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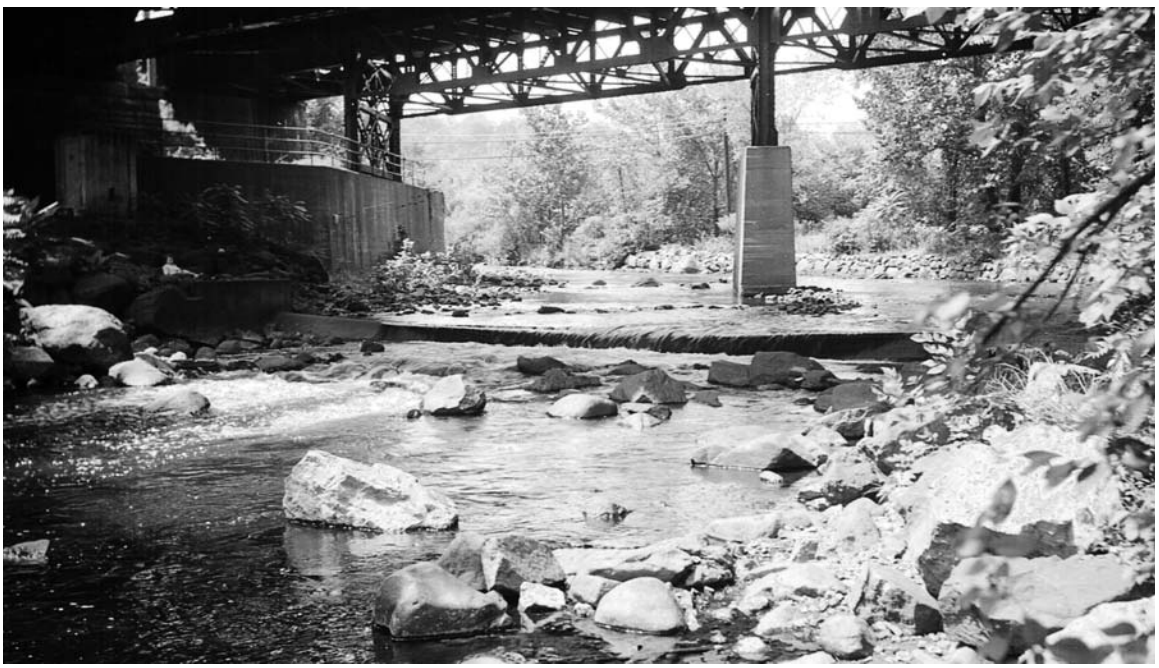
SIMULATION OF TRANSIENT GROUND-WATER FLOW IN THE VALLEY-FILL AQUIFERS OF THE UPPER ROCKAWAY RIVER BASIN, MORRIS COUNTY, NEW JERSEY

Water-Resources Investigations Report 01-4174



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NEW JERSEY DEPARTMENT OF ENVIRONMENTAL PROTECTION

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Cover photo: View looking upstream from the gaging station on the Rockaway River above the Boonton Reservoir with weir and gage house. Photo about 1940's.

SIMULATION OF TRANSIENT GROUND-WATER FLOW IN THE VALLEY-FILL AQUIFERS OF THE UPPER ROCKAWAY RIVER BASIN, MORRIS COUNTY, NEW JERSEY

by Alison D. Gordon

U.S. GEOLOGICAL SURVEY

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NEW JERSEY DEPARTMENT OF ENVIRONMENTAL PROTECTION

West Trenton, New Jersey

2002

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
inches per year (in/yr)	25.4	millimeters per year
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
	Transmissivity	
square foot per day (ft^2/d)	0.09294	meter squared per day
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06309	liter per second
gallon per day per foot ((gal/d)/ft)	264.2	cubic meters per day per foot
million gallons (Mgal)	3,785	cubic meters
million gallons per day (Mgal/d)	0.04381	cubic meter per second

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

SIMULATION OF TRANSIENT GROUND-WATER FLOW IN THE VALLEY-FILL AQUIFERS OF THE UPPER ROCKAWAY RIVER BASIN, MORRIS COUNTY, NEW JERSEY

By Alison D. Gordon

ABSTRACT

More than 90 percent of the public water supply in the upper Rockaway River Valley in Morris County, New Jersey, is obtained from ground-water withdrawals from the valley-fill aquifers. During 1997, an average of 9.6 million gallons per day of ground water was withdrawn from these aquifers. The aquifer system consists of an unconfined aquifer (upper aquifer) and a locally confined aquifer (lower aquifer), which are composed of sands and gravels. These aquifers are separated by a discontinuous confining unit that consists mostly of silt and clay. Increases in ground-water withdrawals can induce movement of water from streams to wells, increase flow from the upper aquifer to the lower aquifer, and reduce base flow in the Rockaway River downstream.

A ground-water-flow model was used to simulate and quantify the effects of current withdrawals on the valley-fill aquifer system under transient monthly conditions. Recharge over the model area varies both spatially and temporally. Part of model calibration consisted of adjusting percentages of monthly precipitation that recharges the valley-fill aquifer system. More recharge occurs during winter and spring than during summer and fall. This seasonal variation affects ground-water discharge to the Rockaway River.

Ground-water withdrawals from the valley-fill aquifers also affect ground-water discharge to the Rockaway River. Three scenarios were simulated to observe the effects of ground-water withdrawals on ground-water discharge to the Rockaway River and to determine the extent to which variations in rates of withdrawals correspond to variations in rates of streamflow depletion. Streamflow depletion was estimated by comparing model-computed ground-water discharge for the three scenarios with the model-computed ground-water discharge under transient conditions. In scenario 1, all pumpage was removed from the model. In scenarios 2 and 3, 1 million gallons per day of ground-water withdrawals in excess of the current pumpage was withdrawn from the valley-fill aquifers. In scenario 2, the additional 1 million gallons per day of withdrawals were made from a hypothetical well located in the upper aquifer about 250 feet from the river. In scenario 3, the additional withdrawals were made from a hypothetical well located in the lower aquifer about 1,750 feet from the river. Results of scenario 1 indicated that the difference between the streamflow depletion and withdrawals is small; increases in ground-water withdrawals from the valley-fill aquifers correspond to decreases in ground-water discharge to the Rockaway River of approximately the same amount. Results of scenario 2 and 3 indicated that a lag time could occur between the introduction of withdrawals and the full magnitude of the effects of the withdrawals on streamflow depletion. A lag time of about seven months occurred for scenario 2 with the well placed in the upper aquifer. A longer lag time of more than 1.5 years occurred with the well placed in the lower aquifer and separated from the upper aquifer by a confining unit (scenario 3).

Extreme low flow in the Rockaway River is mostly base flow. A flow-duration analysis of the Rockaway River at the surface-water gaging station upstream from the Boonton Reservoir during the drought of 1961-66 indicated that streamflow from the upper Rockaway River Basin alone might not be sufficient to meet the minimum passing flow of 7 million gallons per day during a drought. Under similar drought conditions today, during 3.2 percent of the drought time, streamflow at this station upstream from the reservoir would

be less than the minimum passing flow requirement downstream from the reservoir.

INTRODUCTION

More than 90 percent of the public water supply in the upper Rockaway River Valley in Morris County, New Jersey, is obtained from wells that are screened in the valley-fill aquifers. Ground-water withdrawals from these aquifers have increased from an estimated 3 Mgal/d in 1950 to more than 9.6 Mgal/d in 1997. Ground-water withdrawals from the upland areas and bedrock are considered to be negligible compared with withdrawals from the valley-fill aquifers. Increased withdrawals and the potential effects of increased demand for water have resulted in concern about the effects of increased withdrawals on the flow system and on ground-water discharge to the Rockaway River, particularly during periods of low flow and drought. During periods of low flow, increases in withdrawals could reduce the ground-water discharge to the river. This discharge reduction could affect the court-ordered minimum passing flow requirement of 7 Mgal/d (Summers and others, 1978, p. 55), the quantity of water that the Jersey City Water Department must release to protect the quality of water for users downstream from the Boonton Reservoir. Water used by communities upstream from the Boonton Reservoir is carried through sewers to a treatment plant operated by the Rockaway Valley Regional Sewage Authority. The treatment plant is located downstream from both the reservoir and a surface-water gaging station above the reservoir.

The U.S. Geological Survey, in cooperation with the New Jersey Department of Environmental Protection, conducted a study to determine the effects of well locations and seasonal changes in the ground-water flow system in the valley-fill aquifers in the upper Rockaway River drainage basin on ground-water discharge to the Rockaway River. A previous model of the valley-fill aquifer system in the upper Rockaway River Basin (Gordon, 1993), which simulates average steady-state conditions, was modified to simulate transient conditions. The ground-water-flow system is in steady state when water levels or flow are constant with time. The steady-state model was developed to quantify components of the predevelopment flow system and to simulate the effects of ground-water withdrawals on water levels, flow directions, and ground-water discharge under 1986 average conditions and average conditions anticipated in the years 2000 and 2040. Updates to the hydraulic characteristics, withdrawals, and recharge in the upper Rockaway River Basin were incorporated into the previous model to create the transient model.

Purpose and Scope

This report describes (1) the development of a transient ground-water-flow model to simulate seasonal changes in the ground-water flow system of the valley-fill aquifers during April 1994 to September 1998, including the effects of ground-water withdrawals on the flow system and on ground-water discharge to the Rockaway River upstream from the Boonton Reservoir; (2) the use of this model to simulate the effects of locating wells at different sites in the model area on ground-water discharge to the Rockaway River; (3) and the effects of ground-water withdrawals on base flow in the Rockaway River during periods of extreme low flow. The hydrogeology of the model area is summarized. The ground-water-flow system includes an upper and lower aquifer, separated by a confining unit in areas.Water levels in 72 production and observation wells measured during October 7 and 8, 1997, were used to map the water table and potentiometric surface of the valley-fill aquifers. Base-flow measurements from 15 surface-water sites were used to determine ground-water discharge in the Rockaway River within the model area. Monthly precipitation data were used to determine ground-water recharge. Monthly ground-water withdrawals during April 1994 to September 1998 from production wells screened in the valley-fill aquifers were incorporated into the model as stresses on the ground-water-flow system.

Location and Physical Setting

In this report the study area and the model area coincide. The model area covers about 20 mi^2 and includes the valley-fill deposits from south of

Longwood Lake to the Whippany River drainage basin and from Roxbury Township east to about 1 mi from the Boonton Reservoir. This area includes Rockaway, Denville, and Boonton Townships; Wharton, Rockaway, and Mountain Lakes Boroughs; Dover; Boonton; and parts of Jefferson, Parsippany-Troy Hills, Roxbury, and Randolph Townships, and Victory Gardens Borough (fig. 1). The valley-fill deposits are surrounded by till-covered bedrock upland areas. The upper Rockaway River drainage basin is characterized by broad, northeast-trending bedrock ridges separated by deep, flat valleys. The highlands surrounding the valley are sparsely populated; development is centered in the river valley. The upper Rockaway River Basin is separated from the lower Rockaway River Basin at the surface-water gaging station above the Boonton Reservoir (gaging-station number 01380500). Small sections of the Whippany River and Lamington River drainage basins are located within the model area.

Site-Numbering System

Surface-water stations are assigned unique identification numbers on the basis of station position along a stream. The identification number consists of 8 digits, such as 01380500. These numbers increase in the downstream direction.

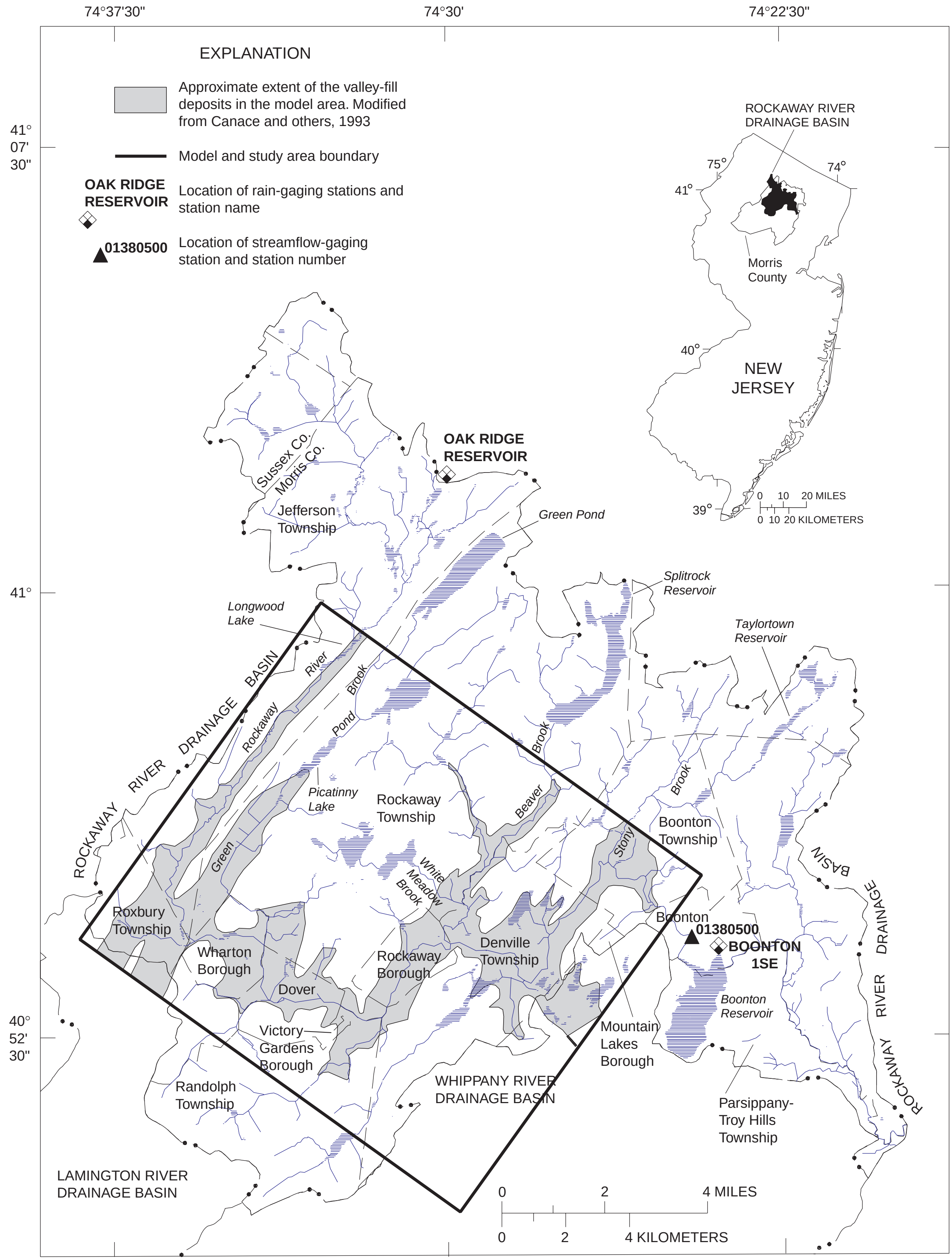
The well-numbering system used in this report was developed by the New Jersey District of the U.S. Geological Survey. The number consists of a 2-digit county code followed by a 3- or 4-digit sequence number. The code for Morris County is 27. A representative well number is 27-29, which is the 29th well inventoried in Morris County.

HYDROGEOLOGY OF THE VALLEY-FILL AQUIFER SYSTEM

The valley fill consists of unconsolidated deposits of glacial, lacustrine, and fluvial origin (Gill and Vecchioli, 1965) that occupy preglacial and glacially deepened river valleys. The delineation of valley-fill deposits in the model area was determined during a previous investigation of the upper Rockaway River Basin (Schaefer and others, 1993). The lithology can vary both laterally and vertically over short distances (tens of feet) throughout the study area as a result of the deposition, erosion, and redeposition of materials by glacial and post-glacial deposition and erosion, so definition of the hydrogeologic units in some areas is difficult. The valley-fill aquifer system described in this report consists of three units. In general, the upper sand-and-gravel unit constitutes an unconfined aquifer, hereinafter called the upper aquifer, and the middle unit functions as a confining unit. The basal sand-and-gravel unit, hereinafter called the lower aquifer, is locally confined. The upper and lower aquifers together are called the valley-fill aquifers. In this report, wells in the study area are designated as being screened in the upper or lower aquifer on the basis of the interpretation of geologic well logs, the altitude of the water level, and the well depth. Because the confining unit varies in extent and is poorly defined in some areas, partially confined or semiconfined conditions can prevail in these areas.

The upper aquifer consists mostly of surficial outwash deposits of sand and gravel as much as 50 ft thick. The upper aquifer is underlain in places by the confining unit that consists of fine-grained, lake-bottom sediments; in other places it can be underlain by till or bedrock. The thickness of the lower aquifer ranges from about 30 to 80 ft in the Rockaway River Valley (Canace and others, 1993) and is locally confined. A thickness map of the valley-fill deposits is given in Gordon (1993).

Precipitation that falls on the valley-fill deposits infiltrates into the valley-fill aquifer system as recharge, flows overland to streams, or is returned to the atmosphere as evapotranspiration. Overland flow from the surrounding till-covered upland areas supplies recharge at the sides of the valley. Precipitation that percolates into the upper aquifer can discharge to streams, discharge through wells, or flow into the lower aquifer. It also can be taken up as evapotranspiration. The lower aquifer can receive recharge at the sides of the valley where the confining unit does not extend across the entire width of the valley. Ground water in the lower



Base from U.S. Geological Survey 1:24,000 quadrangles:
Boonton, 1943; Dover, 1943; Frankilin, 1954; Mendham, 1954;
Morristown, 1954; and Newfoundland, 1954. Universal Transverse
Mercator projection, Zone 18

Figure 1. Location of the model and study area in the Rockaway River drainage basin, Morris County, New Jersey.

aquifer discharges through wells or eventually flows upward to the upper aquifer and discharges to the Rockaway River. A small amount of water can exit from the aquifers to, or enter the aquifers from, the underlying and adjacent bedrock. Underflow from the bedrock is assumed to be small because the bedrock is much less permeable than the valley-fill deposits (Gill and Vecchioli, 1965). A generalized hydrogeologic section showing ground-water flow in the valley-fill aquifers is shown in figure 2.

Description of Hydraulic Characteristics

The valley-fill sediments consist of gravel, sand, silt, and clay deposited in glacial lakes and outwash sheets, and till deposited as a terminal moraine (Stanford, 1989a, 1989b). Typical values of horizontal hydraulic conductivity reported in previous investigations in the study area range from 100 to 17,000 ft/d for sand and gravel, and 10 to 80 ft/d for till (Gordon, 1993; Nicholson and others, 1996). Information on the hydraulic properties of the glaciolacustrine fine-grained materials of the confining unit is limited. Values reported from previous investigations in the area range from 4.3×10^{-3} to 4.2×10^{-2} ft/d (Nicholson and others, 1996). Values for the vertical hydraulic conductivity of streambed material reported for investigation near the Dover well field range from 0.2 to 0.6 (ft/d)/ft (Dysart and Rheaume, 1999). Storage coefficients for the lower aquifer reported in previous investigations range from 3×10^{-4} to 4.6×10^{-2} (Gordon, 1993). Nicholson and others (1996) report values for specific yields of the upper aquifer from 5.1×10^{-4} to 8.1×10^{-2}. Freeze and Cherry (1979) state that typical values of specific yields range from 0.01 to 0.3.

