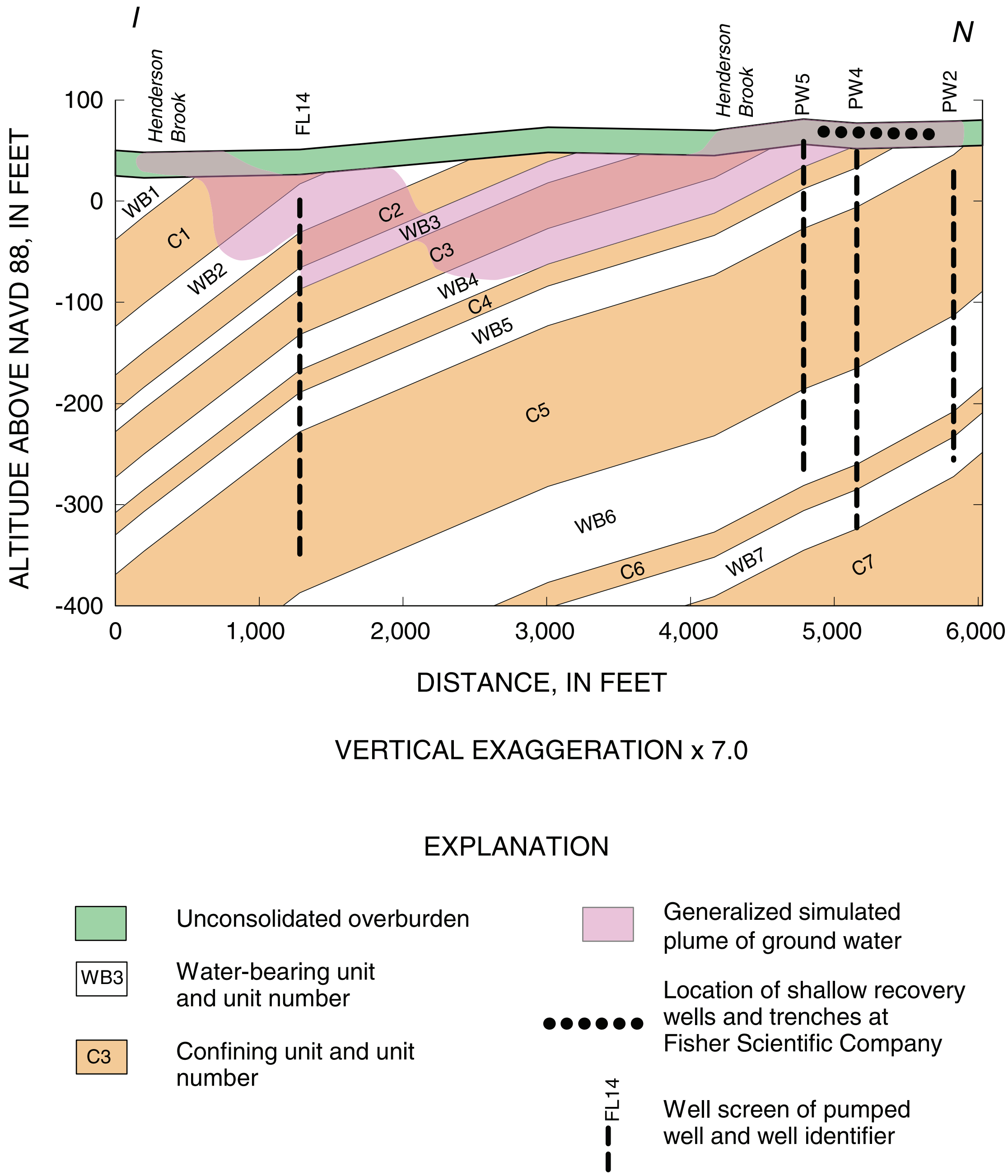


Figure 42. Generalized view along section I-N of simulated plume of ground water originating in the overburden at Fisher Scientific Company for 2000 conditions, Fair Lawn, New Jersey. (Line of section shown in figure 41)

Figure 43. Map view of simulated plume of ground water originating in the bedrock at Fisher Scientific Company for 2000 conditions, and line of section, Fair Lawn, New Jersey. (Model grid shown in figure 16)

