HYDROGEOLOGY OF, AND SIMULATED GROUND-WATER FLOW IN, THE VALLEY-FILL AQUIFERS OF THE UPPER ROCKAWAY RIVER BASIN, MORRIS COUNTY, NEW JERSEY

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West Trenton, New Jersey
1993

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	by	To obtain
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
square mile (mi^2)	2.590	square kilometer
foot squared per day (ft^2/d)	0.09294	meter squared per day
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

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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.

HYDROGEOLOGY OF, AND SIMULATED GROUND-WATER FLOW IN, THE VALLEY-FILL AQUIFERS OF THE UPPER ROCKAWAY RIVER BASIN, MORRIS COUNTY, NEW JERSEY

ABSTRACT

Public water supply in the upper Rockaway River valley in Morris County, New Jersey, is obtained largely from ground-water withdrawals from the valley-fill aquifers. These withdrawals have increased from about 3 million gallons per day in 1950 to more than 9 million gallons per day in 1986. Ground water is withdrawn from valley-fill sands and gravels, which comprise an upper and a lower aquifer. 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 streamflow downstream from the Boonton Reservoir.

A ground-water-flow model was used to simulate and quantify the effects of current and predicted withdrawals on the ground-water flow system under steady-state conditions. Under current (1986) conditions, an average of 9.1 million gallons per day is withdrawn from the valley-fill aquifer system. Average ground-water discharge to the Rockaway River upstream from the Boonton Reservoir of about 37.2 million gallons per day is sufficient to maintain the court-ordered passing flow requirement of 7 million gallons per day that is mandated to dilute effluent discharge downstream from the reservoir. Some reaches of the Rockaway River and its tributaries lose water to the upper aquifer at the pumping centers of the Town of Dover, Boonton Township, and Wharton and Rockaway Boroughs. Vertical flow from the upper aquifer to the lower aquifer has increased near areas of ground-water withdrawals.

Results of simulations show that the average ground-water discharge above the Boonton Reservoir will sustain the mandated minimum flow rate downstream from the reservoir if ground-water withdrawals from the valley-fill deposits increase to 11.5 million gallons per day, as anticipated by the year 2000 and also if ground-water withdrawals increase to 14.6 million gallons per day, as anticipated by 2040. Under pumping conditions modeled for 1986-2040, streamflow depletion will continue near the well fields in the Town of Dover, Boonton Township and Wharton Borough. Relocation of the Rockaway Township well field to the north of its current site probably will cause a loss in streamflow in the Beaver Brook tributary in Rockaway Township. Total streamflow loss from river reaches between the Town of Dover, Rockaway and Denville Townships, and Rockaway Borough pumping centers will increase by about 1 million gallons per day from 1986 to 2000, and about 2.4 million gallons per day from 1986 to 2040 as a result of pumping at the Town of Dover, Rockaway and Denville Townships, and Rockaway Borough pumping centers.

Analysis of flow duration for the Rockaway River at the streamflow-gaging station above the Boonton Reservoir for a period of extreme low flow, the drought of 1962-66, shows that the mandated minimum flow requirement will likely not be met during part of the extended dry periods. During 5.3 percent of the drought of 1962-66, the flow above the reservoir was less than the sum of the minimum passing flow losses, as a result of lake evaporation, and the increased rate of ground-water withdrawals anticipated by 2000. During 11.6 percent of the drought of 1962-66, the flow was less than the sum of the minimum passing flow losses as a result of lake evaporation and less than the increased rate of withdrawals anticipated by 2040.

INTRODUCTION

Public water supply in the Rockaway River valley in Morris County, New Jersey, is obtained mainly from wells that penetrate the valley-fill deposits. Ground-water withdrawals from these deposits along the Rockaway River in the study area have increased from an estimated 3 Mgal/d in 1950 to more than 9 Mgal/d in 1986. Population growth and industrial growth in the Rockaway River valley have led to increased withdrawals from current production wells and to consideration of possible locations in the valley-fill deposits for new sources of ground-water supply. Increased withdrawals and the potential effects of increased demand for water have resulted in concern about water levels in existing production wells, on the ground-water-flow system at potential sites of water supply, and on ground-water discharge to the Boonton Reservoir. Increases in pumpage could reduce the ground-water contribution to the river and potentially affect the court-ordered passing flow requirement of 7 Mgal/d (Summers and others, 1978, p. 55) that the water department of Jersey City must release downstream to the lower Rockaway River Basin to protect the quality of water for users downstream from the Boonton Reservoir. In addition, contamination of existing ground-water supplies from activities at nearby industrial sites (Elson T. Killam Associates, Inc., 1982) has created the need for some municipalities to search for alternative water-supply locations in the Rockaway River valley.