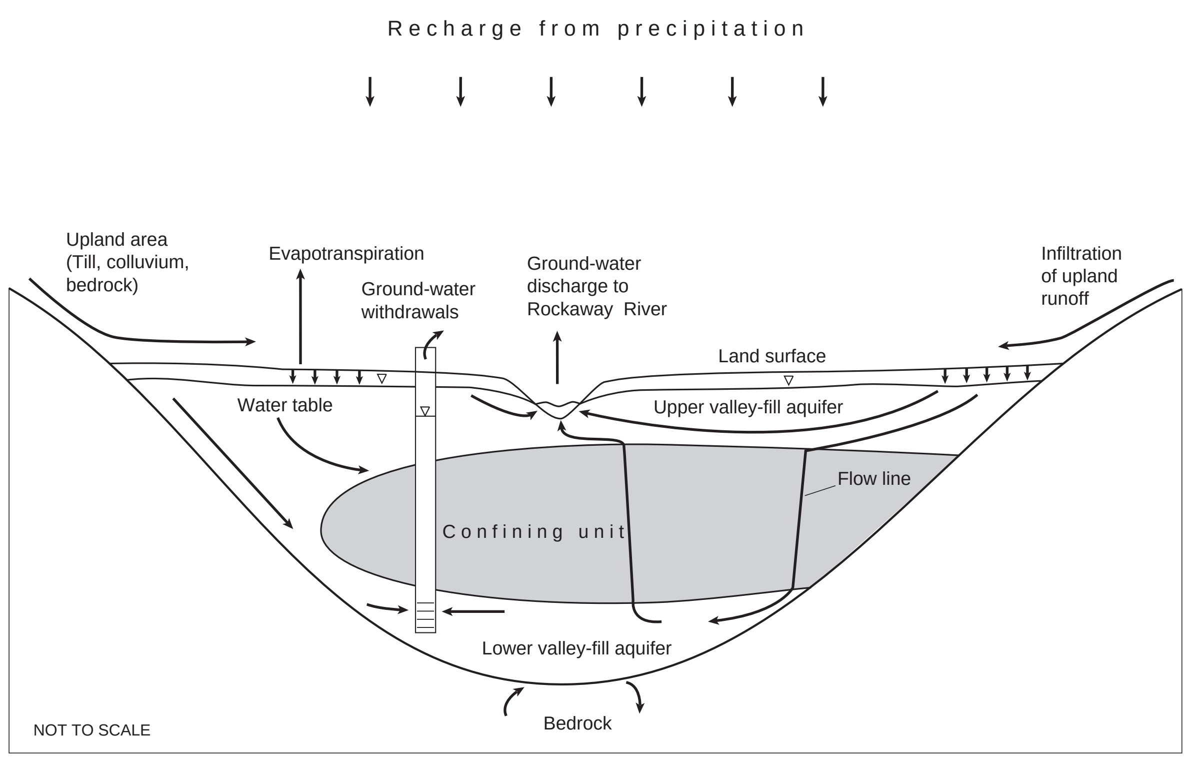


Figure 2. Generalized hydrogeologic section showing ground-water flow in the valley-fill aquifers, Rockaway River drainage basin, Morris County, New Jersey.

Ground-Water Levels and Directions of Flow

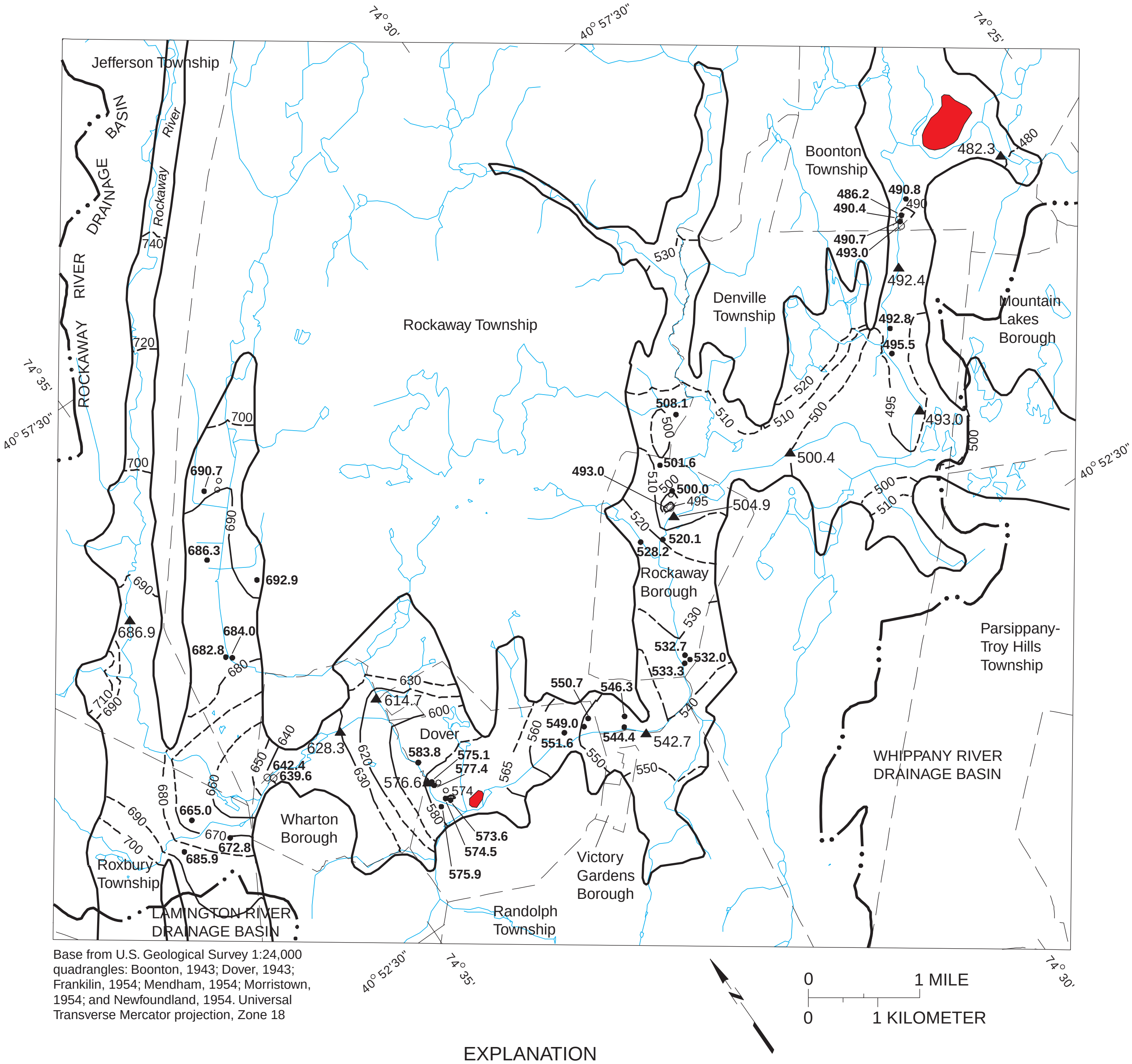
Representations of the water-table and potentiometric surfaces in the upper and lower aquifers under stressed conditions (figs. 3 and 4, respectively) were prepared using water levels measured during October 7-8, 1997, in 72 observation, production, and industrial wells screened in the valley-fill aquifers. The land-surface altitudes of these wells are given in table 1; the locations of the wells along with the New Jersey well number identifiers are shown in figure 5. Land-surface altitude at most of the wells listed in table 1 was determined by surveying methods, so water levels measured at these wells are accurate to within 0.1 ft. Detailed information on local ground-water-flow patterns is not available for parts of the model area because water-level data are sparse.

Streamflow was measured during a seepage run on October 7, 1997, at 15 surface-water sites-- at 12 stations along the river and at 3 tributaries of the Rockaway River (table 2)-- in order to determine base flow. The surface-water gaging sites are shown in figure 5. Gaging-station number 01380500 located about 0.5 mile outside the model area is shown in figure 1. Some of the surface-water elevations, where a reference point has been determined in relation to sea level, were measured during the seepage run and were used to estimate the altitude of the water table in areas near the river. This includes stream altitudes at 10 surface-water gaging sites along the mainstem of the Rockaway River where the hydraulic connection between the aquifer and river probably is good, and a reference point has been established (fig. 3).

The depths to water in the upper aquifer ranged from about 1 ft to more than 29 ft below land surface. Ground-water levels typically are lower near production wells. The water table follows the topography of the land surface; ground water flows downvalley and from upland areas near the valley perimeter to the Rockaway River near the center of the valley (fig. 3), unless it is diverted to production wells. Cones of depression are present around pumping centers in Boonton Township (wells 27-108 and 27-109), Dover (wells 27-286 and 27-288), and Rockaway Borough (well 27-137) (fig. 5). Water levels in these areas are about 14, 16, and 12 ft below land surface, respectively.

Depth to water in the lower aquifer ranged from about 3.5 ft to more than 174 ft below land surface during October 7 and 8, 1997. The potentiometric surface of the lower aquifer indicates a downvalley gradient (fig. 4). Ground water in this aquifer eventually discharges to the Rockaway River or is diverted by pumping. Ground-water withdrawals have caused cones of depression around pumping centers in Rockaway Township (wells 27-62 and 27-80) and Denville Township (wells 27-115 and 27-116) (fig. 5). Water levels measured around the pumping center in Rockaway Township were more than 45 ft below land surface. The lowest water levels in the lower aquifer, about 174 ft below land surface, were measured outside the Rockaway River Basin in Mountain Lakes Borough. The valley-fill deposits here are more than 350 ft deep, and ground water discharges to production wells located in Mountain Lakes Borough and in Parsippany-Troy Hills Township, which is outside the model area.

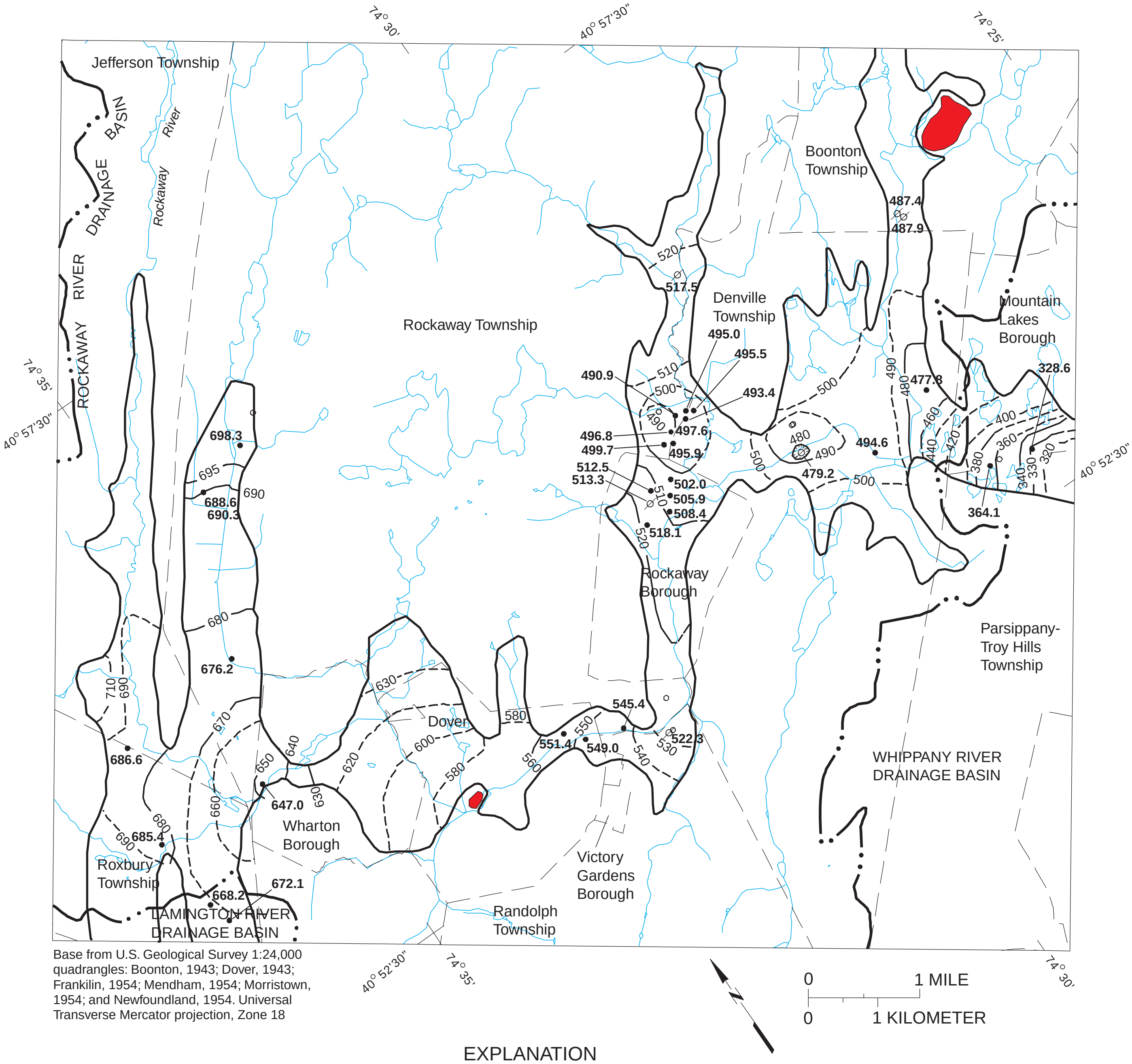
Ground-water-level data for areas near Lamington River Basin indicate that the ground-water divide does not coincide with the surface-water divide. Water levels measured in wells located in the Lamington River Basin near the Rockaway River Basin boundary (Nicholson and others, 1996) indicate that flow in the upper aquifer is towards the Rockaway River Basin. The terminal moraine deposits here are considered to be part of the upper aquifer despite their slight-to-moderate permeability; zones of higher permeability are present in the terminal moraine and may act as conduits for flow (Nicholson and others, 1996). A ground-water divide is present near the boundary of the Lamington and Rockaway River Basins in the lower aquifer (fig. 3).



EXPLANATION

[red box]	Outcrop of bedrock	686.9 ▲	Location of surface-water measurement site. Number is elevation of stream, in feet above sea level
—690 – –	WATER-TABLE CONTOUR--Shows altitude of water table. Dashed where approximately located. Contour interval is variable, in feet. Datum is sea level	○	Location of production well
		692.9 ●	Location of observation well with water-level measurement. Number is altitude of water table, in feet above sea level
———	Approximate extent of the valley-fill deposits modified from Canace and others, 1993, and Stanford, 1989a, 1989b	⌀ 642.4	Location of production well with water-level measurement. Number is altitude of water table, in feet above sea level

Figure 3. Altitude of the water table in the upper aquifer interpreted from ground-water levels and stream stages measured during October 7-8, 1997, Rockaway River model area, N.J.



EXPLANATION

Outcrop of bedrock

—690— — POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface. Dashed where approximately located. Contour interval is variable, in feet. Datum is sea level

Approximate extent of the lower aquifer in the valley-fill deposits modified from Canace and others, 1993, and Stanford, 1989a, 1989b

Location of production well

686.6 Location of observation well with water-level measurement. Number is altitude of water table, in feet above sea level

517.5 Location of production well with water-level measurement. Number is altitude of water table, in feet above sea level

Figure 4. Altitude of the potentiometric surface in the lower aquifer interpreted from ground-water levels measured during October 7-8, 1997, Rockaway River model area, N.J.

Table 1. Records of wells in the Rockaway River model area, New Jersey

[--, data not available]

New Jersey well number	New Jersey permit number	Owner	Primary use of water[1]	Altitude of land surface[2] (feet)	Depth of well[3] (feet)	Aquifer code[4]
		Boonton Township				
27-29	25-12046	Boonton Town Water Dept.	P	495.5	55.0	112SFDF1
27-30	25-07495	Boonton Town Water Dept.	P	499.3	106	112SFDF2
27-32	25-17311	Boonton Town Water Dept.	U	501.6	40.0	112SFDF1
27-108	45--00284	Boonton Town Water Dept.	P	504.9	43.0	112SFDF1
27-109	45--00285	Boonton Town Water Dept.	P	502.9	45.0	112SFDF1
27-919	--	Boonton Town Water Dept.	U	498.9	25.0	112SFDF1
27-1793	25-33228	Boonton Town Water Dept.	P	498.8	130	112SFDF2
		Denville Township				
27-35	25-09515	Denville Township Water Dept.	P	509.2	201	112SFDF2
27-115	45-00324	Denville Township Water Dept.	P	520	147	112SFDF2
27-116	25-05142	Denville Township Water Dept.	P	511.6	117	112SFDF2
27-189	45-00301	Mountain Lakes Water Dept.	P	503.9	64.0	112SFDF1
27-190	45-00300	Mountain Lakes Water Dept.	P	500	64.0	112SFDF1
27-321	--	Rockaway River Country Club	U	514.4	167	112SFDF2
27-324	25-21172	Northwest Covenant Medical Center	U	500.5	200	112SFDF2
		Dover				
27-286	25-13542	Town of Dover Water Dept.	P	590.7	65.0	112SFDF1
27-288	45-00281	Town of Dover Water Dept.	P	590.1	74.0	112SFDF1
27-292	25-24892	U.S. Geological Survey	U	581.2	17.7	112SFDF1
27-291	25-16024	Town of Dover Water Dept.	P	590.1	64.0	112SFDF1
27-295	25-24887	U.S. Geological Survey	U	588.6	28.6	112SFDF1
27-297	25-24897	U.S. Geological Survey	U	591.4	28.4	112SFDF1
27-301	25-24890	U.S. Geological Survey	U	591.0	28.8	112SFDF1
27-303	25-24895	U.S. Geological Survey	U	586.7	22.9	112SFDF1
27-1225	25-29156-4	N.J. Dept. of Environmental Protection	U	553.9	160	112SFDF2
27-1226	25-29170-0	N.J. Dept. of Environmental Protection	U	557.9	58	112SFDF1
27-1228	25-29164-5	N.J. Dept. of Environmental Protection	U	555.9	58	112SFDF1
27-1229	25-29165-3	N.J. Dept. of Environmental Protection	U	555.6	117	112SFDF2
27-1866	25-29160-2	Town of Dover Water Dept.	U	554	17	112SFDF1
		Jefferson Township				
27-27	25-22024	N.J. Dept. of Environmental Protection	U	725.6	98.0	112SFDF2
		Mountain Lakes Borough				
27-191	25-14698	Mountain Lakes Water Dept.	P	505.0	332	112SFDF2
27-323	25-21173	Mountain Lakes Water Dept.	U	502.8	250	112SFDF2
27-914	25-13697	Mountain Lakes Water Dept.	U	505.0	345	112SFDF2
		Randolph Township				
27-117	25-19071	Denville Township Water Dept.	C	545.6	139.6	112SFDF2
27-136	45-00325	Denville Township Water Dept.	P	550	135	112SFDF2

Table 1. Records of wells in the Rockaway River model area, New Jersey--Continued

New Jersey well number	New Jersey permit number	Owner	Primary use of water[1]	Altitude of land surface[2] (feet)	Depth of well[3] (feet)	Aquifer code[4]
		Rockaway Borough				
27-58	25-10403	Rockaway Borough Water Dept.	P	520	80.3	112SFDF2
27-59	25-18231	Rockaway Borough Water Dept.	P	520	83.0	112SFDF2
27-137	45-00348	Rockaway Borough Water Dept.	P	520	48.7	112SFDF1
27-686	25-14015	McWilliams Forge Inc.	N	560	148	112SFDF2
27-876	25-05419	Rockaway Borough Water Dept.	U	530.7	72.0	112SFDF1
27-925	25-23986	McWilliams Forge Inc.	U	536.9	30	112SFDF1
27-926	25-24171	McWilliams Forge Inc.	U	537.8	30	112SFDF1
27-927	25-23987	McWilliams Forge Inc.	U	537.9	30	112SFDF1
27-929	25-27147	N.J. Dept. of Environmental Protection	U	546.2	30.1	112SFDF1
27-930	25-27148	N.J. Dept. of Environmental Protection	U	555.6	92.0	112SFDF2
27-931	25-27149	N.J. Dept. of Environmental Protection	U	515.2	88.3	112SFDF2
27-932	25-27150	N.J. Dept. of Environmental Protection	U	511.0	37.0	112SFDF1
27-933	25-27151	N.J. Dept. of Environmental Protection	U	530.8	73.3	112SFDF1
27-934	25-27152	N.J. Dept. of Environmental Protection	U	532.1	61.0	112SFDF2
27-935	25-27153	N.J. Dept. of Environmental Protection	U	524.7	68.3	112SFDF2
		Rockaway Township				
27-62	25-14324	Rockaway Township Water Dept.	P	520	163	112SFDF2
27-80	25-15364	Rockaway Township Water Dept.	P	520	150	112SFDF2
27-81	45-00365	US ARMY-Picatinny Arsenal	P	704	113	112SFDF2
27-86	45-00366	US ARMY-Picatinny Arsenal	N	711	92.5	112SFDF2
27-104	--	US ARMY-Picatinny Arsenal	U	692.6	20.4	112SFDF1
27-187	45-00037	Rockaway Township Water Dept.	P	510	150	112SFDF2
27-232	--	US ARMY-Picatinny Arsenal	U	695.5	29.	112SFDF1
27-235	--	US ARMY-Picatinny Arsenal	U	690.9	20.	112SFDF1
27-247	25-23214	US ARMY-Picatinny Arsenal	U	700.0	206	112SFDF2
27-248	25-23215	US ARMY-Picatinny Arsenal	U	700.3	140	112SFDF2
27-249	25-23216	US ARMY-Picatinny Arsenal	U	700.2	35.0	112SFDF1
27-251	25-23209	US ARMY-Picatinny Arsenal	U	693.3	65.	112SFDF1
27-252	25-23210	US ARMY-Picatinny Arsenal	U	693.1	157	112SFDF2
27-276	25-22809	US ARMY-Picatinny Arsenal	U	698.9	74.	112SFDF2
27-704	25-09626	Rockaway Township Water Dept.	P	523.5	119	112SFDF2
27-709	25-21465	GlitterWrap	U	524.1	50	112SFDF2
27-910	--	N.J. Dept. of Environmental Protection	U	543.8	68	112SFDF2
27-1223	25-29159-9	N.J. Dept. of Environmental Protection	U	548.8	130	112SFDF2
27-1231	25-29331	N.J. Dept. of Environmental Protection	U	532.4	195	112SFDF2
27-1232	25-29332	N.J. Dept. of Environmental Protection	U	543.1	128	112SFDF2
27-1234	25-29341	N.J. Dept. of Environmental Protection	U	522.3	149	112SFDF2
27-1235	25-29339	N.J. Dept. of Environmental Protection	U	524.1	49.3	112SFDF2
27-1236	25-29342	N.J. Dept. of Environmental Protection	U	528.3	48.7	112SFDF2
27-1238	25-29340	N.J. Dept. of Environmental Protection	U	523.0	75.8	112SFDF2
27-1714	25-14562	Howmet Corp.	N	560	134	112SFDF2
27-1867	--	N.J. Dept. of Environmental Protection	U	542.3	56.6	112SFDF2
27-1869	25-29157-2	Dover Holding Co.	U	548.1	16	112SFDF1
27-1870	--	Dover Holding Co.	U	522.6	18.2	112SFDF1
27-1871	25-29158-1	N.J. Dept. of Environmental Protection	U	552.2	93.	112SFDF1
27-1883	25-35859	US ARMY-Picatinny Arsenal	U	700	51.5	112SFDF1
27-1884	25-35861	US ARMY-Picatinny Arsenal	U	700	51.5	112SFDF1