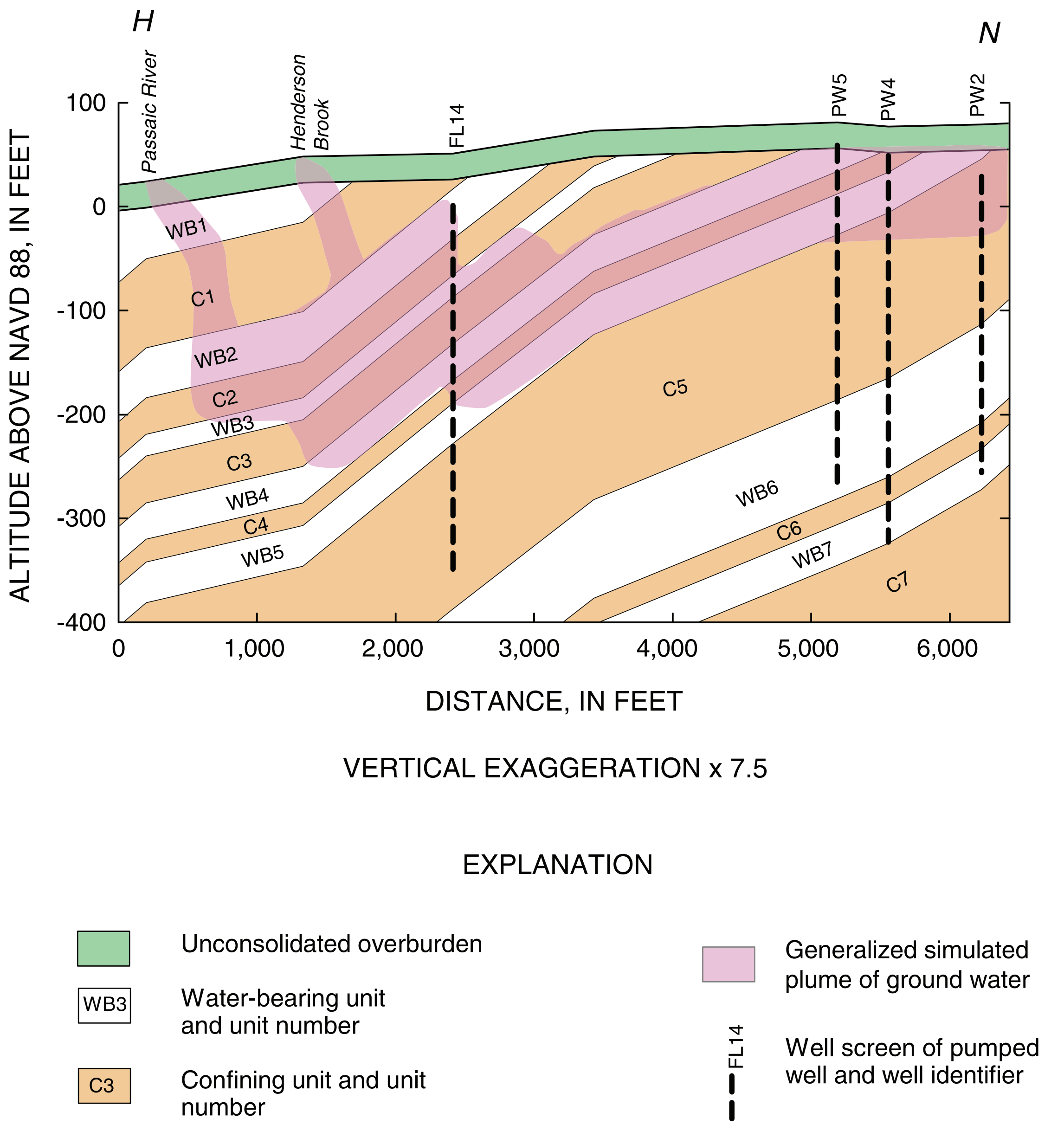


Figure 44. Generalized view along section H-N of simulated plume of ground water originating in the bedrock at Fisher Scientific Company for 2000 conditions, Fair Lawn, New Jersey. (Line of section shown in figure 43)

Table 34. Simulated flux of ground water originating at or passing through Fisher Scientific Company, Sandvik, Inc., and Eastman Kodak Company and discharging to wells and streams, Fair Lawn, New Jersey, 2000.

[All fluxes shown in cubic feet per day; na, not applicable]

Discharge point	Total flux pumped from well	Ground water originating at or passing through Fisher Scientific Company site						Ground water originating at or passing through Sandvik, Inc., site						Ground water originating at or passing through Eastman Kodak Company site		
		From overburden			From bedrock			From overburden			From bedrock			From bedrock		
		Flux	Percent of total flux from site discharging at well or stream	Percent of total pumpage from well originating at or passing through site	Flux	Percent of total flux from site discharging at well or stream	Percent of total pumpage from well originating at or passing through site	Flux	Percent of total flux from site discharging at well or stream	Percent of total pumpage from well originating at or passing through site	Flux	Percent of total flux from site discharging at well or stream	Percent of total pumpage from well originating at or passing through site	Flux	Percent of total flux from site discharging at well or stream	Percent of total pumpage from well originating at or passing through site
Henderson Brook	na	768	35	na	507	4	na	1,443	100	na	6,645	54	na	261	2	na
Passaic River	na	0	0	na	628	5	na	0	0	na	2,497	20	na	11,360	89	na
Well FL10	8,298	0	0	0	0	0	0	0	0	0	375	3	5	0	0	0
Well FL11								Not pumped in 2000								
Well FL14	9,795	141	6	1	4,414	34	45	0	0	0	2,419	20	25	1,196	9	12
Shallow recovery wells and trenches, Fisher Scientific Company	2,025	1,197	55	59	0	0	0	0	0	0	0	0	0	0	0	0
Well PW2	1,679	0	0	0	76	1	5	0	0	0	0	0	0	0	0	0
Well PW4	5,796	0	0	0	1,740	13	30	0	0	0	0	0	0	0	0	0
Well PW5	7,011	88	4	1	5,683	44	81	0	0	0	276	2	4	0	0	0

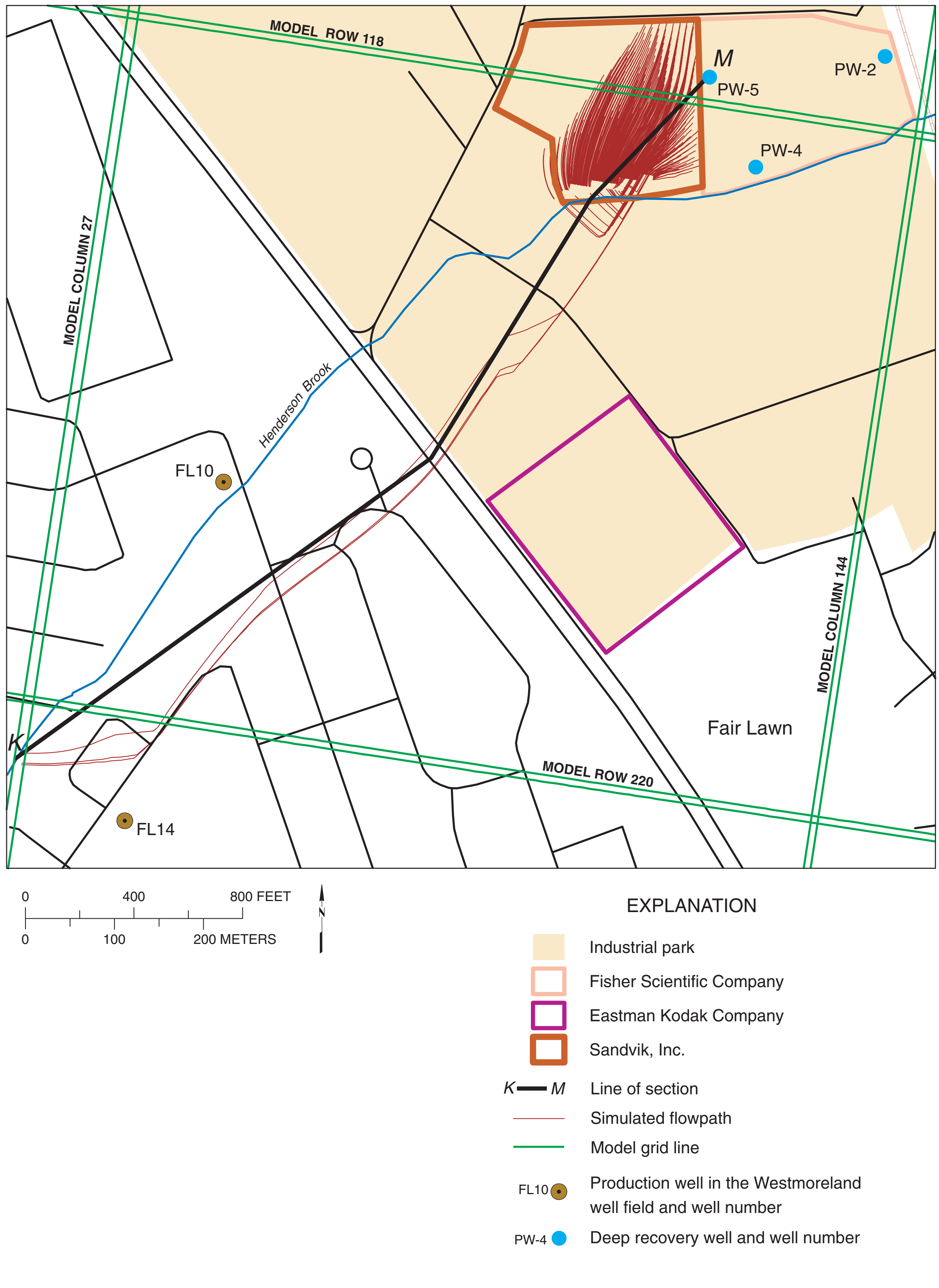


Figure 45. Map view of simulated plume of ground water originating in the overburden at Sandvik, Inc., for 2000 conditions, and line of section, Fair Lawn, New Jersey. (Model grid shown in figure 16)