The U.S. Geological Survey conducted a study in cooperation with the New Jersey Department of Environmental Protection to describe quantitatively the ground-water flow system in the valley-fill deposits. A previous report (Schaefer and others, 1993) describes the hydrologic conditions in the upper Rockaway River Basin, delineates the extent of the valley-fill deposits in the study area, and presents streamflow, water-level, and water-quality data.

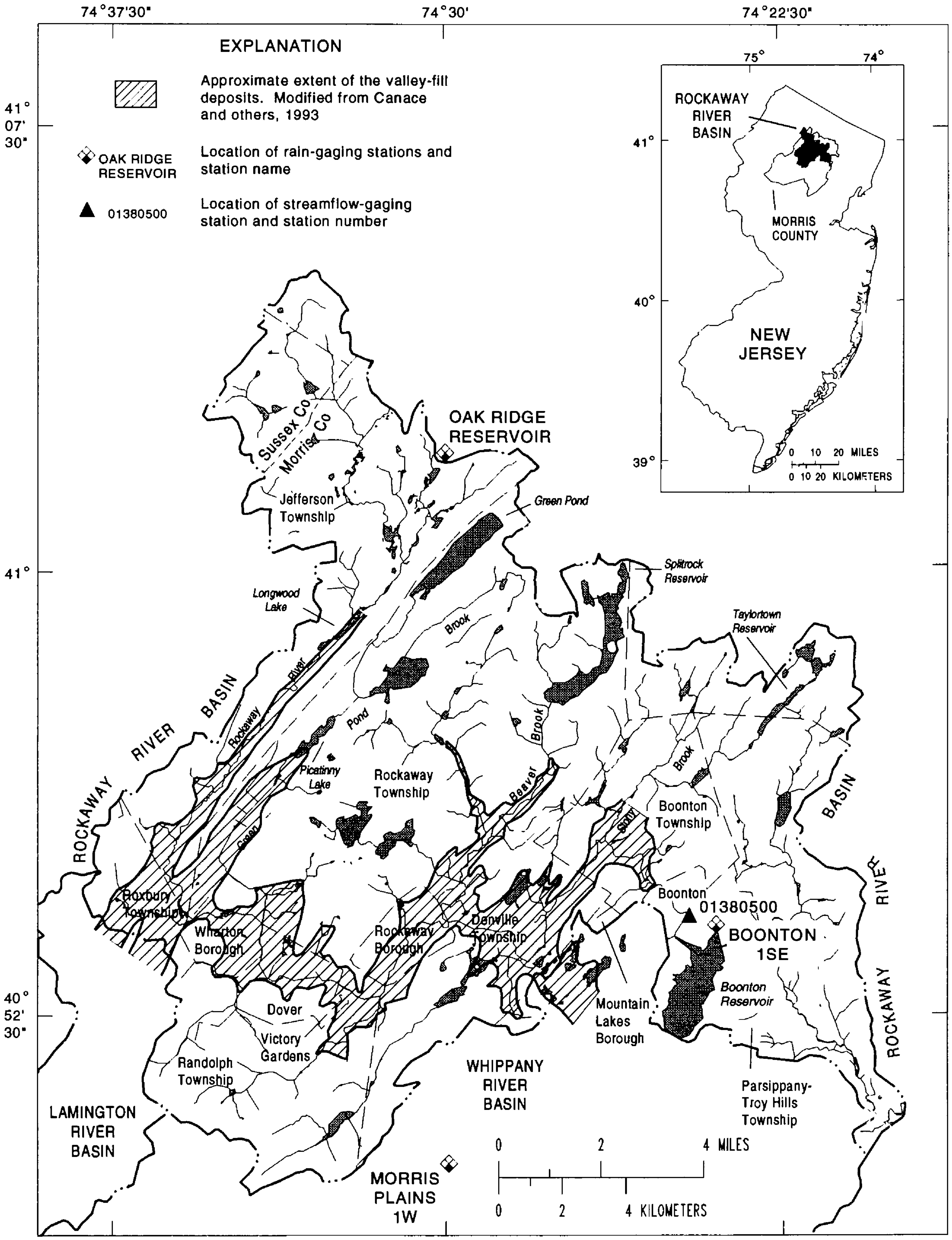
Purpose and Scope

This report describes (1) the hydrogeology of the aquifers; (2) simulated ground-water flow in the valley-fill deposits, including the effects of withdrawals on the flow system at major well fields and on ground-water discharge to the Rockaway River; and (3) the simulated effects of predicted water use during 2000 and 2040 on the ground-water flow system and on ground-water discharge to the river above the Boonton Reservoir. A ground-water flow model of the valley-fill aquifer system was developed to quantify the components of the predevelopment flow system and the effects of pumpage on water levels, flow directions, and ground-water discharge under both current steady-state conditions and conditions anticipated in the years 2000 and 2040.