Table 1. Records of wells in the Rockaway River model area, New Jersey--Continued

New Jersey well number	New Jersey permit number	Owner	Primary use of water[1]	Altitude of land surface[2] (feet)	Depth of well[3] (feet)	Aquifer code[4]
		Roxbury Township				
27-908	25-22364	Zalasky, Minnie	H	710	135.	112SFDF2
27-921	--	N.J. Dept. of Environmental Protection	U	695.5	87.9	112SFDF2
27-976	25-16941	Miller, Lillian	H	686.5	60.	112SFDF1
27-977	25-21483	Roxbury Township Water Dept.	P	705	208	112SFDF2
27-1124	25-32787-9	U.S. Geological Survey	U	725	175	112SFDF2
27-1184	25-15103	Herrs Motor Express	C	720	50.	112SFDF1
27-1660	25-16974	N.J. Dept. of Transportation	U	700	52	112SFDF1
		Wharton Borough				
27-353	25-15799	Wharton Borough Water Dept.	P	597.3	65	112SFDF1
27-826	25-02172	Wharton Borough Water Dept.	P	650	42.0	112SFDF1
27-827	25-08675	Wharton Borough Water Dept.	P	650	32.0	112SFDF1
27-915	25-15572	Wharton Borough Water Dept.	U	597.3	65	112SFDF1
27-1192	25-34668-7	State of N.J.	U	669.1	100.	112SFDF2

[1] Use of water

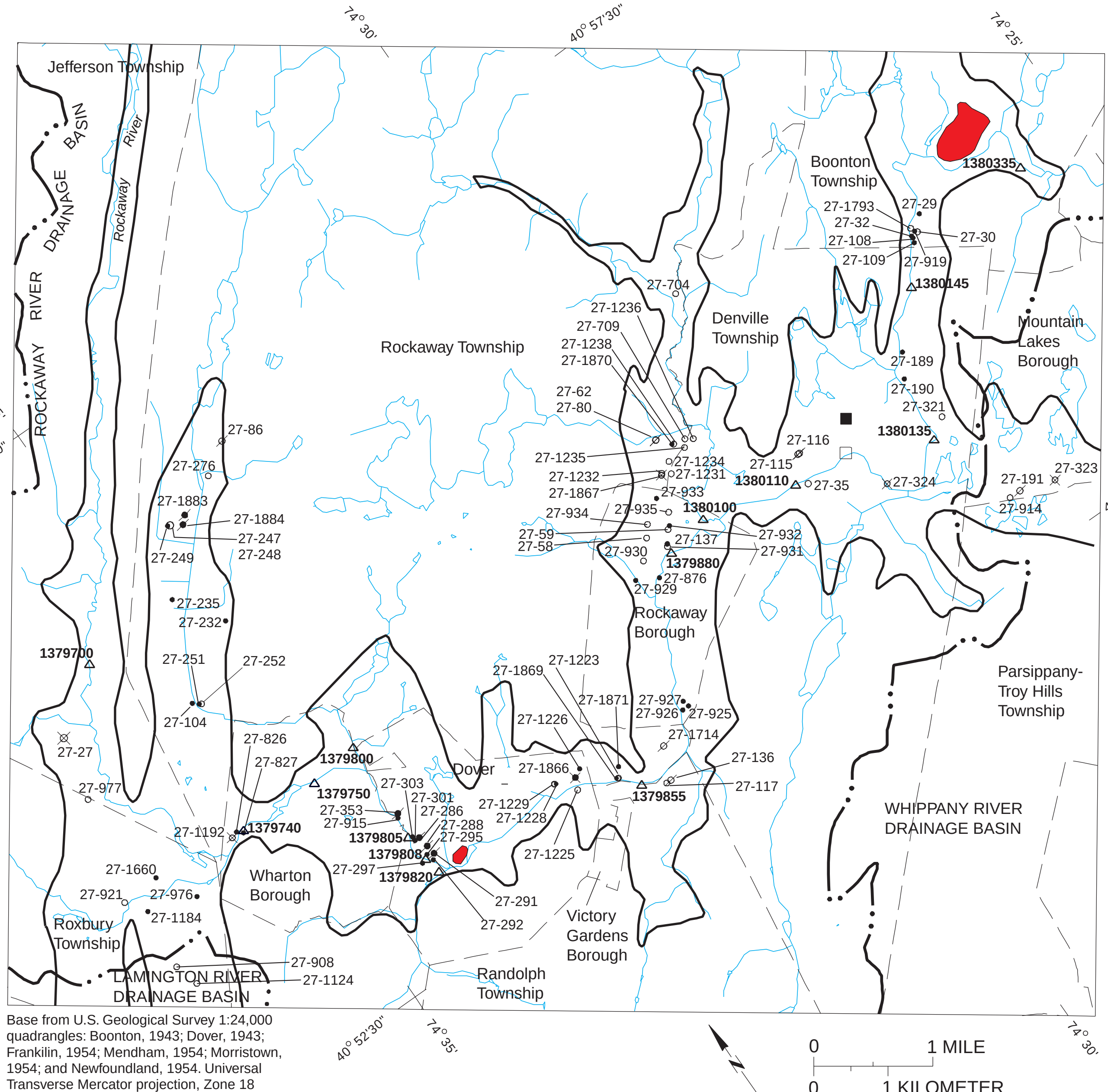
- C commercial
- H domestic
- N industrial
- P public supply
- U unused

[2] Datum is sea level

[3] Datum is land surface

[4] Aquifer units

112SFDF1 Upper aquifer of the stratified drift
112SFDF2 Lower aquifer of the stratified drift



EXPLANATION

- Outcrop of bedrock
- Approximate extent of the valley-fill deposits modified from Canace and others, 1993, and Stanford, 1989a, 1989b
- Hypothetical production well in upper aquifer (model layer 1)
- Hypothetical production well in lower aquifer (model layer 2)
- 1380135 Location and number of surface-water measurement site
- 27-104 Location and well number of production or observation well with water-level measurement in model layer 1
- 27-249 Location and well number of production or observation well with water-level measurement in model layer 2
- 27-288 Location and well number of production well in model layer 1
- 27-116 Location and well number of production well in model layer 2
- 27-1866 Location and number of observation well with continuous water-level measurements in model layer 1
- 27-27 Location and number of observation well with continuous water-level measurements in model layer 2

Figure 5. Locations of surface-water measurement sites, production and observation wells, observation wells with continuous water-level measurements, and hypothetical production wells, Rockaway River model area, N.J.

Table 2. Discharge measurements for the Rockaway River, N.J.

[Station type: L, low-flow partial-record station; G, gaging station; M, miscellaneous discharge station; mi^2, square miles; ft^3/s, cubic feet per second]

Station number	Station name	Station type	Drainage area (mi^2)	Discharge (ft^3/s)	
				6/3/86	10/7/97
01379700	Rockaway River at Berkshire Valley	G	24.4	23.8	10.6
01379740	Rockaway River at West Central Avenue at Dover[1]	M[2]	30.3	36.1	13.9
01379750	Rockaway River at Dover[1]	L	30.8	32.2	16.8
01379800	Green Pond Brook at Dover	M	15.1	10.8	2.6
01379805	Rockaway River above Dover well field at Dover	M	46.3	45.0	21.3
01379808	Rockaway River below Dover well field at Dover	M	47.1	44.5	20.8
01379820	Jackson Brook at mouth at Dover	M	4.87	3.97	2.9
01379855	Rockaway River at Rockaway Road at Randolph	M	56.1	53.7	24.1
01379880	Rockaway River at Rockaway	M	64.3	56.4	28.1
01380100	Beaver Brook at Rockaway	M	22.2	7.91	4.2
01380110	Rockaway River at Savage Avenue at Denville	M	87.6	67.0	31.9
01380135	Rockaway River at Pocono Road at Denville	M	96.7	70.0	32.7
01380145	Rockaway River at Bush Road at Denville	M	99.5	86.5	35.6
01380335	Rockaway River at North Main Street at Powerville	M	115	83.5	48.3
01380500	Rockaway River above Reservoir at Boonton	G	116	74.6	36.9

[1] Located below Dover at Wharton.
[2] Miscellaneous discharge station—a station where measurements of streamflow are made at points other than gaging stations.

Seasonal fluctuations in ground-water levels can be seen in hydrographs of continuously monitored water levels measured by either mechanical water-level recorders or pressure transducers (fig. 6). The locations of the wells where continuous water-level measurements were made are shown in figure 5. The hydrographs of three wells-- 27-323, 27-1866, and 27-1867-- show water-level fluctuations during early November 1997 to early October 1998. Two wells, 27-27 and 27-1192, have a longer period of record from April 1994 through October 1998. The hydrographs, particularly those for the two wells with the longer period of record, show a decline in water levels during summer and fall and a rise in water levels during winter and spring. Water levels typically are lower in summer and early fall because of high rates of evapotranspiration and low rates of ground-water recharge during the summer. In addition, individual storms can cause short-term fluctuations in water levels, over a period of a few days, particularly in wells screened in unconfined or semiconfined aquifers, for example well 27-1866, which is screened in the upper aquifer, and well 27-324 which is screened in the lower aquifer. Wells with large fluctuations in water levels are located in areas with large withdrawals, for example well 27-323, which is located near production well 5 (27-191) in Mountain Lakes Borough. This well was pumped at an average daily rate of 0.67 Mgal/d in 1997.

Ground-Water Withdrawals

Total monthly ground-water withdrawals from the valley-fill aquifers in the upper Rockaway River Basin during April 1994-September 1998 and are shown in figure 7. The average daily withdrawals during 1997 for each production well in the study area are listed in table 3. These wells and their well numbers are shown in figure 5. The wells listed in table 3 include water-supply and some industrial wells in Wharton, Rockaway, and Mountain Lakes Boroughs, Rockaway, Denville, Boonton and Roxbury Townships, and Dover. Private and small industrial wells in the study area with total annual withdrawals of less than 48,000 gallons per month (0.002 Mgal/d) were not included in table 3. The total withdrawals from these wells is estimated to be less than 0.05 Mgal/d. Withdrawal data were obtained from municipal water-supply purveyors and from the New Jersey District Site-Specific Water Use Data System (SWUDS) data base. During the time period shown in figure 7, total monthly withdrawals fluctuated from about 8.2 Mgal/d in October 1995 to about 11.5 Mgal/d in June 1997.

Aquifer/Stream Interactions

Discharge measurements were made at various sites along twelve reaches and three tributaries of the Rockaway River on October 7, 1997. The measurements are listed in downstream order in table 2. For comparison, discharge measurements made on June 3, 1986, also are given (Bauersfeld and others, 1987); the discharge values are assumed to approximate base flow. It is assumed that the reaches along the Rockaway River are gaining reaches, except where natural leakage from streams to the upper valley-fill aquifer occurs at the sides of the valley. Natural leakage from streams to the valley-fill aquifers occurs as upland tributary streams enter large valleys that are underlain by stratified-drift glacial deposits and lose water to the valley-fill aquifers by infiltration through streambeds (Morrisey and others, 1988). No measurements of discharge between reaches of upland tributaries are available. Measurements were made mainly on the mainstem of the Rockaway River and major tributaries. The discharge values for both dates indicate that along the course of the Rockaway River some reaches lose water to the aquifer, whereas other reaches gain water from the aquifer. These losing reaches typically occur in areas where production wells are located near the river, and possibly result from infiltration induced by ground-water withdrawal. Losing reaches were observed between surface-water gaging sites 01379740 and 01379750 in Wharton Borough near production wells 1 (27-826) and 2 (27-827) and between gaging sites and 01379805 and 01379808 located at the well field in Dover (wells 27-286 and 27-288) (fig. 5). The measurements on June 3, 1986, also indicate that the reaches between surface-water gaging sites 01380145 and

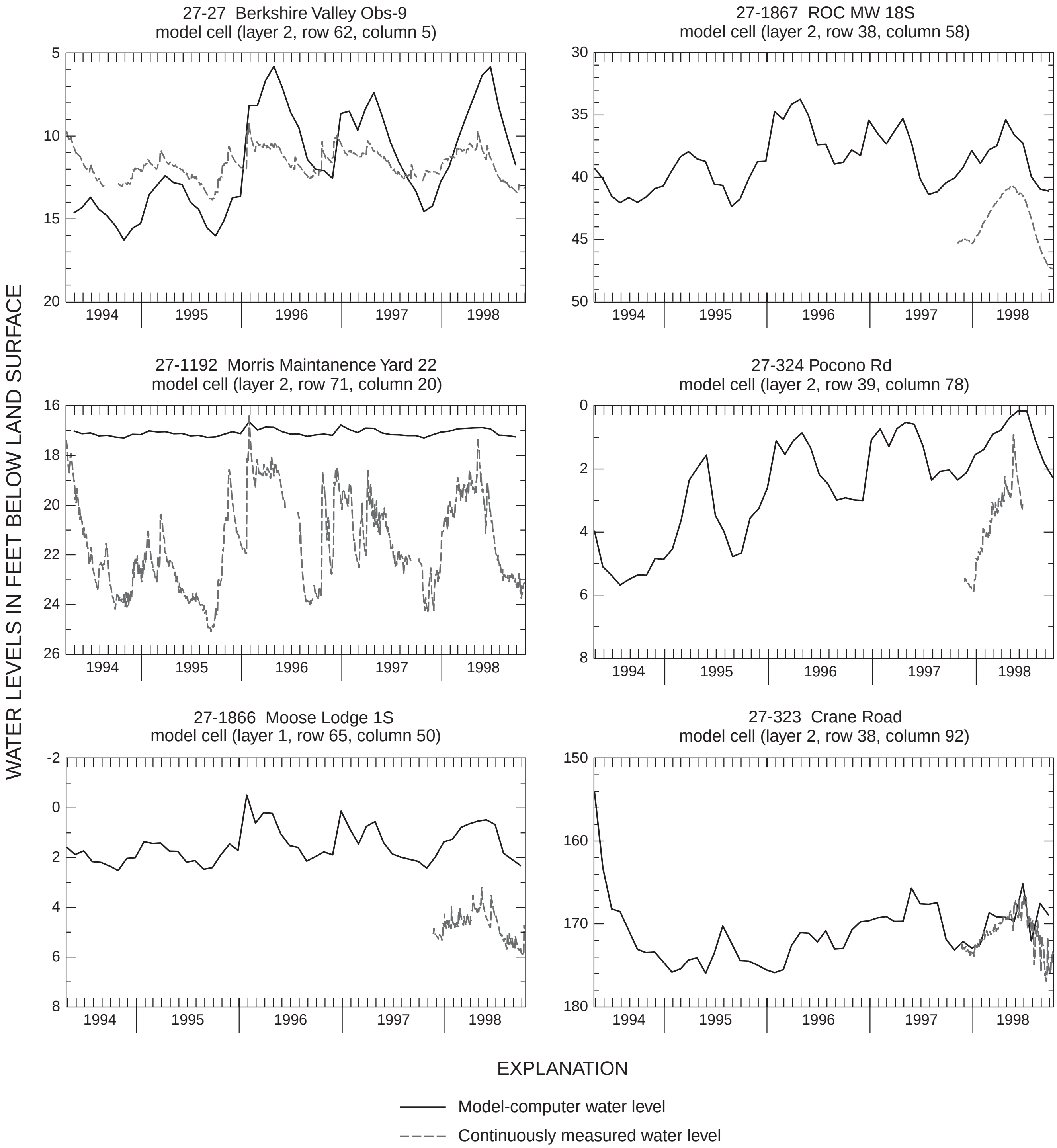


Figure 6. Hydrographs showing continuous water-level measurements and model-computed water levels, Rockaway River model area, N.J. (Discrepancies between model-computed and measured water-level fluctuations are discussed in the section on model-computed water levels. See figure 8 for cell locations)

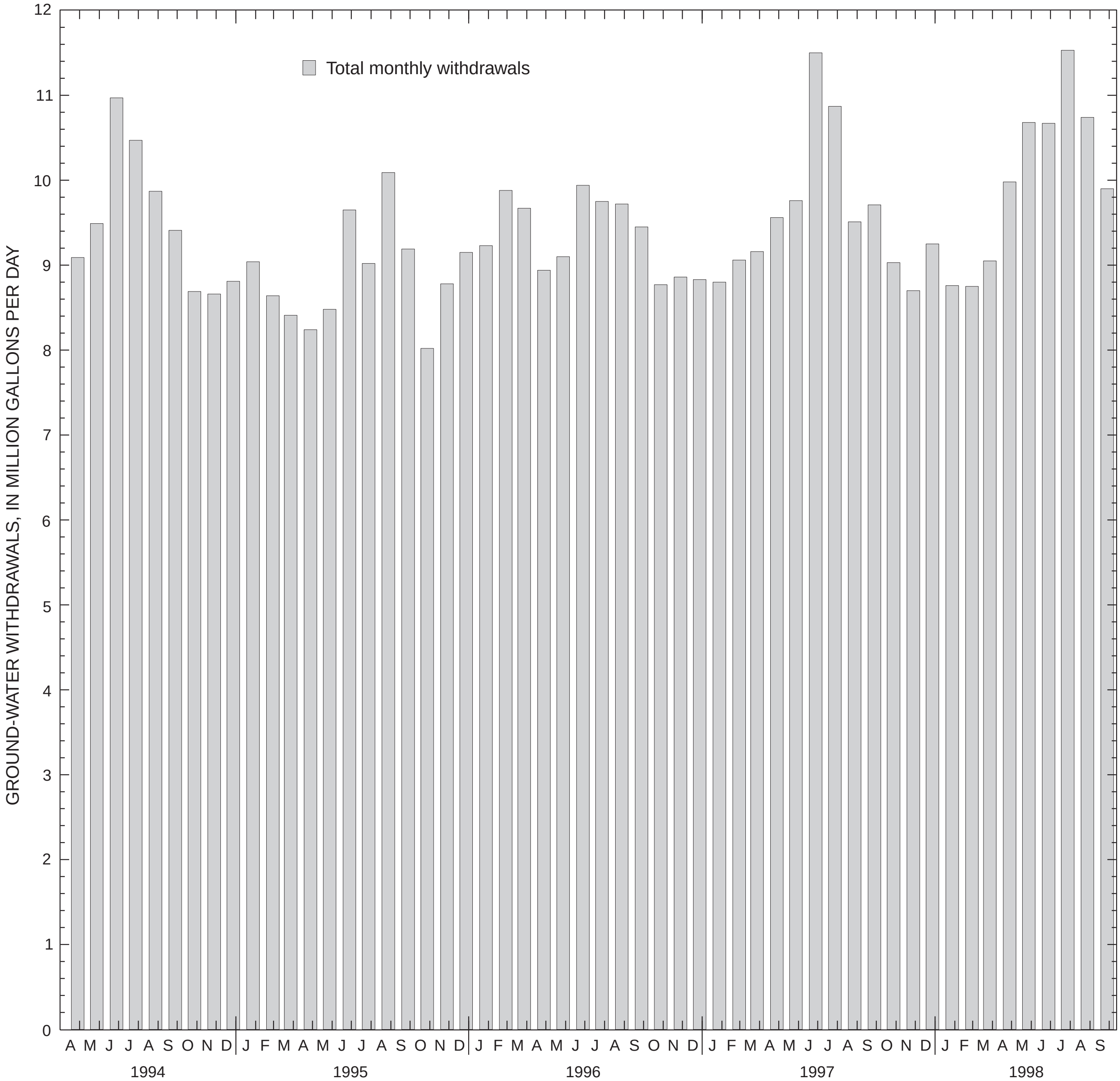


Figure 7. Monthly ground-water withdrawals from the valley-fill aquifers within the Rockaway River model area, N.J., April 1994 – September 1998.