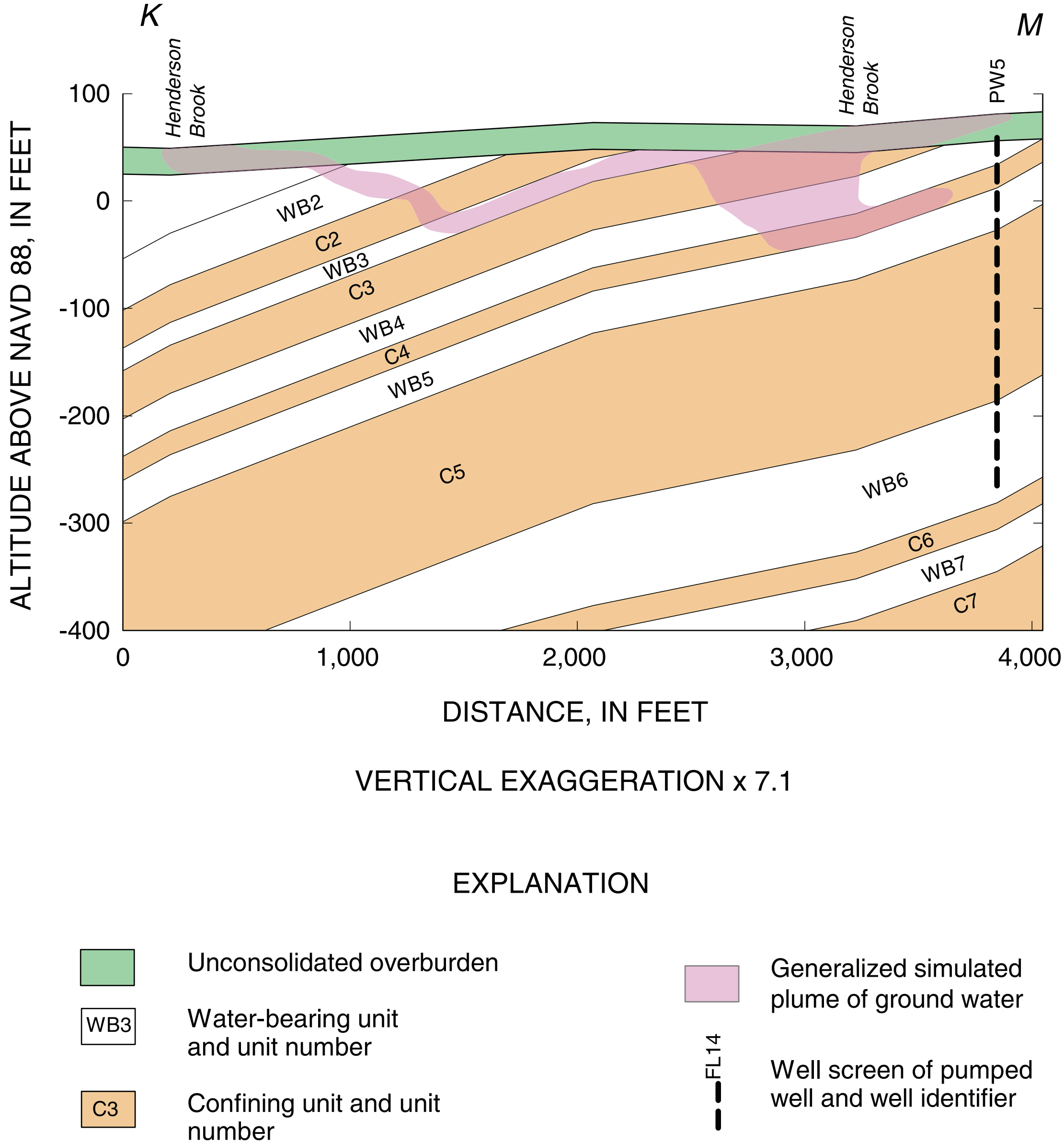


Figure 46. Generalized view along section K-M of simulated plume of ground water originating in the overburden at Sandvik, Inc., for 2000 conditions, Fair Lawn, New Jersey. (Line of section shown in figure 45)

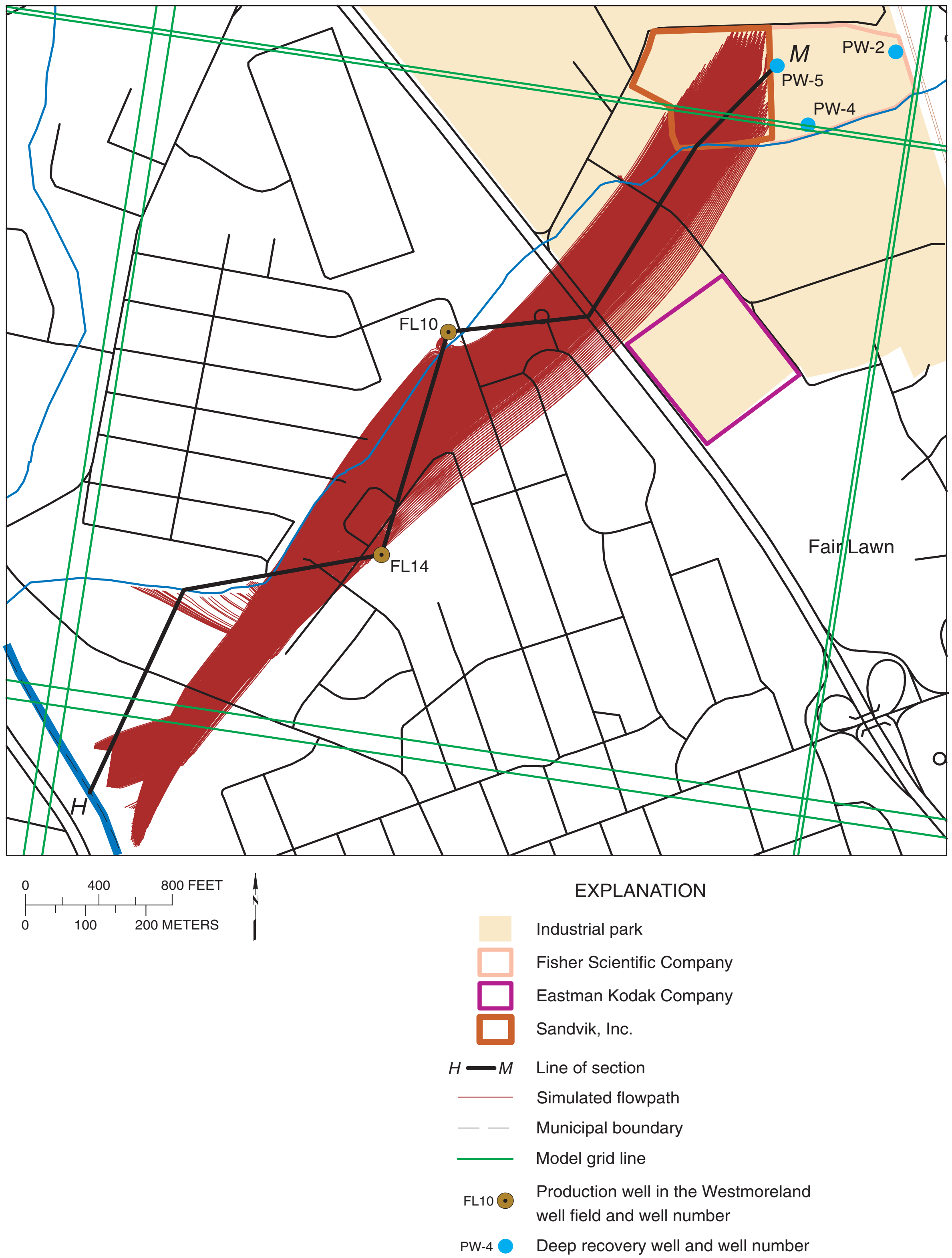


Figure 47. Map view of simulated plume of ground water originating in the bedrock at Sandvik, Inc., for 2000 conditions, and line of section, Fair Lawn, New Jersey. (Model grid shown in figure 16)

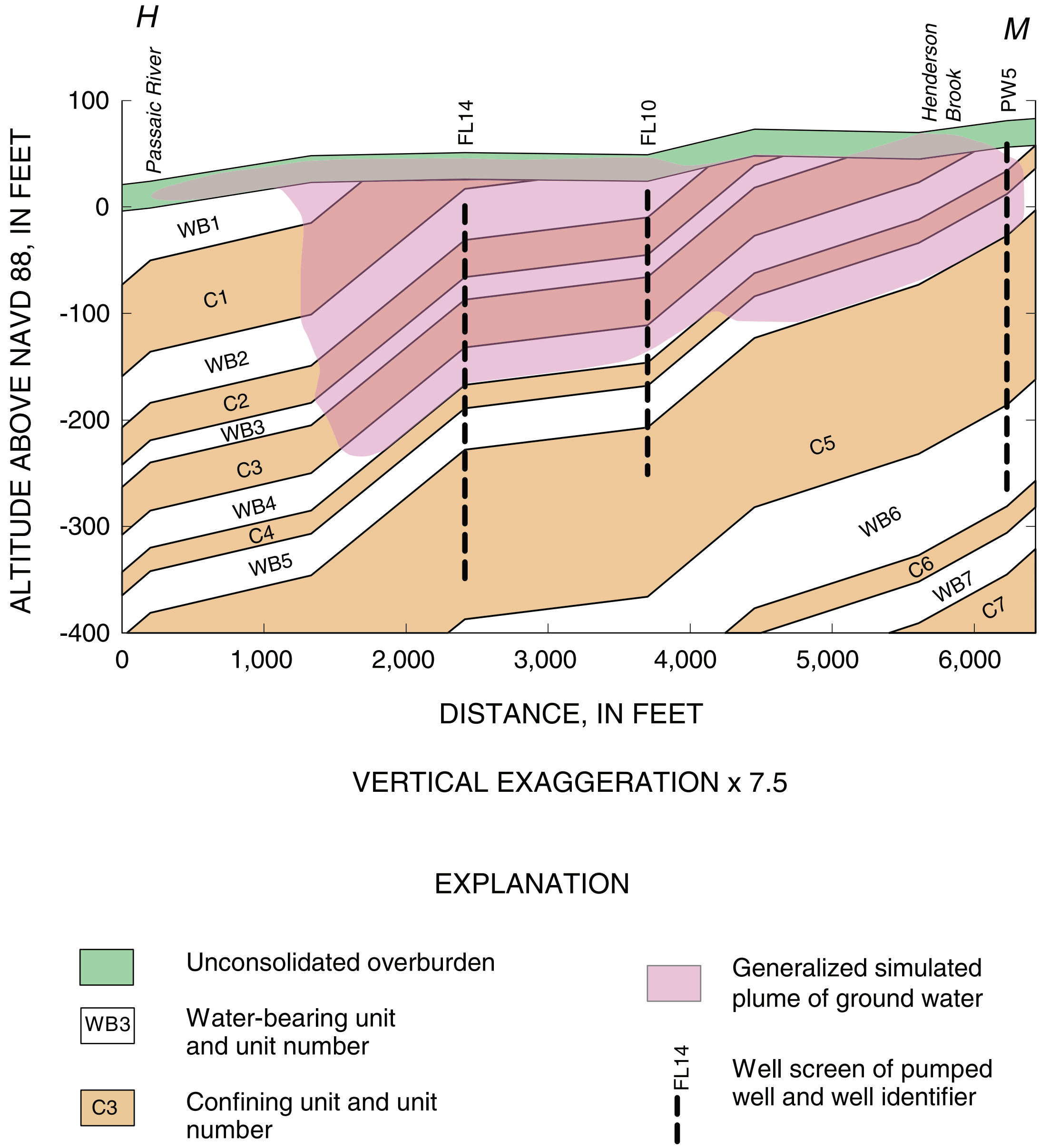


Figure 48. Generalized view along section H-M of simulated plume of ground water originating in the bedrock at Sandvik, Inc., for 2000 conditions, Fair Lawn, New Jersey. (Line of section shown in figure 47)