Table 3. Average daily ground-water withdrawals in 1997 from the valley-fill aquifers in the Rockaway River model area, N.J.

[Mgal/d, million gallons per day; --, well not used in 1997]

New Jersey well number	Owner	Local well number or name	Location in model (fig. 8)			Average daily withdrawals in 1997 (Mgal/d)
			Layer	Row	Column	
27-108	Boonton Town Water Dept.[1]	1	1	17	80	0.04
27-109		2	1	17	80	.04
27-1793		4A	2	16	79	.13
27-30		5	2	16	80	.16
27-115	Denville Township Water Dept.	1	2	36	70	.2
27-136		3	2	65	59	.13
27-116		4	2	36	70	.48
27-35		5	2	39	71	.01
27-117		6	2	65	58	.57
27-286	Town of Dover Water Dept.	1	1	70	37	1.98
27-288		3	1	71	37	.95
27-291		5	1	72	38	--
27-189	Mountain Lakes Water Dept.	4	1	27	79	.001
27-191		5	2	39	89	.67
27-137	Rockaway Borough Water Dept.	1	1	44	58	.3
27-58		5	2	44	57	.23
27-59		6	2	43	58	.7
27-187	Rockaway Township Water Dept.	4	2	35	57	.04
27-62		6	2	35	57	.34
27-80		7	2	35	57	.79
27-704		8	2	23	59	.19
27-977	Roxbury Township Water Dept.	Evergreen Acres	2	67	7	--
27-826	Wharton Borough Water Dept.	1	1	70	21	.105
27-827		2	1	70	21	.105
27-353		3	1	69	35	.71
27-1714	Howmet Corporation	2	2	62	58	.19
17-686	McWilliams Forge, Inc.	339	2	57	61	.003
27-86	U.S. Army-Picatinny Arsenal	410	2	36	19	.38
27-1883		WW3	1	42	15	.09
27-1884		WW5	1	43	15	.09
						Total = 9.624

[1] Withdrawals for Boonton are from wells located in Boonton Township.

01380335 near production wells 1 (27-108) and 2 (27-109) in Boonton Township are losing reaches.

SIMULATION OF GROUND-WATER FLOW

Ground-water flow in the valley-fill aquifers was simulated under transient conditions for the period from April 1994 to September 1998. The transient model used in this study is based on a previously developed steady-state ground-water flow model calibrated to 1986 average annual conditions (Gordon, 1993); that model was revised for this study. The revisions include input of monthly ground-water recharge and withdrawals, and changes to hydraulic characteristics for some areas. This section of the report includes a discussion on revisions to the previous steady-state model to simulate transient conditions, and a discussion of a steady-state model run of the previous steady-state model (Gordon 1993) as a check on how the revisions to hydraulic parameters in some areas may affect the calibration of the steady-state model.

Model Design, Grid, and Boundary Conditions

The ground-water-flow model used in this study was developed by using the Harbaugh and McDonald (1996) ground-water-flow program. The design of the transient model incorporates the same assumptions that were used in the calibration of the steady-state model (Gordon, 1993): the valley-fill aquifers are isotropic in the horizontal direction, the bedrock is a no-flow boundary, and flow is horizontal in the aquifers and vertical in the confining unit. The ground-water-flow model allows for simulations of areal recharge, stream/aquifer interactions, discharge to wells, and general-head and constant-head boundaries. Ground-water evapotranspiration was not simulated explicitly because of the unavailability of data, but was incorporated into the estimate of recharge.

The finite-difference grid used to simulate the valley-fill aquifer system (fig. 8) consists of 85 rows, 96 columns, and 2 layers, which represent an upper and a lower aquifer (fig. 9). The grid is oriented northeast to southwest, parallel to the trend of the bedrock ridges. The grid spacing is uniform and each cell is 500 ft on each side. This cell spacing was chosen in order to simulate a 1,500-ft-wide constriction at Wharton Borough. A minimum of three cells across this narrow constriction was assumed to be necessary for adequate simulation. A uniform grid and cell spacing of 500 ft was considered to be acceptable for simulating the regional ground-water flow system.

The active cells in the grid for layer 1 (upper layer) are shown in figure 8. The active cells in the grid generally correspond to the areal extent of the valley-fill aquifers within the model area; however, in some areas the valley-fill aquifers were not simulated because of the limited saturated thickness of the valley-fill deposits. The active cells for layer 2 (lower layer) are similar to those in layer 1, but some of the cells located along the valley-fill perimeter are inactive because the lower aquifer is not present or is thin. A schematic representation of the 2-layer conceptual model, representing the ground-water-flow system, and model boundaries are shown in figure 9.

A section of the Lamington River Basin was included in the model area to simulate lateral flow in and out of the model boundary there. The model boundary at Mountain Lakes Borough was extended beyond the Rockaway River Basin into the Whippany River Basin to simulate the effects of ground-water withdrawals from the valley-fill aquifers in this part of the model area.

A total of 54 stress periods were simulated to represent each month from April 1994 to September 1998. The length of each stress period was selected on the basis of ground-water-withdrawal, streamflow and precipitation data availability. Twenty time steps were simulated within each stress period.

The types of boundaries used in the model are constant-head, no-flow, specified flow, and head-dependent flow. Constant heads are used to represent lakes in two areas. A no-flow boundary

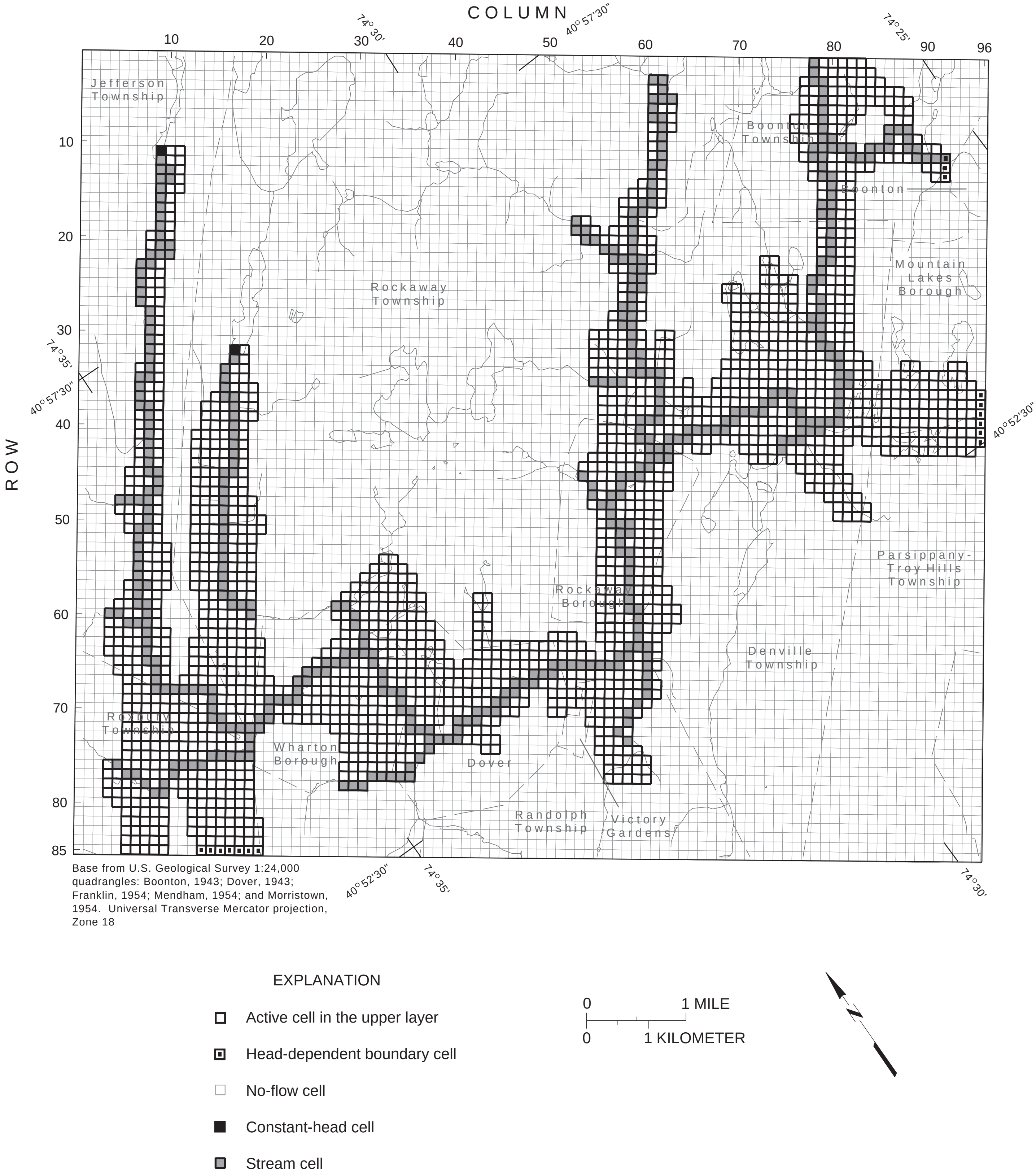


Figure 8. Finite-difference grid for the upper model layer (layer 1), Rockaway River model area, N.J.

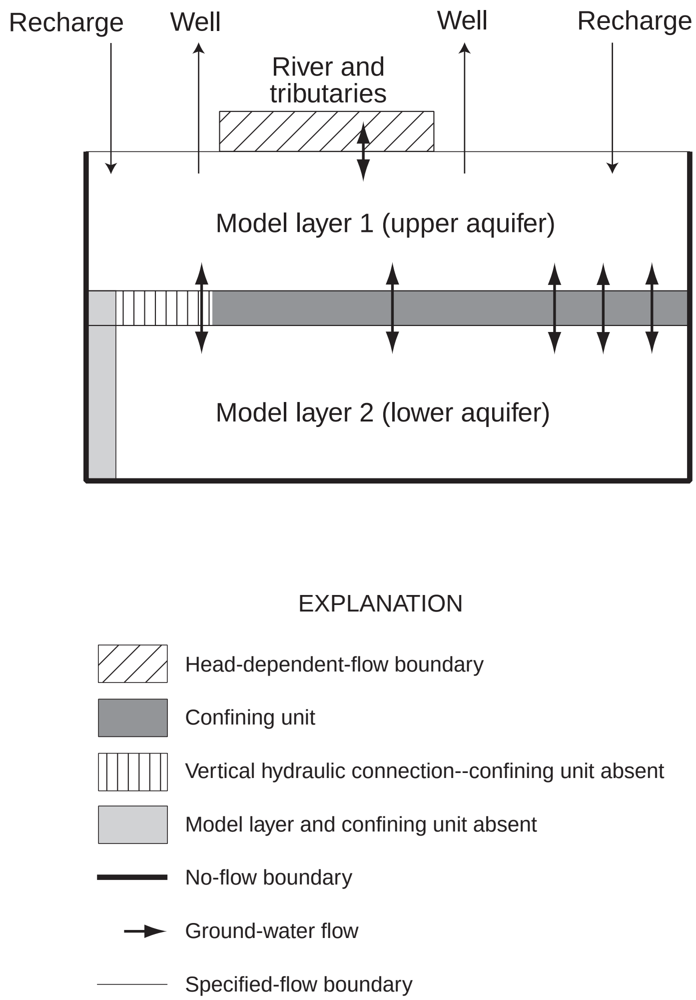


Figure 9. Schematic representation of the ground-water flow system, Rockaway River model area, N.J.

was imposed on the boundary beneath layer 2, beneath layer 1 where layer 2 is absent, and along the perimeter of the valley fill, except where head-dependent and constant-head boundaries were used. The no-flow boundary represents the contact of the valley-fill deposits with the surrounding and underlying impermeable bedrock. A no-flow boundary was assigned from column 6 through column 10 in row 85. This area is assumed to approximately coincide with the ground-water divide between the Rockaway River and the Lamington River. Head-dependent boundaries were assigned by use of the general-head-boundary package of the modular model (McDonald and Harbaugh, 1984) to simulate lateral flow at the specified model boundaries. These boundaries were imposed (1) at the southwestern model boundary in Roxbury Township; (2) near the boundary of Boonton Township and Boonton (fig. 1) where the Rockaway River flows out of the model area; and (3) at Mountain Lakes Borough outside the Rockaway River drainage basin boundary. The head-dependent flow boundary assigned at Roxbury Township simulates flow between the Lamington River and Rockaway River Basins. The head-dependent flow boundary imposed at Mountain Lakes Borough simulates the effects of withdrawals in Parsippany-Troy Hills Township on ground-water flow in the valley-fill aquifers in the model area. The upper model boundary is a specified-flow boundary that represents recharge to all active cells in layer 1. The mainstem of the Rockaway River and its larger and some smaller tributaries within the valley-fill area are simulated as head-dependent flow boundaries at designated cells in the upper layer by use of the river package of the modular model (McDonald and Harbaugh, 1984).

Model Input

Aquifer properties were assigned to each active cell; each assigned value reflects the average value for the aquifer volume represented by that cell. Pumpage stresses, recharge, and stream properties, such as stage, streambed hydraulic conductivity and altitude of streambed, were assigned to appropriate cells. Hydraulic properties that were assigned to the upper layer are the altitude of the bottom of the upper layer and horizontal hydraulic conductivity. A value for specific yield was assigned to active cells in the upper layer. Transmissivity and a storage coefficient were assigned to active cells in the lower layer. A vertical leakance between the upper and lower layers was assigned to active cells in the upper layer and active cells in the lower layer. Total monthly withdrawals were input for each well screened in the valley-fill aquifers that was pumped during April 1994-September 1998. The nodal location-- layer, row and column-- for these wells is given in table 3.

To determine the initial heads (water levels) for the transient simulation, a steady-state simulation was performed using the previously calibrated model (Gordon, 1993) and 1994 average yearly withdrawals. The heads that resulted from this steady-state run were input as the initial heads for the transient simulation.

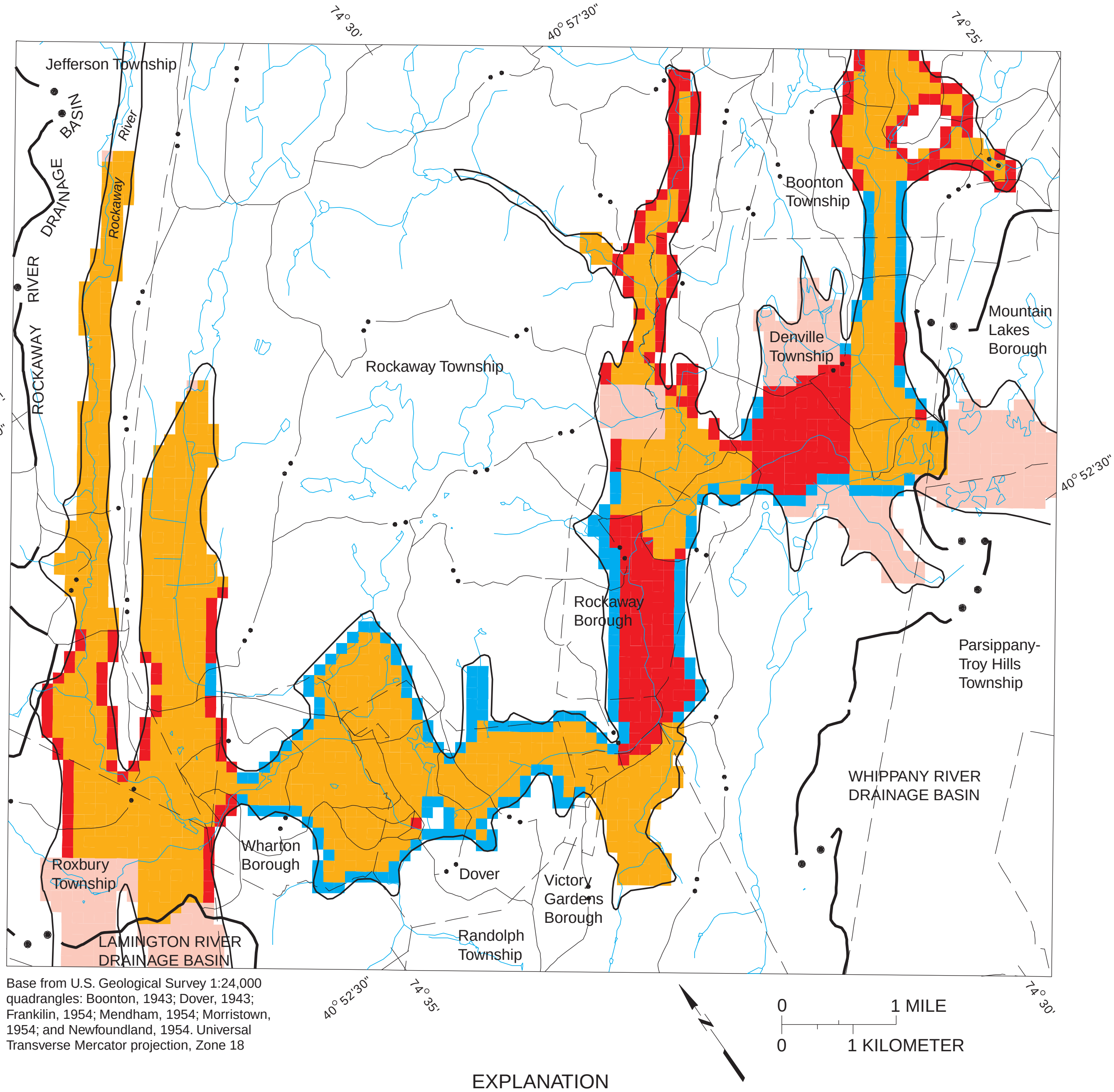
Recharge

Unlike the previous steady-state model, recharge in the transient model was based on monthly conditions so that seasonal changes in base flow could be simulated. The steady-state model incorporated an average ground-water recharge value determined by base-flow separation techniques. This average value was nonuniformly distributed over the model area, depending on permeability of the surficial deposits and the location in the upper Rockaway River Valley. Cells near the valley perimeter received additional recharge from upland sources. For the transient model, recharge to the valley-fill aquifer system was estimated as a percentage of monthly precipitation recorded at rain-gaging station near Oak Ridge Reservoir, northwest of Green Pond Brook (fig. 1), just outside the Rockaway River Basin from April 1994 to September 1998 (National Oceanic and Atmospheric Administration, 1994, 1995, 1996, 1997, and 1998).

Ground-water recharge from precipitation that falls on the valley-fill deposits and infiltrates into the ground-water flow system is the principal source of inflow to the valley-fill aquifers. A percentage of the total monthly precipitation was determined for each month and used to estimate recharge for that month. These percentages were modified during model calibration from percentages determined for an investigation of Picatinny Arsenal (Mary Martin, U.S. Geological Survey, written commun., 1997), which is located south of Picatinny Lake (fig. 1). The total monthly precipitation was multiplied by the percentage specified for each month, and the results were input as recharge, by month. The percentages ranged from 19 percent for August to 91 percent for March and are presented below. The percentages show that recharge increased during the winter and spring months of December through May. During the summer months, the potential evapotranspiration is much higher and affects recharge amounts during this season.

Monthly values of recharge were nonuniformly distributed to active cells in layer 1 (fig. 10). This distribution was achieved by multiplying the recharge amount for that month by a recharge distribution multiple that accounted for additional recharge from upland sources and the permeability of the surficial glacial deposits. The assigned recharge distribution multiplier integrates four recharge mechanisms: (1) precipitation that directly infiltrates the valley-fill deposits, (2) infiltration of unchanneled runoff from the surrounding upland till, (3) streamflow loss from small upland-draining tributaries, and (4) lateral inflow from surrounding surface-water basins. The multiplier has a value of 1.0 if recharge comes only from precipitation that directly infiltrates the valley-fill deposits, and a value greater than 1.0 if the cell receives recharge from upland runoff or other sources. Results of studies of several areas in the glaciated northeastern United States indicated that an appreciable percentage of the natural recharge to glacial valley aquifers is derived from upland runoff (Morrissey and others, 1988). To account for recharge from upland areas, more recharge was applied to model cells that represent the valley edges and to some model cells that underlie areas where stream tributaries, if the stream is not explicitly simulated, are present in the upland area, than to model cells that represent other surficial valley-fill deposits. The percentage of upland area contributing recharge to the valley-fill aquifer system was determined for the previous steady-state model (Gordon, 1993) and is a function of upland drainage patterns, grain-size distribution of the glacial cover, valley width, and slope. Recharge from upland areas includes seepage losses from upland-draining tributaries, infiltration of unchanneled runoff at the bases of hillsides, and underflow of ground water from till or bedrock. Gordon (1993) describes in more

Month	Percent of total monthly precipitation	Month	Percent of total monthly precipitation
January	78	July	23
February	88	August	19
March	91	September	21
April	73	October	24
May	55	November	50
June	35	December	70



Base from U.S. Geological Survey 1:24,000 quadrangles: Boonton, 1943; Dover, 1943; Frankilin, 1954; Mendham, 1954; Morristown, 1954; and Newfoundland, 1954. Universal Transverse Mercator projection, Zone 18

EXPLANATION

Recharge distribution multiple–a value assigned to each active cell in the upper layer by which the total monthly recharge is multiplied

- Rockaway River drainage basin boundary
- Surface-water subbasin boundary
- Approximate extent of the valley-fill deposits modified from Canace and others, 1993, and Stanford, 1989a, 1989b

Recharge distribution multiple (>, greater than)

- Area not modeled
- >1—1.5
- >1.5—2.5
- >2.5—3.5
- >3.5—4

Figure 10. Discretized distribution of recharge applied to the upper model layer (layer 1--upper aquifer) and surface-water subbasins, Rockaway River model area, N.J.

detail how the recharge from the upland areas was distributed to different sections of the model area.