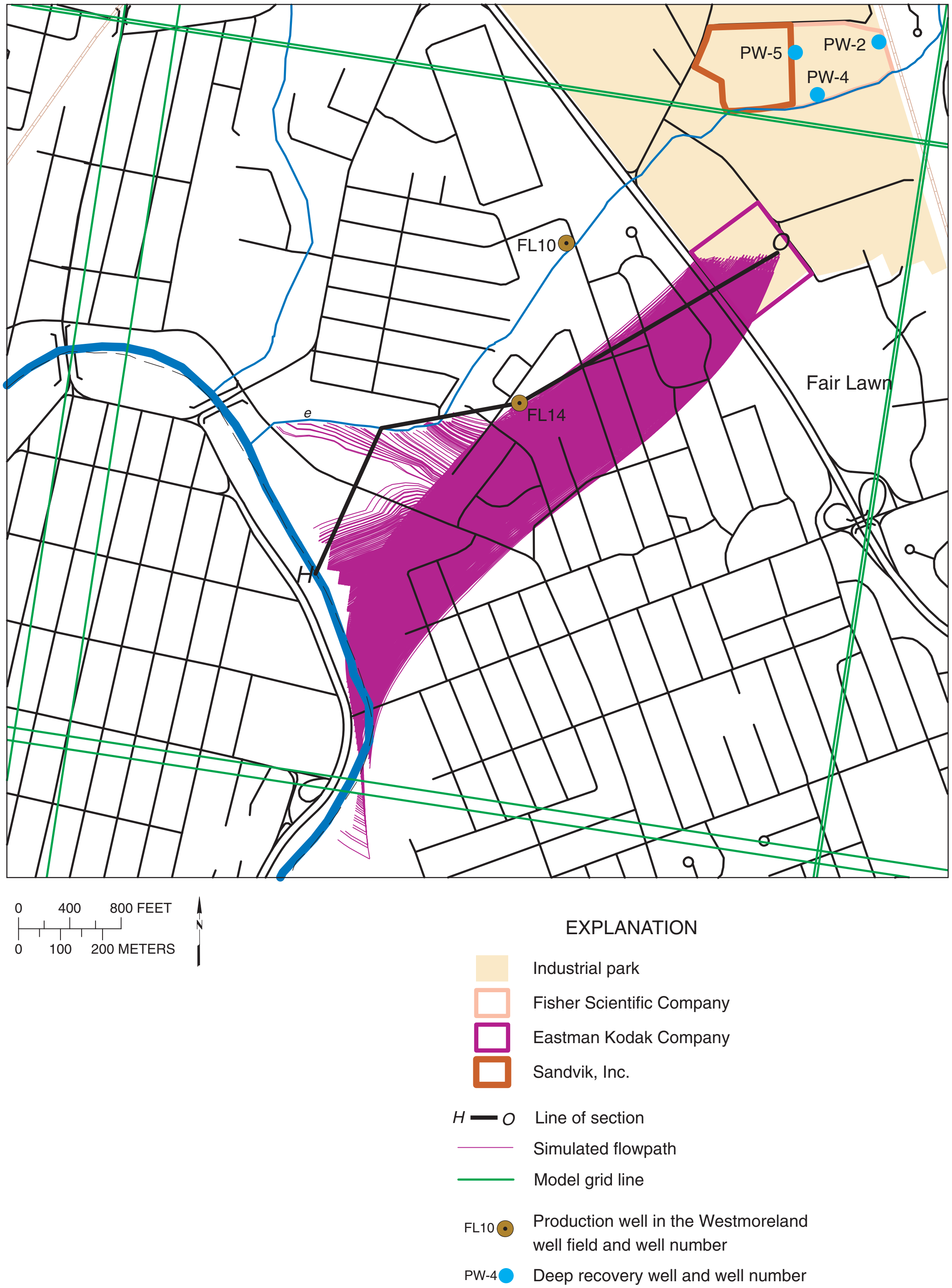


Figure 49. Map view of simulated plume of ground water originating in the bedrock at Eastman Kodak Company for 2000 conditions, and line of section, Fair Lawn, New Jersey. (Model grid shown in figure 16)

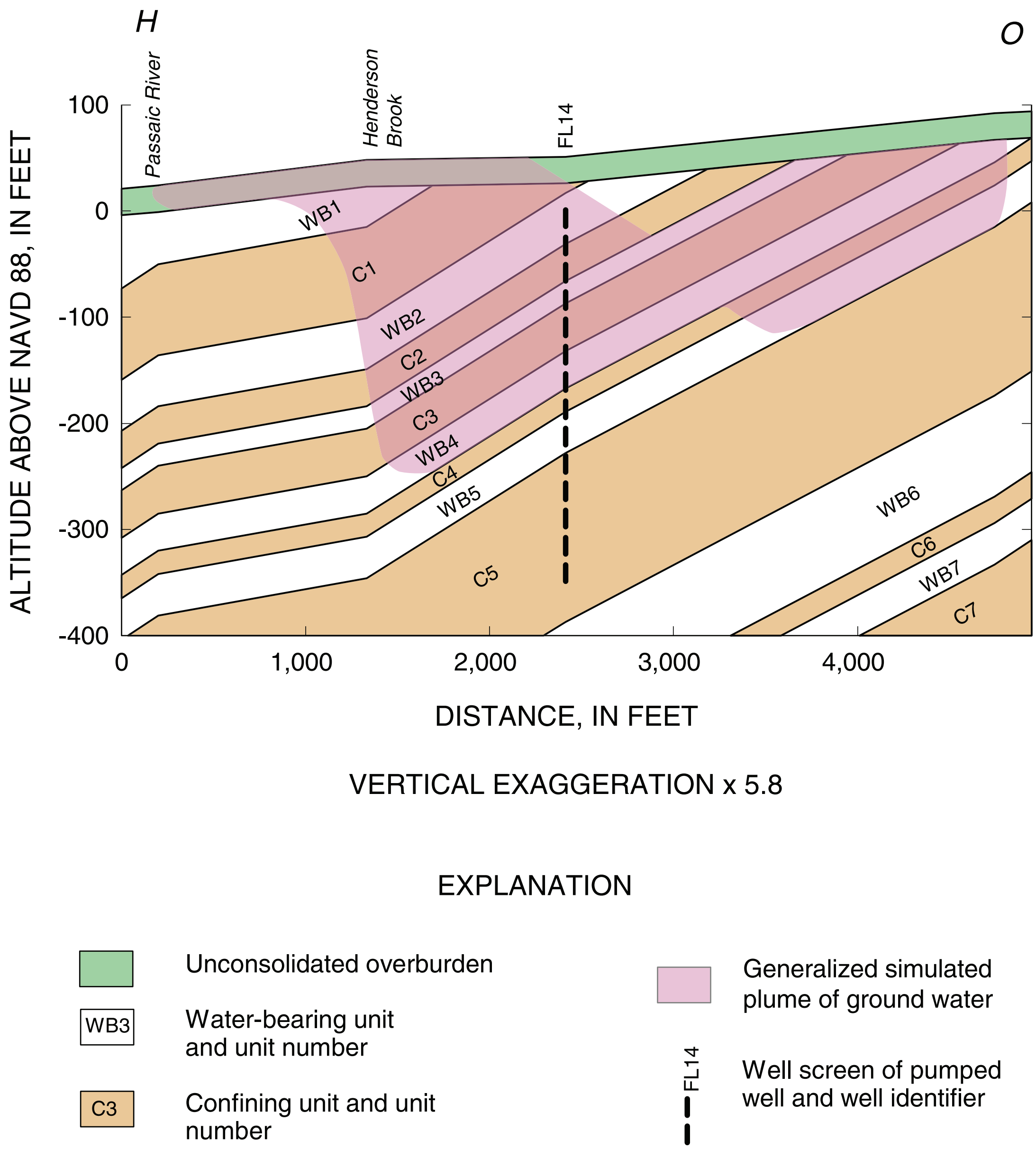


Figure 50. Generalized view along section H-O of simulated plume of ground water originating in the bedrock at Eastman Kodak Company for 2000 conditions, Fair Lawn, New Jersey. (Line of section shown in figure 49)