Hydraulic Characteristics

The horizontal hydraulic conductivities of the upper and lower model layers and the vertical hydraulic conductivity of the confining unit are shown in figures 11 through 13. The horizontal hydraulic conductivity of layer 1 (fig. 11) ranges from about 10 to 250 ft/d. Low hydraulic conductivity corresponds to the surficial deposits of fine sand and till present in Mountain Lakes Borough and in Denville and Rockaway Townships (Stanford, 1989a, 1989b). High hydraulic conductivity corresponds to widespread areas of outwash deposits of sand and gravel and, in some places, boulders, such as those found near Dover and Wharton Borough (Stanford, 1989a, 1989b).

The vertical hydraulic conductivity of the confining unit (fig. 12) ranges from about 5 x 10^{-7} to 10 ft/d. Low vertical hydraulic conductivity corresponds to areas where the confining unit is thick, such as sections of Denville Township and Mountain Lakes Borough, or where thick units of clay are present, such as Roxbury Township. Areas with high hydraulic conductivity correspond to areas where a confining unit is poorly defined or not present.

The horizontal hydraulic conductivity of layer 2 (fig. 13) ranges from about 5 to 200 ft/d. The transmissivity values of the lower aquifer generally are higher in the center of the valley where the valley-fill deposits are thicker.

The vertical hydraulic conductivity of the streambed material ranges from about 0.2 to 20 ft/d. Higher values of vertical hydraulic conductivity were used in areas where sand-and-gravel deposits are in good hydraulic connection with the river, such as in Wharton Borough and Dover. The hydraulic conductivity of the streambed material and the width of the stream is discussed in more detail in Gordon (1993). Four small upland tributaries were added to the transient model that were not incorporated in the steady-state model (Gordon, 1993). Two tributaries are located in Jefferson Township, one is in Rockaway Township, and the one is in White Meadow Brook in Rockaway Township (fig. 1). The steady-state model incorporated primarily the mainstem of the Rockaway River and major tributaries.

The value used for specific yield of the upper layer, representing the upper aquifer under unconfined conditions was 0.14; in Jefferson Township a value of 0.21 was used. These values were determined during calibration of the transient ground-water-flow model. The higher value of specific yield restricted the fluctuation of the water levels in the Jefferson Township area of the model. The lower value yielded a better match of model-computed water levels to measured water levels in the areas of the model. A storage coefficient of 0.004 was used for layer 2.

The horizontal hydraulic conductivities of the upper and lower aquifers, and the vertical hydraulic conductivity for the confining unit between these layers were the same as those used in the previous steady-state model, except where some adjustments to the parameters were made to obtain a better match in areas where water-level data were not available during the calibration of the steady-state model. Some revisions were made to hydraulic characteristics in the steady-state ground-water flow model (Gordon, 1993) to incorporate data made available by recent hydrogeologic investigations in parts of the model area (Nicholson and others, 1996). The aquifer characteristics adjusted include conductances at general-head boundaries, horizontal hydraulic conductivity of layers, and vertical leakance between the layers. More water-level data and well-record information became available for the area between the boundary of the Rockaway River and Lamington River Basins after completion of the previous steady-state model. This area of the steady-state model (Gordon, 1993) was not as well calibrated as other sections because water-level data were sparse. The vertical hydraulic conductivity was increased one order of magnitude, and the horizontal hydraulic conductivity of the lower layer was increased by about 25 percent in this area to obtain a better match of model-computed water levels to measured ground-water levels. Other revisions

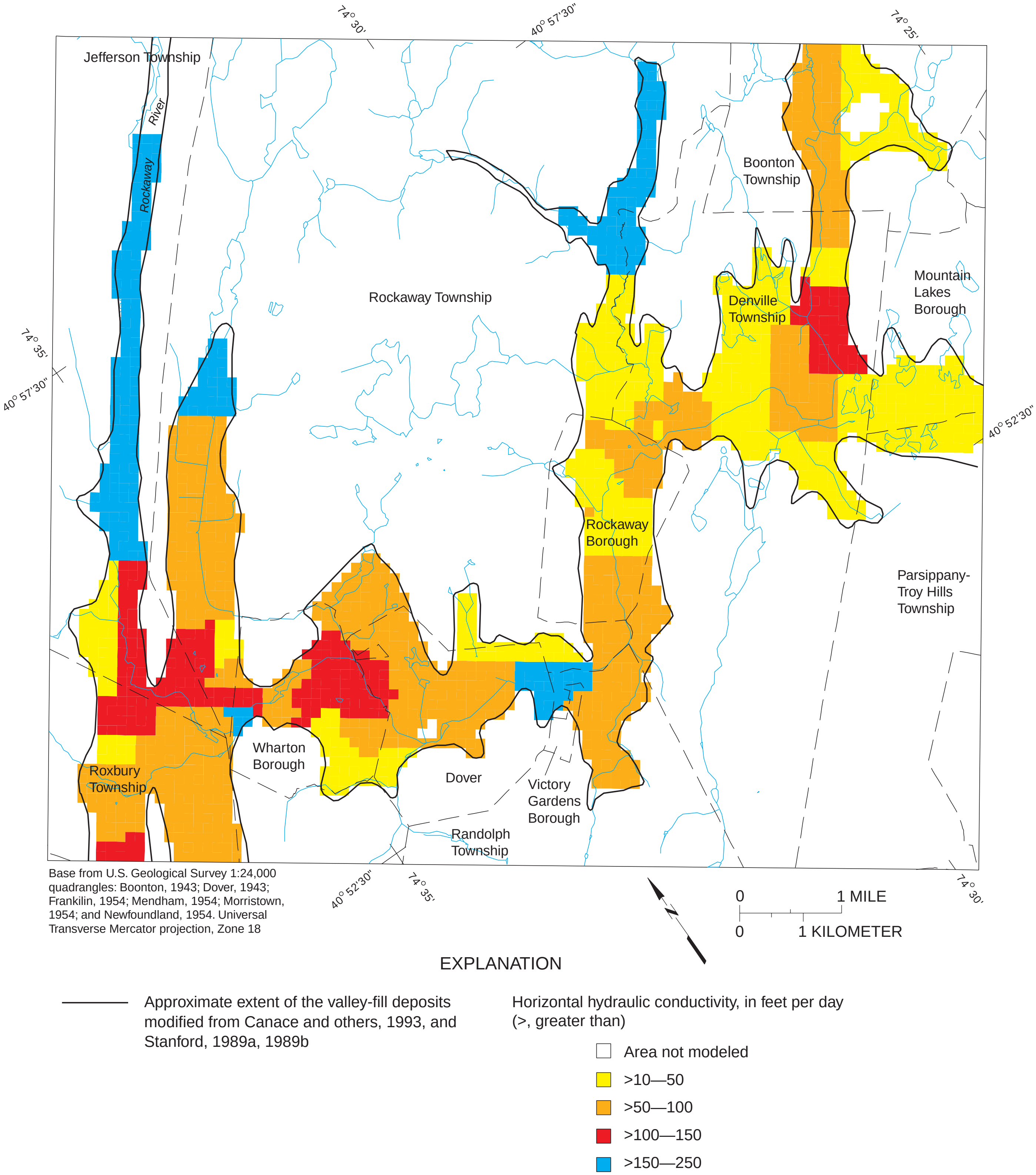


Figure 11. Discretized values of horizontal hydraulic conductivity of the upper model layer (layer 1--upper aquifer), Rockaway River model area, N.J.

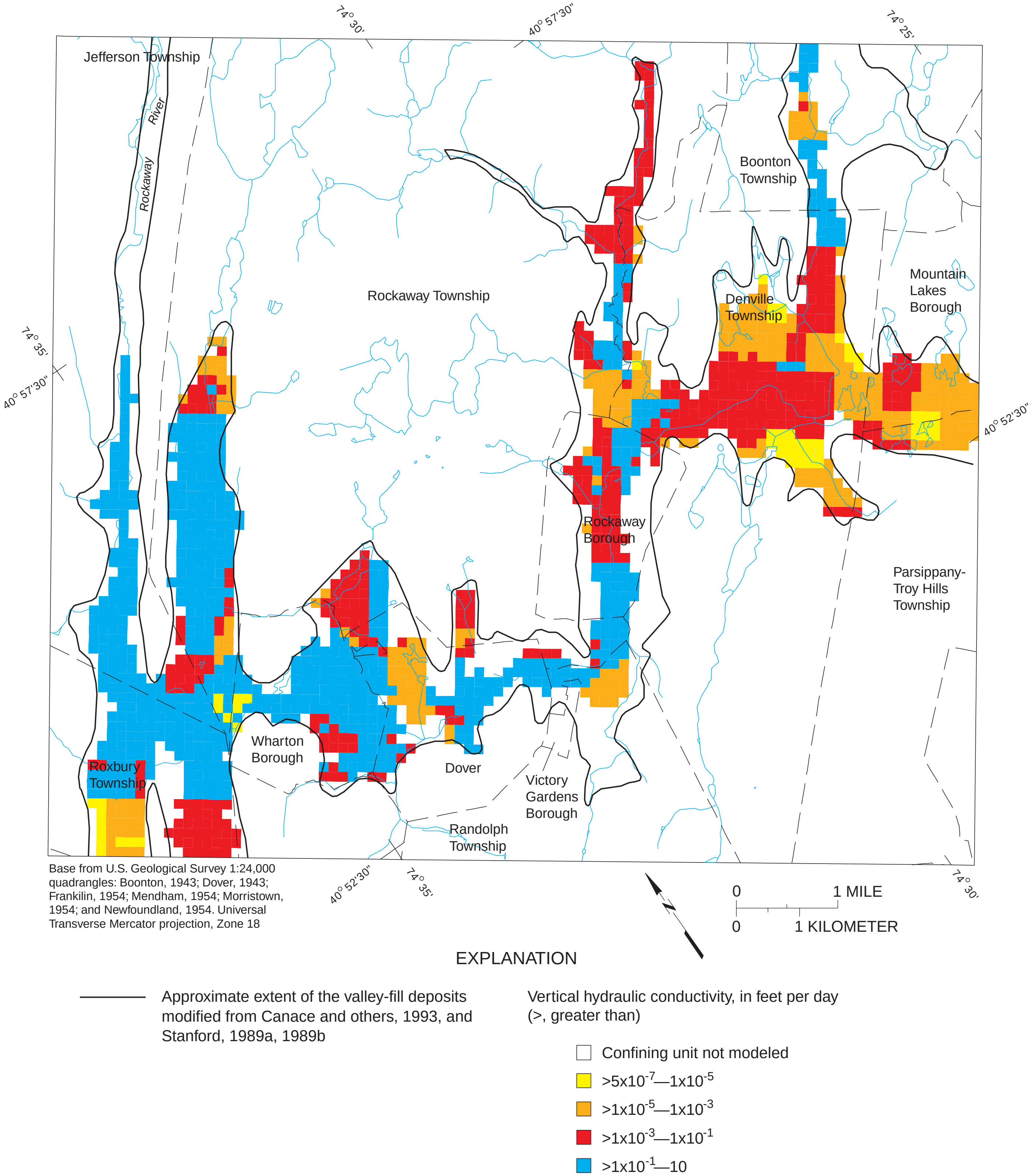


Figure 12. Discretized values of vertical hydraulic conductivity of the confining unit between the upper (layer 1) and lower (layer 2) model layers (upper and lower aquifers), Rockaway River model area, N.J.

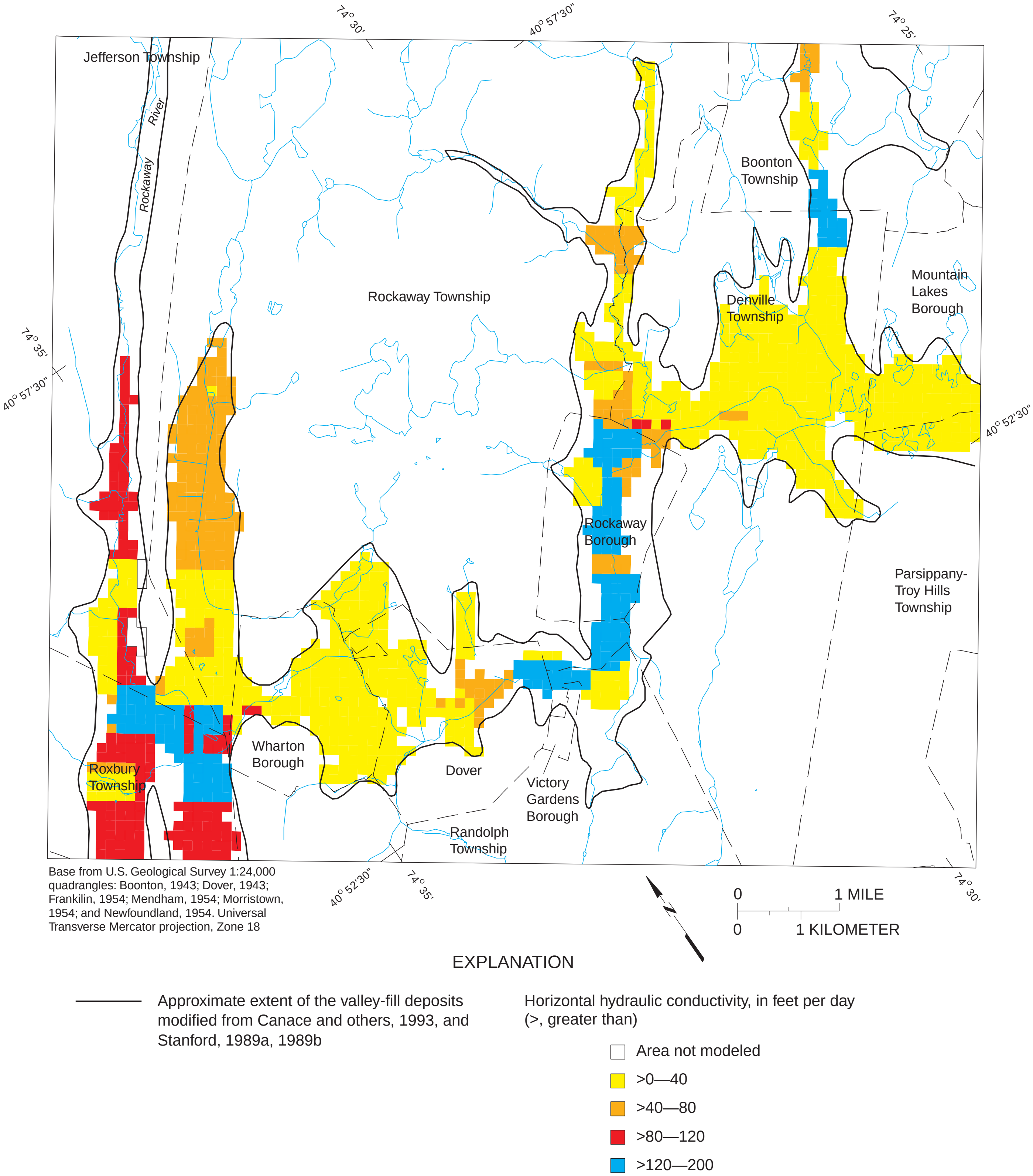


Figure 13. Discretized values of horizontal hydraulic conductivity of the lower model layer (layer 2--lower aquifer), Rockaway River model area, N.J.

were made in areas of new well locations in Rockaway Township, Dover and Rockaway Borough. The new wells provided more water-level and subsurface geologic information in the area of these wells. The well records were obtained from the New Jersey Department of Environmental Protection. In a few cells in the area between Rockaway Township and Rockaway Borough, the vertical hydraulic conductivity was decreased one order of magnitude and (or) the horizontal hydraulic conductivity of the lower layer representing the lower aquifer was decreased by about 25 percent to obtain a better match of the model-computed water levels to measured water levels. In the area between Dover and Wharton Borough, the horizontal hydraulic conductivity was increased by 25 percent at some cells also to obtain a better match of model-computed water levels to measured water levels.

A simulation was performed with the revised steady-state model using the same withdrawal (1986) and recharge values as the previously calibrated steady-state model (Gordon, 1993) to determine the effects of altering the hydraulic conductivities in these areas. The budget output and model-computed water-level output from the two models were similar for most, but not all, of the model area. Water levels differed as much as 20 ft in the area of the Lamington River Basin. Water-level data were sparse for the area near the Lamington River Basin and in the previous steady-state model (Gordon, 1993) this area was not well calibrated as other areas for which more water-level data were available. Model-computed water level error in the previous steady-state model (Gordon, 1993) may have been as much as 20 ft, but the water levels adjacent to the area of adjustments did not differ from those simulated in the steady-state model of Gordon (1993). Model-computed water levels changed most in wells around the pumping center at the Rockaway Borough wellfield of production wells 1, 5, and 6, (wells 27-137, 27-59, and 27-58, respectively) in Rockaway Borough, but no noticeable differences occurred for model-computed water levels or in flow direction at areas surrounding the areas of adjustment.

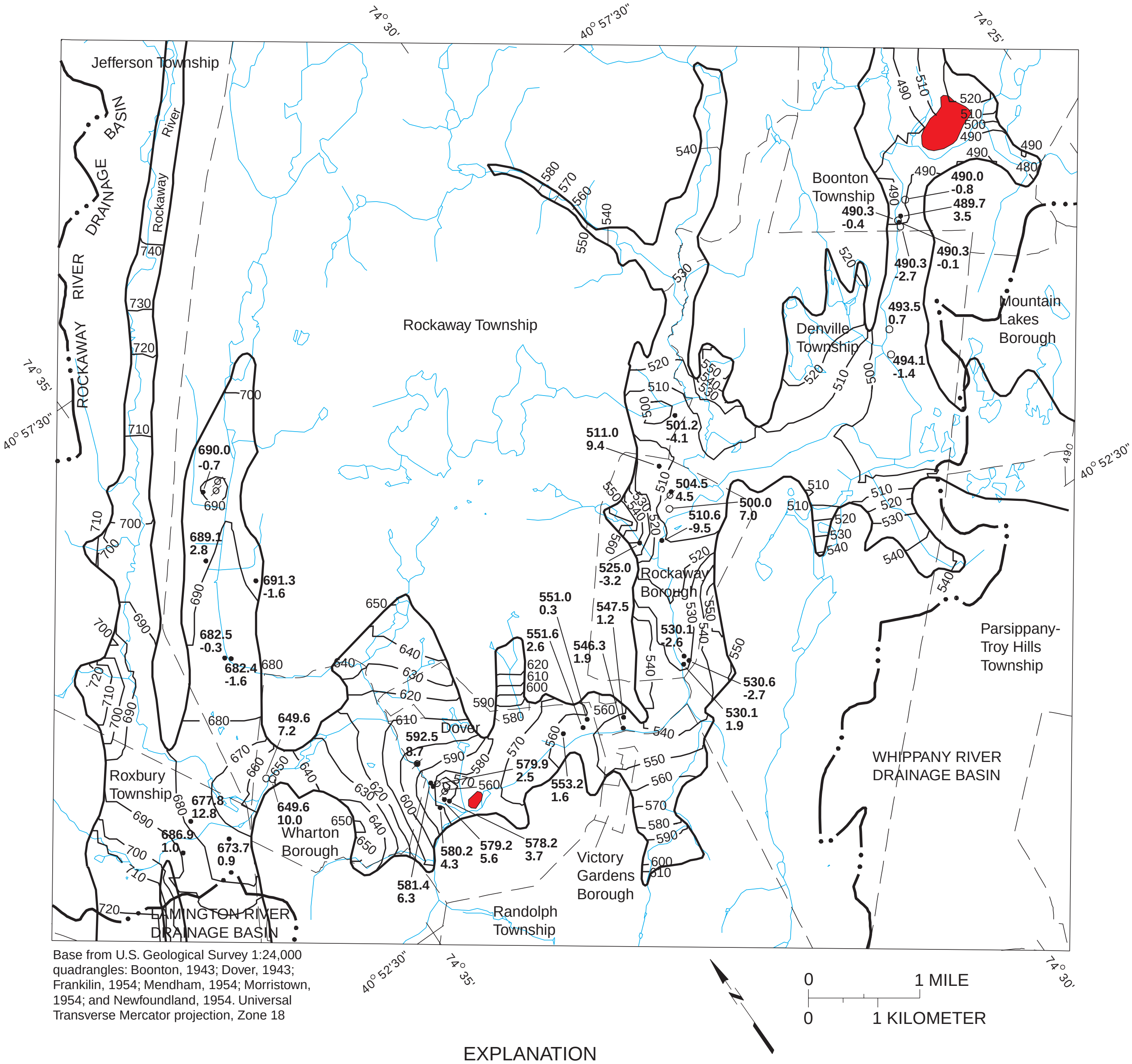
Model Calibration and Results

The transient model was calibrated to stressed water levels measured in 72 observation and production wells during October 7 and 8, 1997, and to base-flow measurements made on October 7, 1997. Hydrographs of ground-water levels in six wells, 1 well screened in the upper aquifer and 5 wells screened in the lower aquifer, were used to calibrate to monthly water-level fluctuations. Simulation results were used to show the effects of ground-water withdrawals from the valley-fill aquifers on the flow system. The results also were used to observe fluctuations in base flow in the Rockaway River under stressed conditions during April 1994 - September 1998.

Model calibration consisted of adjusting the values for recharge, storage coefficient, and specific yield, and the hydraulic properties of the aquifers until (1) model-computed water levels were within 10 ft of measured water levels, and the configurations of the model-computed water-table and potentiometric surfaces were similar to those of the surfaces contoured from water-level measurements in areas were water-level data were available; (2) model-computed base flow followed the same monthly fluctuations as estimated monthly base flow and was within approximately 16 percent of the monthly base flow estimated using hydrograph separation techniques; and (3) estimated fluxes across the boundaries were considered reasonable.

Water Levels

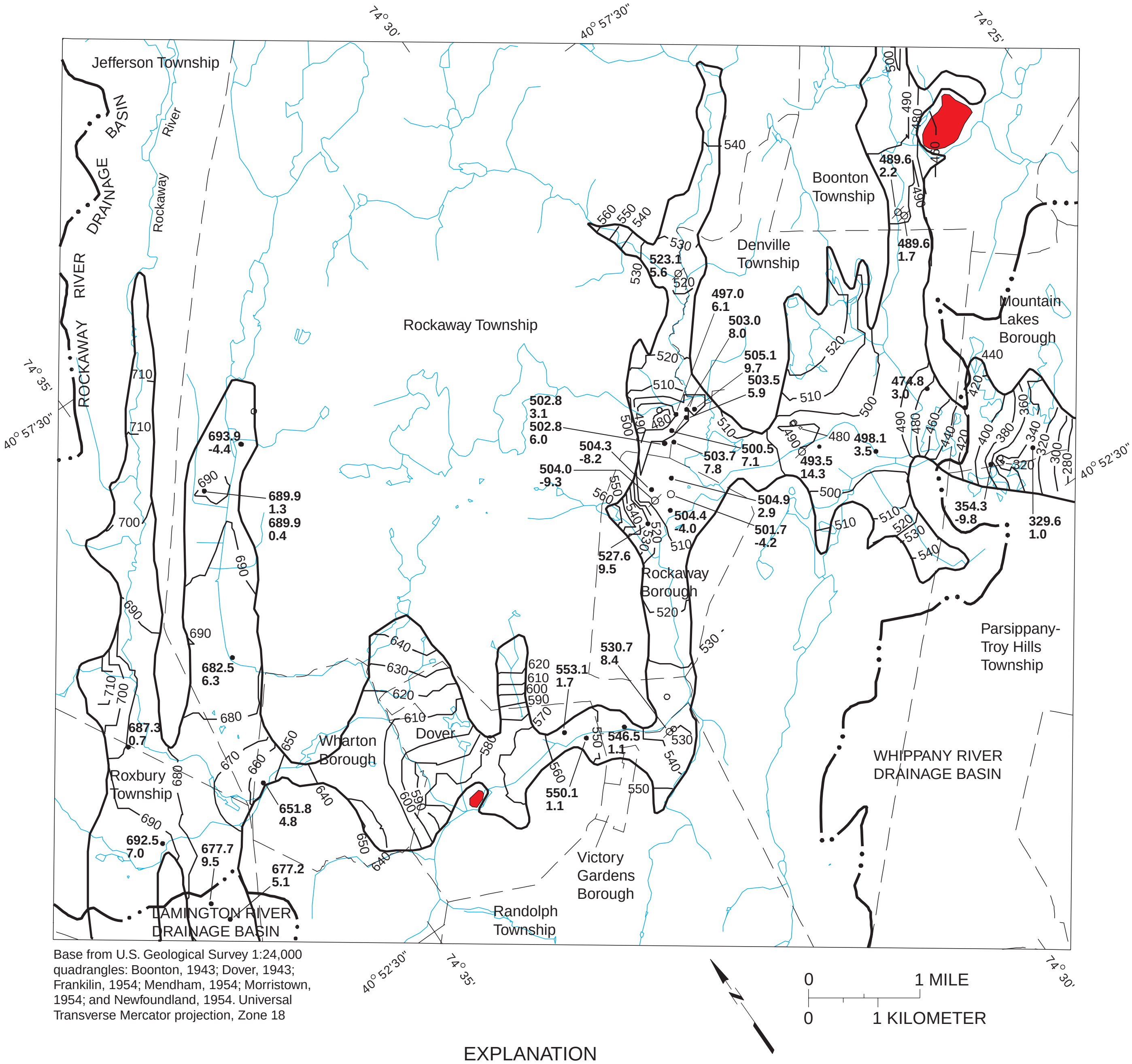
The model-computed water levels under stressed transient conditions for stress period 45 (October 1997) are shown in figure 14 for layer 1 (upper aquifer) and in figure 15 for the layer 2 (lower aquifer). In layer 1, the model-computed water-level contours show ground water flowing downvalley, from upland areas near the valley perimeter to simulated tributaries in upland areas, to the river in the center of the valley, and to wells. Withdrawals by production wells from the upper aquifer in Dover and Boonton and Rockaway Townships have resulted in cones of depression around these wells. In the lower aquifer, cones of depression are present at the pumping centers in



EXPLANATION

- Outcrop of bedrock
- —690— MODEL-COMPUTED WATER-TABLE CONTOUR--Shows altitude of model-computed water table. Dashed where approximately located. Contour interval is 10 feet. Datum is sea level
- Approximate extent of the valley-fill deposits modified from Canace and others, 1993, and Stanford, 1989a, 1989b
- Location of production well in layer 1 pumped during October 1997
- 691.3 / -1.6 ● Location of observation well with water-level measurement. Upper number is altitude of model-computed water table, in feet above sea level; lower number is difference between model-computed water level and measured water level
- 649.6 / 7.2 ○ Location of production well with water-level measurement. Upper number is altitude of model-computed water table, in feet above sea level; lower number is difference between model-computed water level and measured water level

Figure 14. Model-computed water levels in the upper model layer (layer 1--upper aquifer), Rockaway River model area, N.J., October 1997.



EXPLANATION

(red box)	Outcrop of bedrock
—690—	MODEL-COMPUTED POTENTIOMETRIC CONTOUR--Shows altitude of model-computed potentiometric surface. Dashed where approximately located. Contour interval is variable, in feet. Datum is sea level
(solid line)	Approximate extent of the lower aquifer in the valley-fill deposits modified from Canace and others, 1993, and Stanford, 1989a, 1989b
○	Location of production well in layer 2 pumped during October 1997
687.1 ● 0.7	Location of observation well with water-level measurement. Upper number is altitude of model-computed potentiometric surface,in feet above sea level; lower number is difference between model-computed water level and measured water level
⌀ 489.6 1.7	Location of production well with water-level measurement. Upper number is altitude of model-computed potentiometric surface, in feet above sea level; lower number is difference between model-computed water level and measured water level

Figure 15. Model-computed water levels in the lower model layer (layer 2--lower aquifer), Rockaway River model area, N.J., October 1997.

Rockaway Township and Borough, and in Mountain Lakes Borough. A smaller cone of depression is shown around the pumping wells in Denville Township.

The differences between the model-computed transient water levels at the end of stress period 43 and the water levels measured October 7 and 8, 1997, are shown in table 4. Comparisons of water levels were made for other stress periods, but most of the water-level data were collected within this stress period. The water levels simulated for 70 of the 72 wells measured were within about 10 ft of the measured water levels; water levels simulated for two wells were within 15 ft of the measured water levels. The difference between model-computed and measured water levels was greater in wells located in areas with production wells, such as Rockaway Borough and Township, and Denville Township. Differences between measured and model-computed water levels can occur, in part, because the water level in an observation well is a point measurement, whereas a model-computed water level is an average for that cell. The relatively large grid spacing of 500 ft may be too large in some areas to represent localized gradients near production wells. In addition, water levels were measured at specific time and were subject to the effects of short-term changes in stress, but model-computed water levels represent the cumulative effect of constant stress during each time step.

Water-level measurements also were compared for the six wells with continuous water levels measurements. Model-computed fluctuations of water levels were similar to observed fluctuations in four of the six wells shown in figure 6, but in all six wells model-computed fluctuations of water levels were within 8 ft of the observed water levels. Local conditions that were not represented in the model probably account for the discrepancy between the model-computed and measured water-level fluctuations for wells 27-1192 and 27-27. For well number 27-1192, the model-computed water levels fluctuated about 1 ft, whereas the maximum fluctuation of the measured water level was about 9 ft. One possible explanation is that this well, which is screened in layer 2 representing the lower aquifer, is near a stream cell (layer 1), so the model-computed water level is affected by the stream stage. Second, some of the water-level fluctuations in this well may be caused by pumping at local domestic wells that were not simulated. Third, the water-level fluctuations observed at this well could be the result of local confinement at the well, which is not reflected in the simulated conditions. The vertical hydraulic conductivity and the thickness of the confining unit near this well are averaged over the entire cell and may not accurately simulate local confining conditions at a particular point in the cell. A geologic well log indicates that a confining unit of about 45 ft of clay mixed with some gravel is present near this well. The clay unit may be tight in the vicinity of this well, but because of lateral variation that resulted from glacial deposition, the hydraulic conductivity and thickness of the confining unit may vary around the well. For well 27-27, more fluctuation occurred for the model-computed monthly water levels than for the measured monthly water levels (fig. 6). The model-computed water-level fluctuation is at most 10 ft; the measured water-level fluctuation is at most 5 ft. The model-computed water levels, however, do follow the same fluctuation pattern as the measured water levels.

Base Flow

The amount of monthly recharge input into the transient model was adjusted during model calibration by comparing model-computed ground-water discharge to estimated base flow. Base flow from the valley-fill aquifers was calculated by using hydrograph separation (Sloto and Crouse, 1996) of streamflow data collected at surface-water gaging station 01380500 upstream from the Boonton Reservoir (fig. 1). This station is located about 0.5 mi outside the model area, but the difference in recharge area between the model area and the area upstream from this station is small, about 1 mi^2. The increase in base flow over the model area was estimated to be the gain in base flow from station number 01379700 in Jefferson Township to 01380335 (fig. 5), which is located about 1 mi upstream from station number 01380500 (fig. 1). The estimated gain in base flow

Table 4. Ground-water levels measured during October 7 and 8, 1997, and model-computed water levels at the end of stress period 43 under transient conditions for the Rockaway River model area, N.J.

[Water-level altitudes are in feet]

New Jersey well number	Well name	Location in model (fig. 8)		Depth below land surface[1]	Water-level altitude measured October 7 and 8,1997	Model-computed water-level altitude	Difference[2] (in feet)
		Row	Column				
			Upper aquifer				
27-29	BTWD 6	15	80	4.7	490.8	490.0	-0.8
27-32	BTWD FIELD	17	80	10.9	490.4	490.3	-.1
27-104	US Army-Picatinny MW 16	59	17	9.8	682.8	682.5	-.3
27-108	BTWD 1	17	80	14.1	490.7	490.3	-.4
27-109	BTWD 2	17	80	11.8	493	490.3	-2.7
27-137	RBWD 1	44	58	12.2	493	500	7
27-189	MLWD 4	27	79	16	492.8	493.5	.7
27-190	MLWD 3	29	79	4.5	495.5	494.1	-1.4
27-232	US Army-Picatinny MW B	51	19	2.5	692.9	691.3	-1.6
27-235	US Army-Picatinny MW E	50	15	4.6	686.3	689.1	2.8
27-249	US Army-Picatinny 65-4	43	14	9.5	690.7	690	-.7
27-251	US Army-Picatinny LF 2	59	17	9.3	684	682.4	-1.6
27-292	USGS S1	72	38	6.8	574.5	578.2	3.7
27-295	USGS S4	72	37	15	573.6	579.2	5.6
27-297	USGS S6	73	37	15.5	575.9	580.2	4.3
27-301	USGS S10	71	36	15.9	575.1	581.4	6.3
27-303	USGS S12	70	36	9.3	577.4	579.9	2.5
27-826	WBWD 1	70	21	8	642.4	649.6	7.2
27-827	WBWD 2	70	21	10.4	639.6	649.6	10
27-876	RBWD TW 4	47	58	10.5	520.1	510.6	-9.5
27-915	WBWD TW 3	68	35	13.4	583.8	592.5	8.7
27-919	BTWD TW 2	16	80	12.7	486.2	489.7	3.5
27-925	McWilliams MW 1	58	60	4.9	532	530.1	1.9
27-926	McWilliams MW 2A	59	60	4.6	533.3	530.6	-2.7
27-927	McWilliams MW 3A	58	60	5.2	532.7	530.1	-2.6
27-929	SAIC 1	47	56	18	528.2	525	-3.2
27-932	SAIC 4	43	58	11	500	504.5	4.5
27-933	SAIC 5	40	57	29.2	501.6	511	9.4
27-976	Miller Dom - 1973	76	17	13.7	672.8	673.7	.9
27-1184	Herrs Motor Express Com	77	13	14.1	685.9	686.9	1
27-1226	Dover MW 6I	64	51	7.3	550.7	551	.3
27-1228	Dover MW 5I	65	49	4.3	551.6	553.2	1.6
27-1660	NJDOT 11A	74	13	3.4	665	677.8	12.8
27-1866	Moose Lodge 1S	65	50	5	549	551.6	2.6
27-1869	Dover MW 2S	65	54	3.7	544.4	546.3	1.9
27-1870	ROC MW 6S	35	59	14.5	508.1	503.9	-4.2
27-1871	Dover MW 2I	64	54	5.9	546.3	547.5	1.2

Table 4. Ground-water levels measured during October 7 and 8, 1997, and model-computed water levels at the end of stress period 43 under transient conditions for the Rockaway River model area, N.J. --Continued

[Water-level altitudes are in feet]

New Jersey well number	Well name	Location in model (fig. 8) Row	Column	Depth below land surface[1]	Water-level altitude measured October 7 and 8,1997	Model-computed water-level altitude	Difference[2] (in feet)
			Lower Aquifer				
27-30	BWD 5	16	80	11.3	487.9	489.6	1.7
27-35	DTWD 5	39	71	30	479.2	493.5	14.3
27-58	RBWD 5	44	57	6.7	513.3	504	-9.3
27-59	RBWD 6	43	58	14.1	505.9	501.7	-4.2
27-117	DTWD 6	65	58	23.3	522.3	530.7	8.4
27-247	US Army-Picatinny 65-2	43	14	11.4	688.6	689.9	1.3
27-248	US Army-Picatinny 65-3	43	14	10	690.3	689.9	.4
27-252	US Army-Picatinny LF 3	59	17	16.8	676.2	682.5	6.3
27-276	US Army-Picatinny 178	39	18	.6	698.3	693.9	-4.4
27-321	RRCC (Geonics 2)	33	82	36.6	477.8	474.8	-3
27-323	Crane Rd (Geonics 1)	38	92	174.1	328.6	329.6	1.
27-324	Pocono Rd (Geonics 4)	39	78	5.9	494.6	498.1	3.5
27-704	RTWD 8	22	59	6	517.5	523.1	5.6
27-709	K&E 2	35	60	29.1	495	503	8.
27-908	ZALASKY	82	15	51.8	668.2	677.7	9.5
27-914	MLWD TW 5	40	89	140.9	364.1	354.3	-9.8
27-921	NJDEP TW 10	76	11	10.1	685.4	692.5	7
27-930	SAIC 2	46	56	37.5	518.1	527.6	9.5
27-931	SAIC 3	44	58	6.7	508.4	504.4	-4
27-934	SAIC 6	42	57	19.6	512.5	504.3	-8.2
27-935	SAIC 7	41	58	22.6	502	504.9	2.9
27-977	Evergreen Acres 1	67	7	17.4	686.6	687.3	.7
27-1124	Kenvil Newcrete 2 OBS	83	17	52.9	672.1	677.2	5.1
27-1192	Morris Maintance Yd 22	71	20	22.1	647	651.8	4.8
27-1223	Dover MW 2D	65	54	3.5	545.4	546.5	1.1
27-1225	Dover MW 4D	66	51	4.8	549	550.1	1.1
27-1229	Dover MW 5D	65	49	4.2	551.4	553.1	1.7
27-1231	ROC MW 17D	38	59	36.5	495.9	503.7	7.8
27-1232	ROC MW 18D	38	58	45.9	499.7	502.8	3.1
27-1234	ROC MW 8D	37	58	28.9	493.4	500.5	7.1
27-1235	ROC MW 12D	36	60	26.5	497.6	503.5	5.9
27-1236	ROC MW 9D	35	61	33	495.5	505.1	9.7
27-1238	ROC MW 6D	35	59	32.1	490.9	497	6.1
27-1793	BTWD 4A	16	80	11.4	487.4	489.6	2.2
27-1867	ROC MW 18S	38	58	45.4	496.8	502.8	6

[1] Measured depth below land surface in October 1997.

[2] Difference = model-computed water level minus measured water level.

was decreased by a factor that is an estimate of the base-flow component that enters the stream as upland flow from the bedrock and till and from parts of the basin outside the model area. This decreased base-flow value is the sum of the gain in base flow over the drainage area of the valley-fill aquifer system and represents base flow contributed from the valley-fill aquifers.

Model-computed ground-water discharge and estimated ground-water discharge are shown in figure 16. Discharge measured on October 7, 1997, at 11 surface-water gaging sites along the mainstem of the Rockaway River between pumping centers, and the model-computed ground-water discharge at those sites are listed in table 5. The discharge at these sites is an estimate of the gain or loss in base flow between the successive river reaches. Discharge measurements also are given in table 5 for two tributaries of the Rockaway River. For purposes of comparison, measurements previously made at these sites also are included in the table.

The gain or loss in measured discharge at a surface-water station can differ from the model-computed ground-water recharge because a small amount of flow to or from the bedrock may occur. Some difference occurs as a result of the spatial variation in rainfall patterns over the river basin. Precipitation data from the Oak Ridge Reservoir rain-gaging station were used to estimate recharge because data are complete for the period of record. Amounts of precipitation differ from those at the Boonton Reservoir rain-gaging station (National Oceanic and Atmospheric Administration, 1994, 1995, 1996, 1997, 1998); however, localized differences in precipitation probably did not appreciably affect recharge over the model area.

Flow Budget

Inflow to the ground-water-flow system includes recharge to surficial deposits, leakage from streams and lakes, lateral flow across the boundaries, and water from storage. Recharge input to the model varied depending on monthly precipitation. The surface-water measurements were made on October 7, 1997, and the ground-water levels were measured on October 7 and 8, 1997. The ground-water flow budgets under transient conditions for September and October 1997 are presented in table 6. During September 1997, recharge from precipitation accounted for 65.4 percent of inflow to the ground-water-flow system, whereas in October 1997, recharge accounted for 33.3 percent. Stream leakage from naturally losing streams along the valley walls and infiltration of streamflow at pumping centers located near the river and along its tributaries accounted for 13.9 percent in September 1997 and about 21.9 percent in October 1997. A small amount of the inflow for both months (1.1 percent in September and 1.4 percent in October) resulted from leakage from the lakes. Storage inflow is the amount of water that is released from storage in the valley-fill deposits and enters the flow system. Storage inflow accounted for 19.6 percent of the inflow in September 1997 and 43.4 percent in October 1997. Outflow consists of ground-water discharge to streams, ground-water withdrawals, leakage to streams and boundary fluxes out of the model area. In September 1997, ground-water discharge to streams accounted for 74.1 percent of the outflow from the ground-water-flow system, whereas in October 1997, the ground-water discharge to streams accounted for 69.1 percent. Ground-water withdrawals accounted for 23 percent of the outflow in September, whereas in October, the withdrawals accounted for about 27.4 percent. Flow at the model boundaries accounted for approximately 2.9 and 3.5 percent of the model flow budget in September and October. Storage outflow is the amount of water that leaves the flow system and becomes storage in the valley-fill deposits. This storage accounts for an extremely small amount of outflow for both September and October 1997.