Summary and Conclusions

Volatile organic compounds (VOCs) have been detected in ground water in production wells in the Westmoreland well field, Fair Lawn, Bergen County, New Jersey, since 1978. The predominant compounds detected in these wells are trichloroethylene (TCE), tetrachloroethylene (PCE), *cis*-1,2-dichloroethylene (*cis*-1,2-DCE), and 1,1,1-trichloroethane (1,1,1-TCA). Results of an investigation by the N.J. Department of Environmental Protection (NJDEP) showed that two industrial sites—Fisher Scientific Company (Fisher) and Sandvik, Inc. (Sandvik)—are contributing sources of the contamination. During the course of the current study, a third potential contributing source, Eastman Kodak Company (Kodak) (also on the NJDEP list of known contaminated sites), was identified. VOCs detected in wells in the Westmoreland well field also have been detected in soil, overburden, and shallow bedrock at these three sites. In 1999 the U.S. Geological Survey (USGS), in cooperation with the U.S. Environmental Protection Agency (USEPA), began a study to determine ground-water flow patterns and contributing areas to production wells in Fair Lawn, contaminant-plume boundaries, and the effect of present pump-and-treat systems at the Westmoreland well field and at Fisher on flowpaths of contaminated ground water.

The hydrogeologic framework of, distribution of contaminants in, and ground-water flow patterns in Fair Lawn were determined from the results of borehole-geophysical logging and straddle-packer testing and by the use of a digital ground-water flow model. Contributing areas to production wells, contaminant-plume boundaries, and the effect of the pump-and-treat systems on flowpaths were simulated using the digital model.

The study area, which encompasses about 15 mi^2 in and near Fair Lawn, is underlain by 6 to 100 ft of glacial deposits and alluvium which, in turn, are underlain by the Passaic Formation. In the study area, the Passaic Formation consists of brownish-red pebble conglomerate, medium- to coarse-grained feldspathic sandstone, and micaceous siltstone. The bedrock strata strike generally N. 9^o E. and dip 6.5^o to the northwest.

Anisotropic ground-water flow in the fractured-rock aquifer formed by rocks of the Passaic Formation is caused by the interlayering of dipping water-bearing and confining units. Ground water flows predominantly in the direction of strike of the bedding, although in some places pumping skews flowpaths toward pumped wells. Wells of similar depths aligned along the strike of the bedding intersect the same water-bearing units, but wells of similar depths aligned along the dip of the bedding intersect different water-bearing units. Consequently, wells aligned along strike are in greater hydraulic connection than wells aligned along dip.

In 2000, the Borough of Fair Lawn pumped approximately 770 Mgal of water from 13 production wells: 332 Mgal from the Memorial well field, 154 Mgal from the Dorothy Street well field, 234 Mgal from the Cadmus well field, and 49 Mgal from the Westmoreland well field. Hydrographs from six deep observation wells in Fair Lawn show that water levels in many parts of the study area are affected by pumping from production wells. The water-level rise in the observation wells ranges from 1 to 27 ft when pumps in production wells are turned off.

Straddle packers were used to isolate discrete intervals in six open-hole observation wells owned by the Fair Lawn Water Department: wells FL4 and FL29, in the Cadmus well field; well FL12, in the Westmoreland well field; well FL18, in the Memorial well field; well FL23, in Fair Lawn Industrial Park; and well FL27, in the Dorothy Street well field. Transmissivity, water-quality, and static-water-level data were obtained from the isolated intervals. Measured transmissivity ranged from near 0 to 8,900 ft^2/d. The broad range in measured transmissivity is a result of the heterogeneity of the fractured-rock aquifer.

Eight water-bearing units and eight confining units were identified in the study area on the basis of transmissivity. The water-bearing units range in thickness from 21 to 95 ft; the mean thickness is 50 ft. The confining units range in thickness from 22 to 248 ft; the mean thickness is 83 ft. Long term, continuous water-level data indicate a hydraulic connection between wells open to the same water-bearing units but no connection between wells that are not open to any of the same water-bearing units.

Water samples were collected from the six observation wells at 16 depth intervals isolated by the straddle packers (one interval in well FL4, five intervals in well FL12, one interval in well FL18, and three intervals each in wells FL23, FL27, and FL29) for analysis for VOCs. The samples from well FL12 also were analyzed for semi-volatile organic compounds, pesticides, polychlorinated biphenyls, and metals. Contaminant concentrations in the samples from wells FL4, FL18, FL27, and FL29 generally were low and probably are unrelated to the contamination at the Fisher, Sandvik, or Kodak property because the sampled intervals in these four wells are not hydraulically connected to the overburden or the bedrock at any of these three sites. Also, in some cases, the types of contaminants in the wells are different from those found at the industrial sites. VOC concentrations were higher in samples from wells FL12 and FL23 than in samples from the other four wells.

Water samples were collected from intervals in water-bearing units 2, 3, 4, and 5 in well FL12 in the Westmoreland well field. Subcrops of water-bearing units 3 and 4 underlie the Sandvik and Kodak sites; subcrops of water-bearing units 4 and 5 underlie the Fisher site. PCE, 1,1,1-TCA, and TCE were detected in all samples from well FL12. The highest PCE concentration (13 µg/L) and the highest 1,1,1-TCA concentration (35 µg/L) were detected in water-bearing unit 3; the highest TCE concentration (60 µg/L) was detected in water-bearing unit 5. Degradation products of PCE and TCE (*cis*-1,2-DCE, 1,1-dichlorethane (1,1-DCA) and 1,1-dichloroethene (1,1-DCE)) also were detected in all samples from well FL12. The highest concentrations of 1,1-DCA and 1,1-DCE were in samples from water-bearing unit 3; the highest concentration of *cis*-1,2-DCE was in the sample from the water-bearing unit 5.

All six of these VOCs (PCE, 1,1,1-TCA, TCE, *cis*-1,2-DCE, 1,1-DCA, and 1,1-DCE) also were present at the Fisher and Sandvik sites; all but PCE were present at the Kodak site. On the basis of the distribution of VOCs and the hydraulic connection between well FL12 and the water-bearing units at the three sites, any or all of these sites could contribute VOCs to well FL12.

Five additional VOCs were detected in samples from well FL12: toluene, 4-methyl-2-pentanone, chloroform, acetone, and 2-butanone. The types and concentrations of VOCs differed markedly among the four water-bearing units, indicating that the water-bearing units are separated effectively by the confining units.