Because recharge and withdrawals can vary monthly, ground-water discharge also varies. The amount of monthly recharge affects the volume of inflow and outflow of the ground-water-flow system. Recharge to the valley-fill aquifer system is dependent on the amount of precipitation that falls on the river basin. The difference in recharge between the 2 months was 25.7 ft^3/s. An increase in water released from storage of 9.4 ft^3/s was simulated because the recharge decreased from September to October. Ground-water withdrawals decreased by 1 ft^3/s over the same period. During this period, stream leakage to the aquifer increased

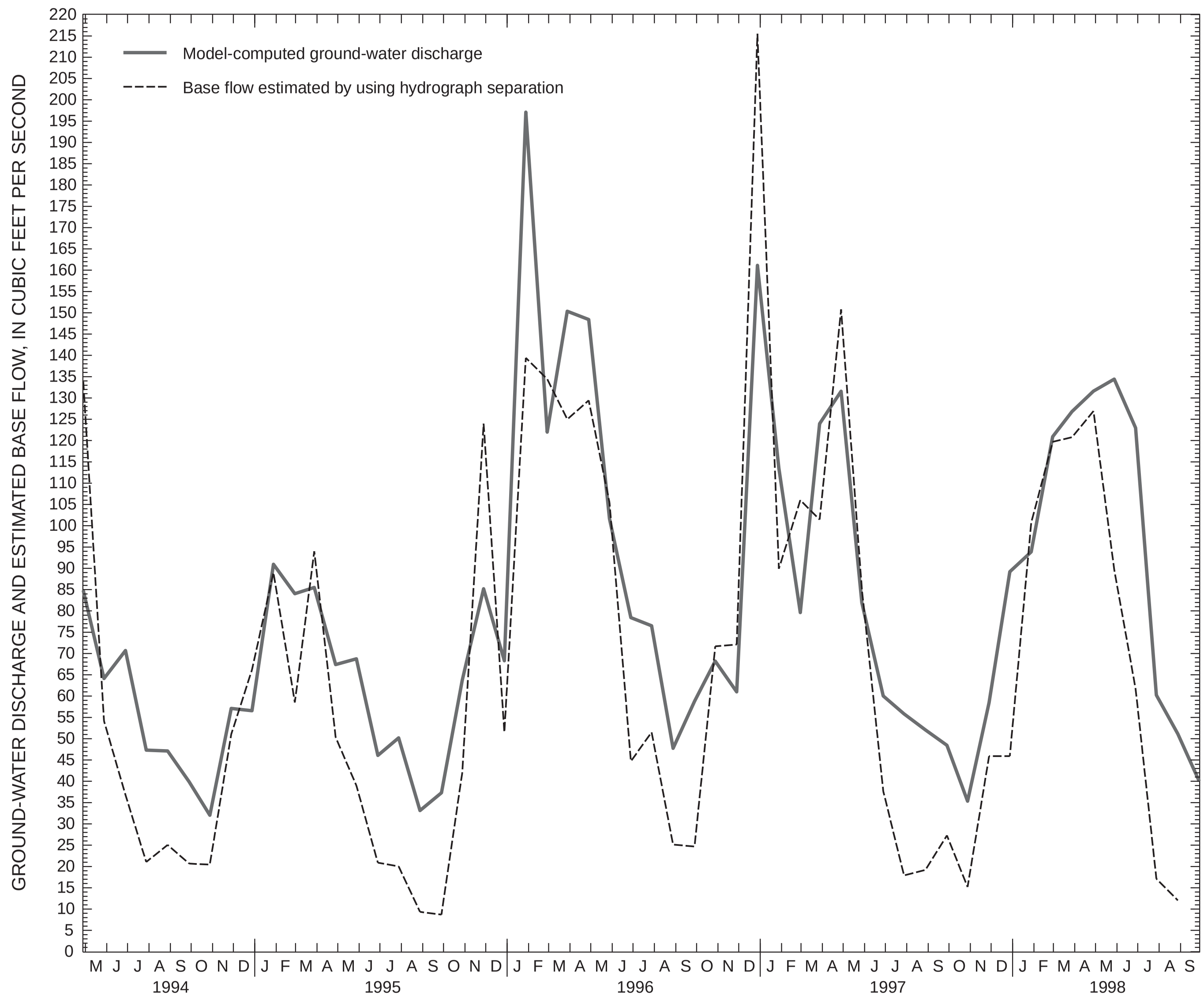


Figure 16. Model-computed ground-water discharge and estimated base flow in the valley-fill aquifer system within the model area, upper Rockaway River drainage basin, N.J., April 1994 – September 1998.

Table 5. Measured ground-water discharge and model-computed ground-water discharge along reaches and tributaries of the Rockaway River, N.J.

[ft^3/s, cubic feet per second]

Surface-water stations (See fig. 5 for locations of stations and table 2 for discharge measurements)	Discharge 10/7/97 (ft^3/s)	Model-computed ground-water discharge for stress period ending 9/30/97 (ft^3/s)	Model-computed ground-water discharge for stress period ending 10/31/97 (ft^3/s)	Average model-computed ground-water discharge[1] (ft^3/s)	Average difference[2]	Average percent difference
01379700	10.6	10.2	8.4	9.3	1.3	12.3
01379740	13.9	13.2	10.4	11.8	2.1	15.1
01379750	16.8	15.9	12.3	14.1	2.7	16.1
01379800	2.6	3.4	2.3	2.8	-.2	7.7
01379805	21.3	22.9	17.7	20.3	1	4.7
01379808	20.8	22.9	17.7	20.3	.5	2.4
01379820	2.9	.9	.6	.8	2.1	7.2
01379855	24.1	28.9	22	25.4	-1.1	4.6
01379880	28.1	33.3	25.2	29.2	-1.1	4.1
01380110	31.9	37.9	27.9	32.9	-1	3.1
01380135	32.7	41.5	30.5	36	-3.3	9.2
01380145	35.6	44.6	32.6	38.6	-3	8.4
01380335	48.3	48.4	35.3	41.9	6.4	13.2

[1]Average model-computed discharge for stress periods ending on September 30 and October 31, 1997.
[2]Measured discharge minus average model-computed discharge.

Table 6. Ground-water-flow budgets for the transient simulations and scenario 1 for September 1997 and October 1997, Rockaway River model area, N.J.

[ft^3/s, cubic feet per second]

	Inflow (ft^3/s)					Outflow (ft^3/s)			
	Transient		Scenario 1			Transient		Scenario 1	
	9/1997	10/1997	9/1997	10/1997		9/1997	10/1997	9/1997	10/1997
From storage	12.8	22.2	12.5	22.3	To storage	0	0	0	0
Recharge	42.7	17.0	42.7	17.0	Discharge to streams	48.4	35.3	59.1	45
Leakage from lakes	.7	.7	.7	.7	Leakage to lakes	0	0	0	0
Boundary fluxes	0	0	0	0	Boundary fluxes	1.9	1.8	2.2	2.1
Stream leakage	9.1	11.2	5.4	7.1	Withdrawals	15.0	14.0	0	0
Total	65.3	51.1	61.3	47.1	Total	65.3	51.1	61.3	47.1

by 2.1 ft^3/s, and ground-water discharge to the Rockaway River decreased by 13.1 ft^3/s. This result is a net decrease in ground-water discharge of 15.2 ft^3/s.

Sensitivity Analysis of Storage Properties

Estimates of storage properties were evaluated during model calibration to determine model sensitivity to these estimates. The storage coefficient of 0.004 input to layer 2 of the calibrated transient model was increased and decreased by 25 percent to observe the changes in model-computed water levels and ground-water discharge to streams. Water-level values that resulted from the simulations in which the storage properties were changed were compared to the water-level values that resulted from the calibration model run. Hydrographs for the wells shown in figure 5 also were compared. When the storage coefficient of the lower aquifer (model layer 2) was increased by 25 percent to 0.005, the model-computed water levels fluctuated less than +0.5 ft compared to those of the calibration run, except in Mountain Lakes Borough where the lower aquifer is much deeper. This range in water-level fluctuations also was observed when the storage coefficient was decreased 25 percent to 0.003. Model-computed water levels in the lower aquifer in the Mountain Lakes Borough area fluctuated as much as 3 ft more when the storage coefficient was decreased by 25 percent and as much as 2.5 ft less when the storage coefficient was increased by 25 percent. Water-level fluctuations were less responsive to an increase in specific yield. When the specific yield was increased by 20 percent, in general, the model-computed water levels fluctuated less than those from the calibration model run. When the values for specific yield used in the calibrated transient model were decreased by 20 percent, in general, a larger fluctuation in the model-computed water levels was observed. For example, model-computed water levels in layer 2 in Rockaway Borough showed the effects of increasing and decreasing the storage values (fig. 17). The hydrograph for well 27-1867 in this area shows the magnitude of actual water-level fluctuations in the lower aquifer. The differences between the model-computed water levels for the October 1997 and that of the calibration run ranged from -0.5 to 0.4 ft when the specific yield was decreased 20 percent. When the specific yield was increased 20 percent, the differences ranged from -0.3 to 0.4 ft. This analysis shows that changing the storage coefficient by 25 percent and the specific yield by 20 percent did not greatly affect water-level fluctuations.

Fluctuations in base flow, as ground-water discharge, also are affected by changes in specific yield and storage coefficients. Model-computed ground-water discharge that resulted from simulations where the values for specific yield or storage coefficient were increased and decreased were compared to that of the calibration model run (fig. 17). The time period shown in this figure is the same as the period of water-level record for well number 27-1867. Base flow that was generated by the calibration model run did not appreciably differ from the base flow that resulted when the storage coefficient was increased or decreased by 25 percent. The difference was less than 0.9 ft^3/s for all monthly stress periods. When calibration values for specific yield were decreased by 20 percent, ground-water discharge differed from the ground-water discharge from the calibration model run by -12.4 to 4.25 ft^3/s; ground-water discharge differed by -9.7 to 3.2 ft^3/s when the specific yield was increased by 20 percent.

The sensitivity analysis, in general, quantifies the uncertainty created by estimates of values for specific yield and storage coefficient. Results of the sensitivity analysis indicate that water levels are less sensitive to changes in storage coefficient and specific yield over the model area for a range of values that are 25 and 20 percent, respectively, of the calibrated values. Base flow was sensitive to changes in specific yield, particularly a decrease in specific yield. Base flow and water-level fluctuations were affected by increases and decreases in monthly recharge rates. Monthly rates of recharge were adjusted during model calibration and are discussed in a previous section of the report on model input.

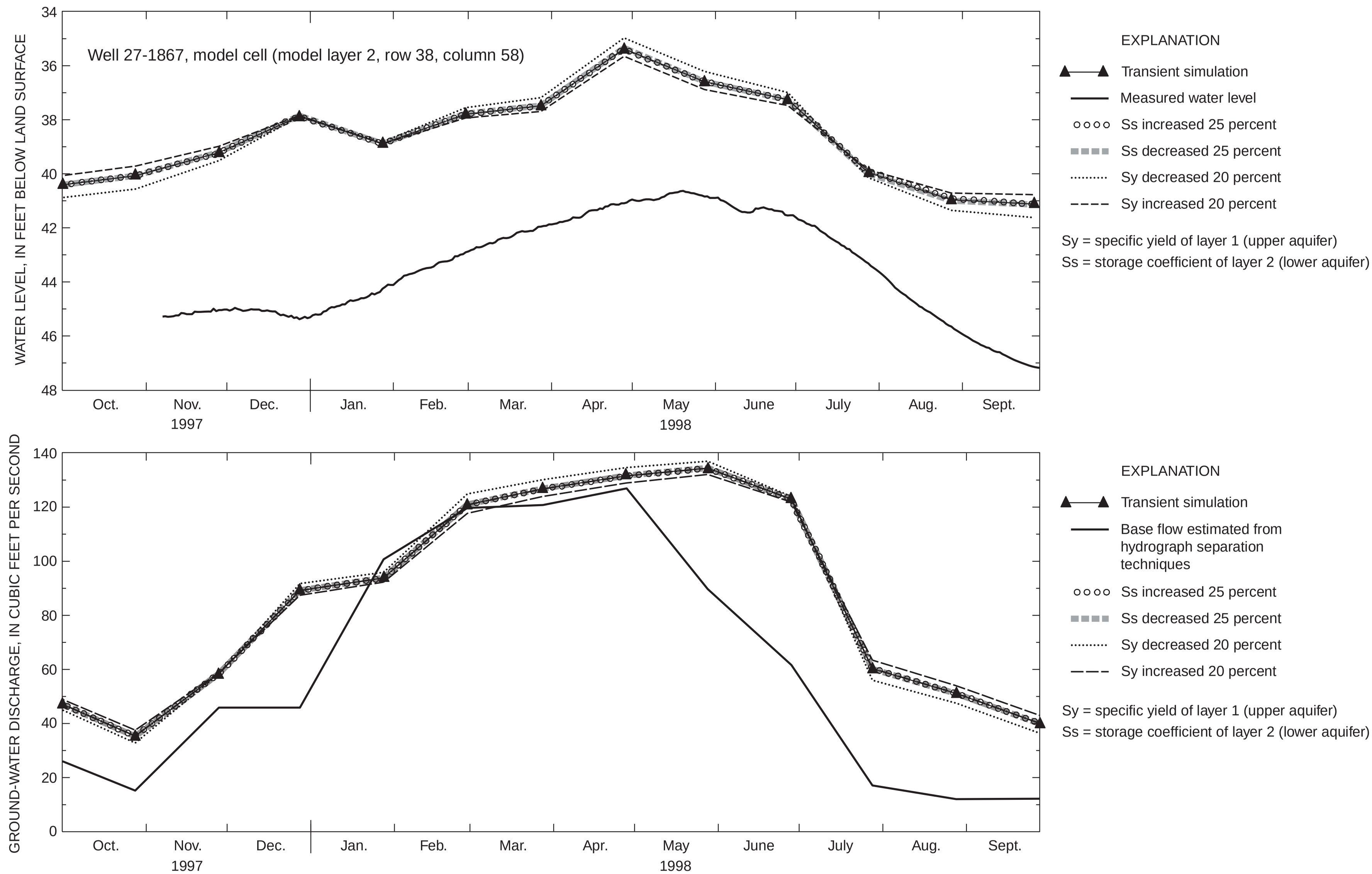


Figure 17. Model-computed water levels and ground-water discharge resulting from changes to storage values, Rockaway River model area, N.J., October 1997 – September 1998.

Simulated Effects of Hypothetical Ground-Water Withdrawals

The transient calibrated ground-water flow model was used to evaluate the effects of hypothetical increases and decreases in withdrawals and relocation of production wells on the flow system and on ground-water discharge to the Rockaway River. Three scenarios were simulated using the calibrated transient model to determine the response of the valley-fill aquifers to the effects of hypothetical ground-water withdrawals. In particular, the effects of ground-water withdrawals on the ground-water discharge (base flow) to the Rockaway River were examined to determine the extent to which variations in rates of withdrawals correspond to variations in rates of streamflow depletion. In scenario 1, all ground-water withdrawals were removed from the calibrated transient model. For the scenario 2, an additional 1 Mgal/d of ground-water withdrawal was input for layer 1 in addition to actual withdrawals. For the scenario 3, an additional 1 Mgal/d of withdrawals was input for layer 2, in addition to actual withdrawals.

The results of scenario 1, which simulated the effects of removing all ground-water withdrawals on ground-water discharge to the river, were compared to the results of the calibrated transient model with withdrawals (table 6). In the transient simulation for September, ground-water withdrawals of 15 ft^3/s (9.7 Mgal/d) from the glacial deposits resulted in a decrease in ground-water discharge to the river of 10.7 ft^3/s from the scenario 1 value of 59.1 ft^3/s, and an increase in stream leakage of 3.7 ft^3/s, or a net reduction of 14.4 ft^3/s. In the transient simulation for October, ground-water withdrawals of 14 ft^3/s (9.0 Mgal/d) from the glacial deposits resulted in a decrease in ground-water discharge to streams of 9.7 ft^3/s from the scenario 1 value of 45 ft^3/s and an increase in stream leakage of 4.1 ft^3/s from the scenario 1 value of 7.1 ft^3/s to the aquifer, or a net reduction in streamflow of 13.8 ft^3/s. Streamflow measurements made on October 7, 1997, and previous discharge measurements given in Schaefer and others (1993) (table 2) indicate that at some losing reaches along the Rockaway River pumping has induced leakage from the river to the aquifer.

Model-computed streamflow depletion and the total monthly withdrawals from wells in the valley-fill aquifers are shown in figure 18. Streamflow depletion here is defined as the difference of the ground-water discharge with pumpage removed (scenario 1) and the ground-water discharge simulated by the transient model with pumpage (calibration run). The difference between the streamflow depletion and pumpage for any particular month is small, indicating that month-to-month increases in ground-water withdrawals from the valley-fill aquifers correspond to decreases in ground-water discharge to the Rockaway River that are approximately equal to withdrawals. The range of monthly total withdrawals for the wells simulated within the Rockaway River drainage basin was 11.4 to 16.8 ft^3/s (7.4 to 10.8 Mgal/d), whereas the range of simulated depletion was 12.0 to 15.7 ft^3/s. Mountain Lakes Borough production well 5 was not included in the total monthly withdrawals. This well is located outside the Rockaway River Basin, and ground-water flow in this area of the model, when not diverted to the production well at Mountain Lakes, discharges to the Whippany River drainage basin. Some of the discrepancy between the two curves in figure 18 resulted from lateral flow at the model boundaries.

Storage inflow and storage outflow over the period of simulation also are shown in figure 18. The withdrawals and streamflow depletion curves in this figure usually peak during the summer and fall. During this time water is released from storage in the valley-fill aquifers, which causes water levels to decline. During the winter and spring, water goes into storage in the valley-fill aquifers which causes water levels to increase as water enters or is stored in the aquifers.

The streamflow depletion and ground-water withdrawals are shown along with total estimated ground-water discharge (base flow) in figure 19. When compared to total estimated base flow, the difference between total monthly withdrawals from wells within the valley-fill aquifers and monthly streamflow depletion resulting from the

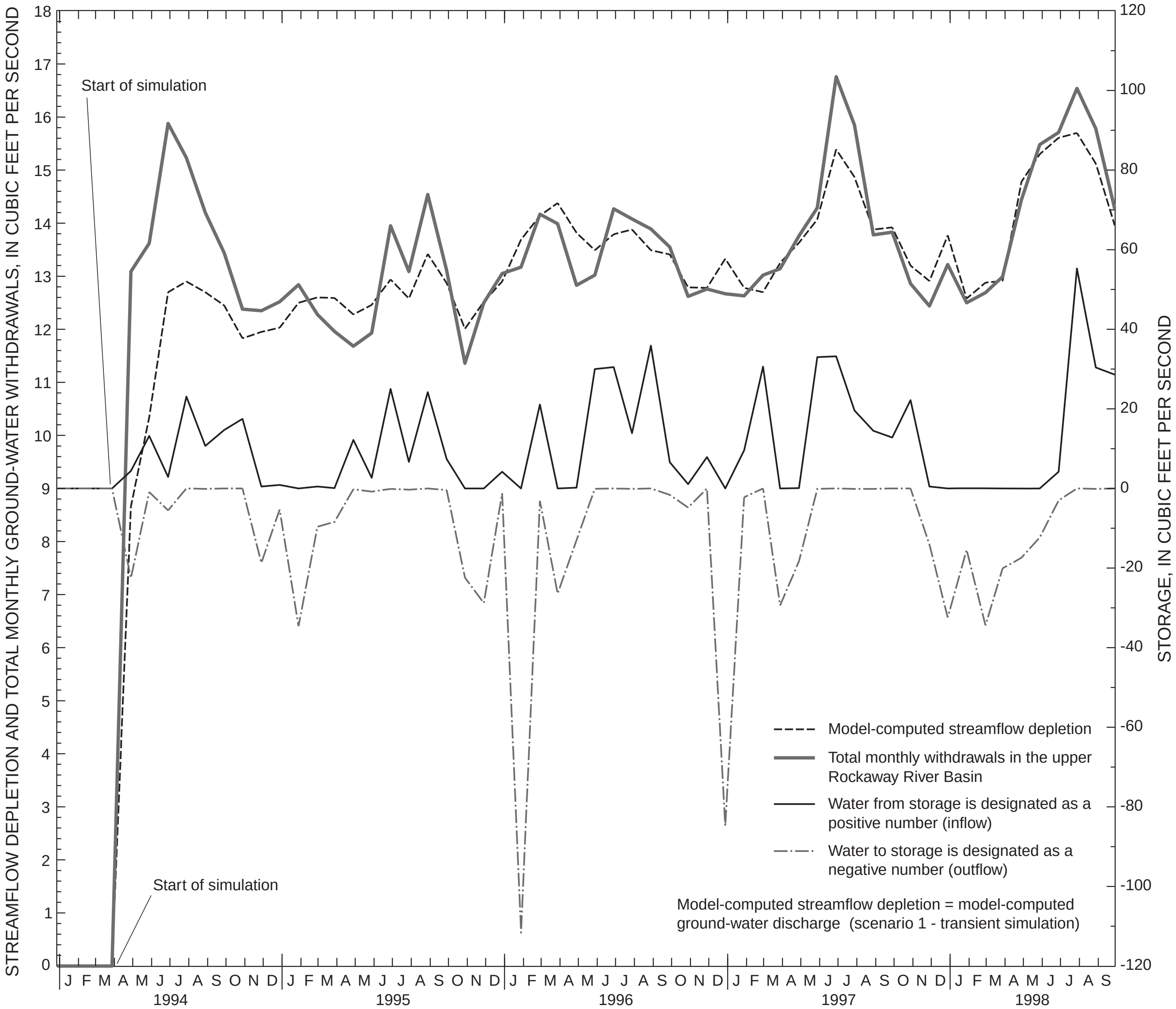


Figure 18. Difference between model-computed streamflow depletion and total monthly ground-water withdrawals from the valley-fill aquifers, and storage inflow and outflow, upper Rockaway River drainage basin, N.J., April 1994 – September 1998.