Although the primary contaminants of concern in this study are VOCs, the detection of arsenic in well FL12 is an important finding. The concentration of 102 µg/L in the deepest sampled interval (water-bearing unit 5) exceeds the current (2004) USEPA drinking-water standard of 50 µg/L. It is not known whether the arsenic is naturally occurring or anthropogenic. If it is anthropogenic, a possible source is Fisher, which overlies the subcrop of water-bearing unit 5.

Well FL23 is in Fair Lawn Industrial Park, about 1,200 ft south of Fisher and Sandvik and immediately east of Kodak. Water samples were collected from water-bearing units 5 and 7 in this well; nine compounds were detected. TCE was detected in samples from both water-bearing units, at concentrations up to 120 µg/L. *Cis*-1,2-DCE was detected in all samples from water-bearing unit 5 at concentrations up to 140 µg/L. Two other TCE degradation products, *trans*-1,2-dichlorethylene and 1,1-DCE, were detected in samples from water-bearing unit 5. VOC concentrations were much higher in the samples from water-bearing unit 5 than in those from water-bearing unit 7. Contaminant types and concentrations in samples from water-bearing unit 5 were similar to those in the samples from the same water-bearing unit in well FL12, however, indicating continuity of the water-bearing unit and a hydraulic connection between wells FL23 and FL12.

Water-bearing unit 5, which contained the highest concentration of VOCs in well FL23, is present beneath all three industrial sites (directly beneath the overburden at Fisher and as shallow bedrock beneath Sandvik and Kodak). All VOCs detected in well FL23, like those in well FL12, are present at one or all of the Fisher, Sandvik, and Kodak sites. Consequently, the VOCs detected in well FL23 could be derived from any or all of the three sites.

A three-dimensional, finite-difference ground-water flow model (MODFLOW-2000) was used to simulate ground-water flow in the study area. A particle-tracking post-processor (MODPATH) was used to delineate contributing areas to wells and compute flowpaths from potential contaminant sources. Another post-processor (ZONEBUDGET) was used to compute water budgets, to determine the flux of water from each potential contaminant source to each well, and to determine the effect of the pump-and-treat systems at the Westmoreland well field and Fisher on flowpaths of contaminated ground water.

Model layer 1 represents the unconsolidated overburden materials overlying bedrock. These materials range in thickness from 6 to 100 ft. Model layers 2 through 41 represent the alternating water-bearing and confining units in the fractured-rock aquifer formed by rocks of the Passaic Formation.

The model extends as far as 3.5 mi beyond Fair Lawn. The model boundaries were chosen to ensure that the entire flowpath of any particle of water that passes through Fair Lawn is included in the model. All of the model boundaries are no-flow boundaries, except the eastern boundary, which is formed by the Saddle River and is represented as a head-dependent flux boundary, and part of the western boundary, which is a specified-flux boundary representing water flowing into the model area from the west.

Four steady-state ground-water scenarios were simulated. Two of the simulations represent ground-water conditions in 1991 and 2000. These years were chosen because pumpage from the Westmoreland well field and at Fisher differed greatly between these two years. Recharge in both scenarios was assumed to be 20 in/yr.

Because 2000 was a relatively dry year compared to the 98-year period of record, a high-recharge scenario in which the recharge rate was 22 in/yr was developed. The purpose of this scenario was to determine the effects of an increased recharge rate on the contributing areas to wells. The fourth scenario, the “recovery” scenario, was used for calibration only. This scenario represents periods when pumps in some production wells were turned off.

Measured ground-water levels in 70 wells, water levels in 15 intervals in observation wells isolated by straddle packers, and base flow in five streams were used to calibrate the 2000 model. The measured rise in water levels in observation wells in response to shutdown of pumps in production wells was used to calibrate the model simulation of the recovery scenario. The measured rise in water levels in response to increased recharge was used to evaluate the accuracy of the high-recharge scenario.

The horizontal hydraulic conductivity of model layer 1 (representing the overburden) is 30 ft/d except in the areas representing fluvial sediments, where conductivity is 5 ft/d. The horizontal hydraulic conductivity of model layers representing bedrock water-bearing units varies from 1.4 to 79 ft/d. The horizontal hydraulic conductivity in bedrock confining units varies from 0.035 to 2 ft/d. The conductivity of all bedrock units varies among layers and was set to decrease with depth. The vertical hydraulic conductivity of the overburden (model layer 1) is 0.1 ft/d. Vertical conductivity is 4.4 ft/d in all bedrock water-bearing units and 0.12 ft/d in all bedrock confining units. The vertical hydraulic conductivity of all streambed material is 1 ft/d. Areal recharge throughout the model area was set at 20 in/yr.

Water budgets computed with the digital model indicate substantial interbasin transfer of ground water. For example, approximately 136,000 ft^3/d of water flows into the Henderson Brook drainage basin from neighboring basins, and approximately 175,000 ft^3/d flows out of the basin to neighboring basins. To put these amounts in perspective, recharge to the basin from precipitation is approximately 159,000 ft^3/d.

Water budgets also indicated that most of the water (66 percent) that enters the unconsolidated overburden (model layer 1) flows downward into the bedrock layers (model layers 2-41). The other 34 percent remains in layer 1 and discharges to nearby streams and to recovery wells and trenches at Fisher. About 72 percent of the water that enters the bedrock layers eventually flows back into layer 1 and discharges to streams. The remainder flows to pumped wells.

The digital model was used to delineate contributing areas to production well fields in Fair Lawn and contaminant plumes from Fisher, Sandvik, and Kodak. In 1991, when 130 Mgal of water was pumped from the Westmoreland well field, the contributing area to that well field encompassed about one-fourth of Fair Lawn Industrial Park and included nearly all of the Fisher property, less than 1 percent of the Sandvik property, and about three-fourths of the Kodak property. The contributing area to the Westmoreland well field in 1991 extended southwest almost to the well field and about 2.5 mi north of Fair Lawn.

In 1991, the contributing area to the Memorial well field was northeast of the wells and south and east of the Fisher, Sandvik, and Kodak properties. The area was less than 500 ft from three other known contaminated sites. The contributing area to the Cadmus wells encompassed an area generally northeast of the wells. It included five known contaminated sites and was less than 500 ft from another site. The contributing area to the Dorothy Street wells included two known contaminated sites and was less than 500 ft from another site; however, no contamination has been detected in water samples from the Dorothy Street wells.

In 2000, when only 49 Mgal of water was pumped from the Westmoreland well field, the contributing area to that well field was much smaller than in 1991. The contributing area included only a small part of the Fisher and Kodak properties and none of the Sandvik property. In contrast to the contributing area to the Westmoreland well field in 1991, which included most of the Fisher property, the contributing area in 2000 included only a small part of the Fisher property, partly because of the decreased pumpage from the Westmoreland well field and partly because recently installed shallow (less than 18 feet deep) wells and trenches on the property were pumping water at a rate of 2,025 ft^3/d.