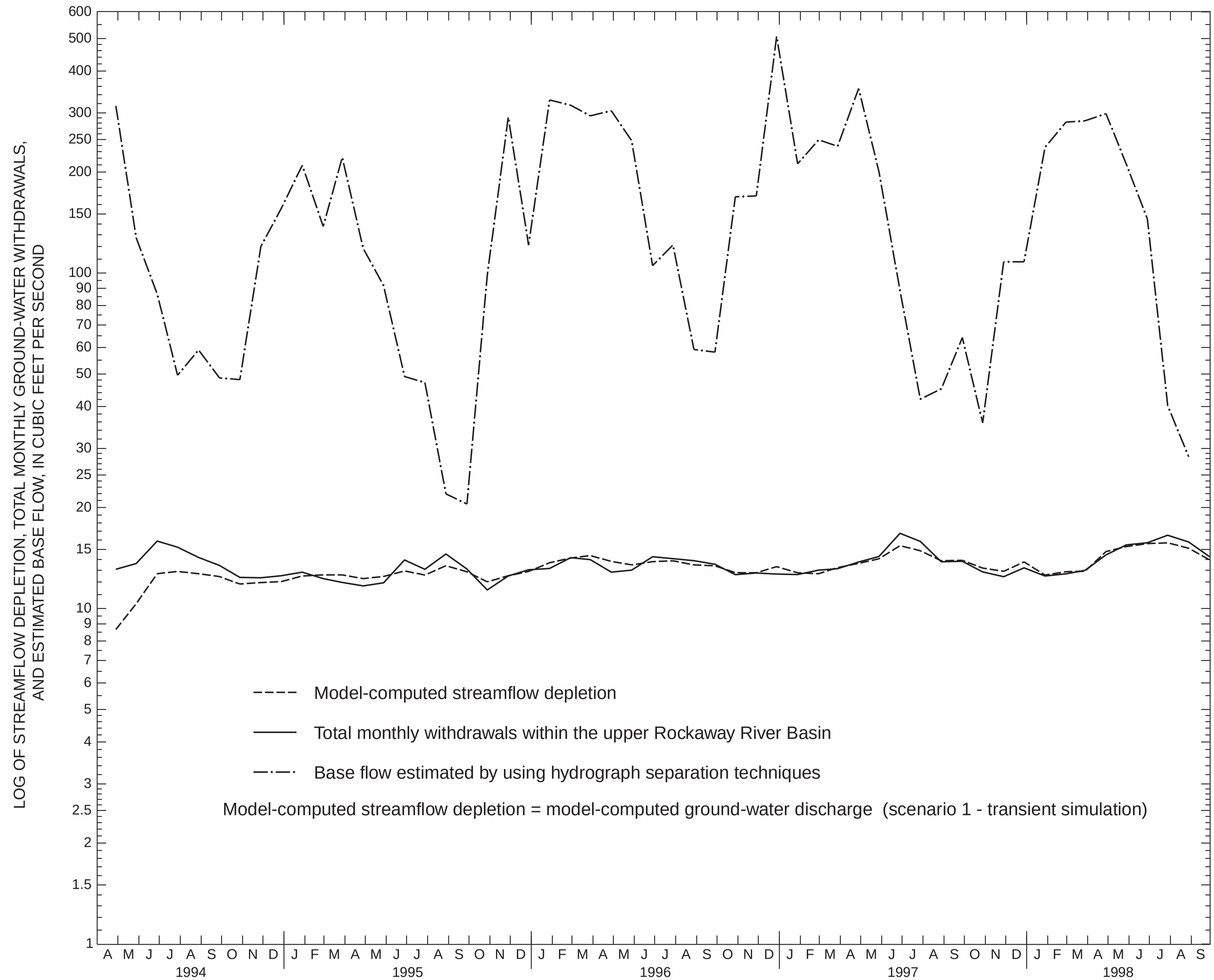


Figure 19. Difference between streamflow depletion and total monthly withdrawals, and base flow estimated by using hydrograph separation techniques, upper Rockaway River drainage basin, N.J., April 1994 – September 1998.

withdrawals is negligible, except under extreme low-flow conditions when streamflow depletion approaches the total estimated base flow.

Production wells screened in the valley-fill aquifers within the upper Rockaway River Basin are located primarily near the river or streams. Locating wells at a distance from the river is difficult in some parts of the upper Rockaway River Valley because of the limited valley width. Also, the glacial deposits are thick in the center of the valley and thin out at the valley sides. Two scenarios were simulated to evaluate the effects of withdrawals and their proximity to streams on streamflow depletion. These scenarios were designed to indicate whether a lag period could occur between the time a production well started pumping in an area in the river valley and the time when the full magnitude of the effects of the pumping on ground-water discharge in the Rockaway River is observed. The initial conditions imposed for scenarios 2 and 3 are the same as those imposed on the transient model, except that an additional production well was added in each of these scenarios. In scenario 2, the hypothetical well was located in a river cell (36, 74) in layer 1 (figs. 5 and 8). In scenario 3, the well was located in a cell (33, 74) in layer 2 (figs. 5 and 8), about 1,750 ft from the river and was separated from the upper aquifer by a confining unit. The thickness of the confining unit in this area is approximately 57 ft, and the thickness of the lower aquifer is about 78 ft. The pumping rate of the hypothetical well was 1 Mgal/d for both scenarios 2 and 3.

The results of scenarios 2 and 3 are shown in figure 20. The additional withdrawals did affect discharge to the river. When ground water was withdrawn from the upper aquifer (scenario 2), most of the resulting streamflow depletion occurred within the first month and became approximately equal to the amount pumped after about 7 months. When the production well was located in the lower aquifer, the lag time (scenario 3) was longer between the start of the pumping and the time at which the full magnitude of the effects on streamflow depletion occurred, approximately 19 months.

The differences in storage inflow and outflow between the two simulations also are shown in figure 20. The storage inflow of scenario 2 is subtracted from the storage inflow of scenario 3, and the storage outflow for scenario 2 is subtracted from the storage outflow of scenario 3. The differences show that during the early stress periods, more water is released from storage when water is withdrawn from the lower aquifer (scenario 3) than when water is withdrawn from the upper aquifer (scenario 2). The differences in flow rates into and out of storage between the two scenarios decreased as the lag time between the simulations decreased. The flow budgets for September and October 1997 for scenarios 2 and 3 are shown in table 7. There is a small change in storage for September (0.1 ft^3/s) between scenarios 2 and 3, but there is no change in the storage for October resulting from these two scenarios.

Because the ground-water-flow model (Harbaugh and McDonald, 1996) uses a quasi-3D (dimensional) approach, the transient model was not set up to simulate flow explicitly within a confining unit. One limitation of the quasi-3D approach is that storage properties of the confining unit are not directly simulated; however, if flow were simulated explicitly, the lag time most likely would be a little longer than the 1.5 years simulated.

These results could have implications for the location and pumping of wells in the valley-fill aquifers, particularly during low-flow conditions. The use of a well screened in the lower aquifer during periods of low-flow condition or during a drought might reduce streamflow depletion. In scenario 3 the hypothetical production well was located in the lower aquifer at a distance farther from the river. During the initial months of pumping more water was released from storage to supply the flow system than from later months. The width of the Rockaway River Valley and the transmissivity and thickness of the lower aquifer are factors that affect the placement of wells in relation to the river. The thickness of the lower aquifer in the middle of the valley ranges from 40 to 200 ft over the model area; typically, the aquifer thins out as it approaches the valley sides. The lower aquifer may be too thin in these areas for

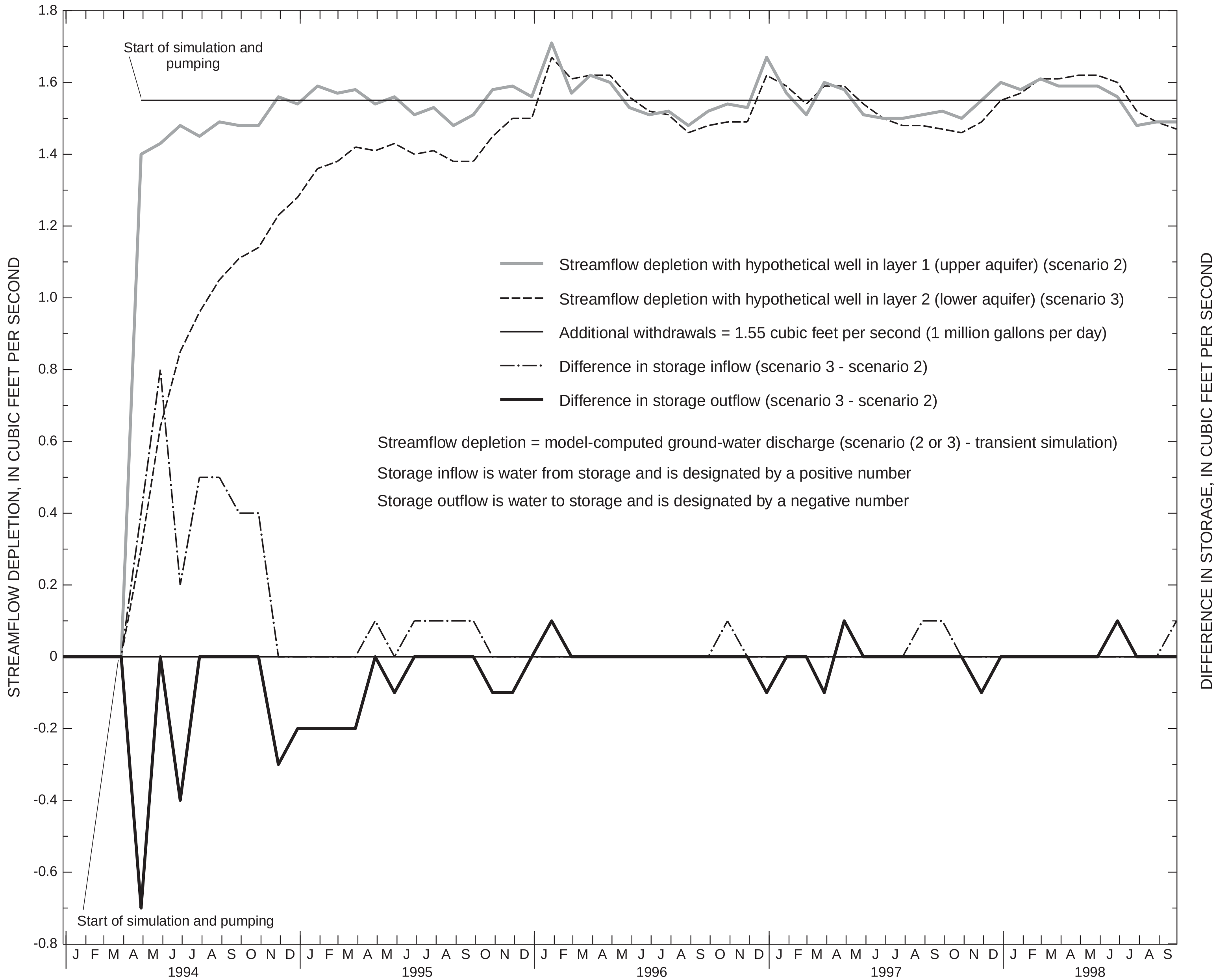


Figure 20. Difference between streamflow depletion and difference in storage when additional withdrawals are added to the upper and lower aquifers, Rockaway River model area, N.J., April 1994 – September 1998.

Table 7. Ground-water-flow budgets for scenarios 2 and 3 for the Rockaway River model area, N.J.

[ft^3/s, cubic feet per second]

	Inflow (ft^3/s)					Outflow (ft^3/s)			
	Scenario 2		Scenario 3			Scenario 2		Scenario 3	
	9/1997	10/1997	9/1997	10/1997		9/1997	10/1997	9/1997	10/1997
From storage	12.8	22.3	12.9	22.3	To storage	0	0	0	0
Recharge	42.7	17.0	42.7	17.0	Discharge to streams	47.9	35.	47.2	34.2
Leakage from lakes	.7	.7	.7	.7	Leakage to lakes	0	0	0	0
Boundary fluxes	0	0	0	0	Boundary fluxes	1.9	1.7	1.8	1.7
Stream leakage	10.2	12.3	9.3	11.5	Withdrawals	16.6	15.6	16.6	15.6
Total	66.4	52.3	65.6.	51.5	Total	66.4	52.3	65.6	51.5

water-supply use. In some areas of the Rockaway River Valley, such as near Beaver Brook and in Jefferson Township (fig. 1), the lower aquifer is about 500 ft wide (fig. 14), so locating a well more than 1,750 ft from the river may not be possible.

Implications for Streamflow Reduction Under Low-Flow Conditions

Statistics of flow duration of the Rockaway River at the station upstream from Boonton Reservoir (surface-water gaging station 01380500) can be used to determine the frequency of occurrence of flow that is less than that needed to provide the minimum passing flow. The flow-duration curve indicates the percentage of time that specified discharges were equaled or exceeded in a particular stream during a given period of time. Flow-duration statistics for the drought in early 1960’s were used as a baseline to provide an indication of the probable magnitude of flows during future droughts. The period of record for the flow duration analysis was water years 1962 to 1966 (October 1961 to September 1966). The amount of water needed upstream from the Boonton Reservoir to provide the mandated flow downstream was estimated to be 8.6 Mgal/d. This amount is the minimum passing flow requirement of 7 Mgal/d plus the estimated average annual rate of evaporation from the reservoir of 1.6 Mgal/d (Gordon, 1993). During approximately 0.7 percent of this drought period, the flow upstream from the Boonton Reservoir was less than 8.6 Mgal/d. Ground-water withdrawals from the valley-fill aquifers in the study area totaled approximately 8.2 Mgal/d in 1960 (Schaefer and others, 1993), a difference of almost 1.4 Mgal/d from the 1997 average yearly total (9.6 Mgal/d).

A steady-state ground-water flow analysis (Gordon, 1993) was used to evaluate the effects of increases in withdrawals on streamflow under average steady-state conditions in 1986. The results of the steady-state simulation and flow-duration analysis for the surface-water gaging station on the Rockaway River upstream from the Boonton Reservoir indicated that under average flow conditions, streamflow at this station would continue to exceed the flow needed to provide the minimum passing requirement of 7 Mgal/d downstream from the reservoir if withdrawals from valley-fill wells in the upper Rockaway River Basin increased to 14.6 Mgal/d by the year 2040 (Gordon, 1993). A one-to-one correspondence between increases in withdrawals in the Rockaway River Basin and streamflow depletion to the Rockaway River was assumed for an analysis of streamflow reduction under low-flow conditions in the previous report (Gordon, 1993). The results of the simulation, presented in figure 18, demonstrate that this assumption is reasonable.

Changes in precipitation, however, can affect ground-water recharge and ground-water discharge to streams over time. During periods of extreme low flow, streamflow measured at gaging station 01380500 alone may not be sufficient to provide the minimum passing flow downstream from the reservoir. Ground-water withdrawals from the valley-fill aquifers in the model area increased from an average of 8.2 Mgal/d in 1960 to an average of 9.6 Mgal/d in 1997. The flow needed upstream from the Boonton Reservoir if ground-water withdrawals increased 1.4 Mgal/d is the sum of the mandated minimum passing flow (7.0 Mgal/d), the anticipated loss to evaporation (1.6 Mgal/d), and the increase in the rate of ground-water withdrawals (1.4 Mgal/d), or 10.0 Mgal/d. From the flow duration analysis of the 1960’s drought, during 3.2 percent of the time, the flow upstream from the Boonton Reservoir was less than 10.0 Mgal/d. When base flow in the Rockaway River upstream from the Boonton Reservoir is less than 10.0 Mgal/d, the minimum passing flow below the reservoir cannot be provided solely by ground-water discharge in the upper Rockaway River Basin.

SUMMARY

The valley-fill aquifers include (1) an upper, unconfined aquifer of sand and gravel that was deposited over a discontinuous and, in some areas, leaky confining unit consisting of glaciolacustrine silt, clay, fine sand, and till, or, in some areas, over bedrock; and (2) a lower aquifer that locally is confined and consists of deposits of sand and gravel. Most of the public water supply in the Rockaway River Valley is ground water from the valley-fill aquifers. Ground-water withdrawals have increased from a yearly average of about 3 Mgal/d in 1950 to more than 9.6 Mgal/d in 1997. Increases in ground-water withdrawals can induce the flow of water from streams to wells; increase flow from the upper aquifer to the lower aquifer; and reduce streamflow, which may affect flow to the Boonton Reservoir.

A ground-water-flow model was used to simulate transient conditions in the valley-fill aquifers in an area of about 20 mi^2 in the upper Rockaway River Valley by incorporating monthly withdrawal totals during April 1994 to September 1998. Recharge input to the model varied both spatially and temporally. A percentage of the total monthly precipitation measured during April 1994 to September 1998 was input as ground-water recharge. The percentage of precipitation that was input varied by month. More recharge was input for the spring and winter months; less recharge was input to the model for the summer and fall months. The percentage for each month was determined during model calibration. The recharge was assumed to approximate the estimated mean monthly base flow. The model was calibrated to water levels measured in October 1997, continuous water levels collected at six observation wells, and mean monthly ground-water discharge (base flow), which was estimated by using hydrograph separation techniques. Simulation results indicate the effects of ground-water withdrawals from the valley-fill aquifers on the flow system, particularly on base flow in the Rockaway River.

The calibrated transient model was used to evaluate the effects of increases and decreases in ground-water withdrawals, and the relocation of production wells on the flow system by simulating three scenarios. The effects of ground-water withdrawals on the ground-water contribution (base flow) to the Rockaway River were examined to determine the extent to which variations in rates of withdrawals correspond to variations in rates of streamflow depletion. The first scenario (scenario 1) was designed to evaluate potential effects of withdrawals on ground-water discharge and streamflow infiltration. This simulation was performed with all pumpage removed. The flow budgets that resulted from scenario 1 and the transient simulation were compared. They indicate that ground-water withdrawals from the valley-fill aquifers reduce ground-water discharge to the Rockaway River and increase leakage from the river to the valley-fill deposits along certain reaches where major pumping centers are located near the river. The difference between the streamflow depletion and withdrawals for any particular month is small, which indicates that month-to-month increases in ground-water withdrawals from the valley-fill aquifers correspond to decreases in ground-water discharge to the Rockaway River of approximately the same amount.

In scenario 2, a hypothetical well was located near the river (250 ft) in model layer 1; and in scenario 3, the hypothetical well was located farther (1,750 ft) from the river in model layer 2, and separated from the upper aquifer by a confining unit. The pumping rate in both scenario 2 and 3 was 1 Mgal/d. In both scenarios, the increase in ground-water withdrawals corresponds to an increase in streamflow infiltration and a decrease in ground-water discharge to streams. For scenario 2, a lag time of seven months between the start of pumping and the full magnitude of the effect of these withdrawals on streamflow depletion was observed. For scenario 3, the observed lag time was more than 1.5 years (19 months) between the introduction of additional withdrawals and the occurrence of the effects of withdrawals on streamflow depletion.

During periods of extreme low flow, streamflow measured at the surface-water gaging station above the Boonton Reservoir may not be sufficient to provide the minimum passing flow of 7 Mgal/d below the Boonton Reservoir. A flow-duration analysis for the Rockaway River at the surface-water gaging station upstream from the Boonton Reservoir during the drought of 1961-66 was used to evaluate the probable magnitude of streamflow during subsequent droughts. Using the results of the flow-duration analysis of the 1960's drought and average annual ground-water withdrawals in 1997 of 9.6 Mgal/d, it was determined that during 3.2 percent of the duration of a drought, the minimum passing flow downstream from the reservoir could not be provided solely by ground-water discharge in the upper Rockaway River Basin.

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