The contributing area to the Memorial well field in 2000 was nearly identical to the area in 1991. The contributing area to the Cadmus wells was larger than in 1991 and added an area of about 0.3 mi^2 around well FL8 as a result of increased pumpage from that well. The 2000 contributing area to Cadmus wells included, or was less than 300 ft from, eight known contaminated sites. The configuration of the contributing area to the Dorothy Street wells in 2000 was substantially different from that in 1991 because of changes in the distribution of pumpage among the three wells.

In the high-recharge scenario, when 22 in/yr of recharge was applied, the contributing area to each well field was smaller than in the 2000 scenario because the increased recharge rate enabled wells to draw the same amount of water from smaller areas. In this scenario, the contributing area to the Westmoreland well field included none of the Fisher or Sandvik property and only a small part of the Kodak property.

The ground-water flow model was used to delineate contaminant plumes from the three industrial sites (Fisher, Sandvik and Kodak). In this study, the delineated contaminant plume is defined as the three-dimensional area containing flowpaths from a contaminated source area to their point of discharge in a stream or a pumped well. Because only advective flow is simulated with the model, the effects of density, dispersion, diffusion, dilution, and degradation of contaminants are not accounted for in the plumes. Plumes were tracked from areas within each site known to contain VOCs. Although ground water in the starting area of each plume is known to contain VOCs, it is not known whether VOCs are present along the entire path of the plumes, except where they pass through wells known to be contaminated with VOCs.

The simulated plume from Fisher in the 1991 scenario extends to the Westmoreland well field, Henderson Brook, and the Passaic River, reaching a maximum depth of 260 ft below land surface. Part of the plume passes through the southeastern part of the Sandvik property and the northwestern corner of the Kodak property. In 1991, Westmoreland well FL14 captured 94 percent of the water from the overburden and 31 percent of the water from the bedrock at Fisher, and Westmoreland well FL11 captured 16 percent of the water from the bedrock at Fisher. The deep recovery wells at Fisher (PW2, PW4, and PW5) captured 3 percent of the water originating in or passing through the overburden and 49 percent of the water originating in or passing through the bedrock at Fisher. The plume from the bedrock at Fisher does not reach well FL10, but it does pass within 150 ft of it. Because the plume does not include the effects of diffusion or dispersion, the possibility that water from the Fisher property contributed some of the water pumped from well FL10 under 1991 conditions cannot be ruled out. In 1991, 3 percent of the water from the overburden and 4 percent of the water from the bedrock at Fisher was not captured by any well, but flowed instead to Henderson Brook.

The simulated plume from Sandvik in the 1991 scenario extends to the Westmoreland well field, Henderson Brook, and the Passaic River, reaching a maximum depth of 200 ft below land surface. In 1991, Westmoreland well FL14 captured 3 percent of the water from the overburden and 24 percent of the water from the bedrock at Sandvik. Westmoreland wells FL10 and FL11 captured 27 percent and 42 percent, respectively, of the water from the bedrock at Sandvik. In 1991, 97 percent of the water from the overburden and 7 percent of the water from the bedrock at Sandvik was not captured by any well, but flowed instead to Henderson Brook.

The simulated plume from Kodak in the 1991 scenario extends to the Westmoreland well field, Henderson Brook, and the Passaic River, reaching a maximum depth of 260 ft below land surface. In 1991, Westmoreland well FL14 captured 73 percent of the water from the bedrock at Kodak, and 26 percent of the water from Kodak flowed to the Passaic River rather than being captured by any well.

The simulated plume from Fisher in the 2000 scenario extends to the Westmoreland well field, Henderson Brook, and the Passaic River, reaching a maximum depth of 260 ft below land surface. Part of the plume from Fisher passes through the southeastern part of the Sandvik property and the northwestern corner of the Kodak property. In 2000, Westmoreland well FL14 captured 6 percent of the water from the overburden and 34 percent of the water from the bedrock at Fisher. In 2000, the recently installed shallow recovery system, consisting of seven wells and two trenches, captured 55 percent of the water originating in or passing through the overburden at Fisher. Deep recovery wells at Fisher captured 4 percent of the water originating in or passing through the overburden and 58 percent of the water originating in or passing through the bedrock at Fisher. Although the plume from the bedrock at Fisher does not reach Westmoreland well FL10, it does pass within 300 ft of it. Because the plume does not include the effects of diffusion or dispersion, the possibility that well FL10 captured some of the water from the bedrock at Fisher under 2000 conditions cannot be ruled out. In 2000, 35 percent of the water from the overburden and 9 percent of the water from the bedrock at Fisher flowed to Henderson Brook and the Passaic River rather than being captured by any well.

The simulated plume from Sandvik in the 2000 scenario extends to the Westmoreland well field, Henderson Brook, and the Passaic River, reaching a maximum depth of 260 ft below land surface. Nearly all of the plume from the overburden discharged to Henderson Brook adjacent to the Sandvik property; the remainder flowed to a more distant reach of Henderson Brook. Of the water from the bedrock at Sandvik, 20 percent was captured by Westmoreland well FL14, 3 percent was captured by Westmoreland well FL10; and the remainder flowed to Henderson Brook and the Passaic River rather than being captured by any well.

The simulated plume from Kodak in the 2000 scenario extends from Kodak to the Westmoreland well field, Henderson Brook, and the Passaic River, reaching a maximum depth of 260 ft below land surface. In 2000, Westmoreland well FL14 captured 9 percent of the water from Kodak. The remainder was not captured by any well, but flowed instead to the Passaic River and Henderson Brook.

The following conclusions can be drawn from the results of this study:

- The production wells in the Westmoreland well field (FL10, FL11, and FL14) all are in hydraulic connection with the bedrock and unconsolidated overburden underlying all three industrial sites that have been identified as potentially contributing sources of the VOCs in those wells.
- The types of VOCs detected in the wells in the Westmoreland well field also are detected at the three industrial sites.
- Under 1991 pumping conditions, the simulated plume of ground water from Fisher Scientific Company reaches Westmoreland wells FL11 and FL14 and is within 125 ft of Westmoreland well FL10; the plume from Sandvik, Inc., reaches wells FL10, FL11, and FL14; and the plume from Eastman Kodak Company reaches well FL14.
- Under 2000 pumping conditions, the simulated plume of ground water from Fisher Scientific Company reaches well FL14 and is within 300 ft of well FL10; the plume from Sandvik, Inc., reaches wells FL10 and FL14; and the plume from Eastman Kodak Company reaches well FL14. (Well FL11 was not pumped in 2000.)
- In 1991 and 2000, some ground water flowing from all three industrial sites was not captured by any of the wells in the pump-and-treat system at the Westmoreland well field or any of the wells or trenches in the pump-and treat system at Fisher Scientific Company, but discharged instead to Henderson Brook and the Passaic River.

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