Location and Physical Setting

The study area is located almost entirely in Morris County, New Jersey; a small part is located in Sussex County, New Jersey. The study area consists of the upper Rockaway River Basin and a small part of the Whippany and Lamington River Basins (fig. 1). Both the Rockaway and the Whippany River Basins are part of the Passaic River Basin. The Lamington River Basin is part of the Raritan River Basin. The upper Rockaway River Basin is separated from the lower Rockaway River Basin by the Boonton Reservoir.

The modeled area covers about 20 mi^2 and consists of the valley-fill deposits from below Longwood Lake to about 1 mi upstream from the Boonton Reservoir. This area includes Rockaway, Denville, and Boonton Townships; Dover, Wharton, Rockaway, and Mountain Lakes Boroughs; and smaller sections of Jefferson, Parsippany-Troy Hills, Roxbury, and



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

Figure 1. Location of the study area in the Rockaway River drainage basin in New Jersey.

Randolph Townships, and Victory Gardens (fig. 1). The valley-fill deposits are surrounded by till-covered bedrock upland areas, that supply a portion of the recharge to the valley-fill deposits.

The study area is characterized by broad, northeast-trending bedrock ridges separated by deep, flat valleys. The elevations of the ridges range from 600 to 1,000 ft above sea level. Bedrock in the study area is predominantly Precambrian granitoid gneiss; however, Green Pond valley is surrounded and underlain by Paleozoic sedimentary limestone, shale, and sandstone. The bedrock ridges surround the Rockaway River and its tributaries--Green Pond Brook, Beaver Brook and Stony Brook. Streams generally follow the trend of the valleys; however, the main drainage course of the Rockaway River traverses this trend and flows southeast until it reaches Denville Township, where it flows northeast through a gap in the ridges at Boonton Township. The terminal moraine of the Wisconsinan glaciation arcs from east to west across the southern part of the basin. The terminal moraine forms a ridge that locally marks the southern extent of the late Wisconsinan glaciation; its width in the Rockaway River area ranges from 1.0 to 2.2 mi (Sims, 1958).

The Rockaway River Basin receives an average of 49.7 in/yr of precipitation, which is fairly evenly distributed over the basin (Schaefer and others, 1993). This average was determined from annual precipitation measured during 1951-80 at three rain-gaging stations: Boonton 1SE, Oak Ridge Reservoir, and Morris Plains 1W (fig. 1). Average annual evapotranspiration was not estimated for the study area but is assumed to be within the range of 18 to 24 in/yr for the glaciated northeastern United States cited by Lyford and Cohen (1988).

The Rockaway River valley is an industrialized area. The highlands surrounding the valley are sparsely populated; development is centered in the river valley.

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 downstream.

The well-numbering system used in this report was developed by the U.S. Geological Survey, New Jersey District. 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 27-914, which is the 914th well inventoried in Morris County.

HYDROGEOLOGY OF THE VALLEY-FILL AQUIFERS

The valley fill consists of unconsolidated sediments of glacial, lacustrine, and fluvial origin (Gill and Vecchioli, 1965) that occupy preglacial and glacially deepened river valleys. Sediments from at least two glaciations were deposited in the valleys of the study area--deposits from an earlier Wisconsinan glaciation, and deposits from the most recent Wisconsinan glaciation which extended to the terminal moraine (Stanford, 1989a, 1989b). The older Wisconsinan deposits are not present at the surface in the study area. Younger deposits are glacial-lake sediments which are extensive in Denville and Jefferson Townships, Dover, and Green Pond valley (Canace and others, 1993). These lakes were formed when ice blocked preglacial river valleys, modifying the preglacial drainage patterns.

The valley fill is bounded on the sides by bedrock ridges, composed of Precambrian granitoid gneiss, which are covered by till. It is bounded on the bottom by the bedrock. Green Pond valley is surrounded and underlain by Paleozoic sedimentary rocks of shale, sandstone, and dolomitic limestone of low permeability. The thickness and configuration of the valley fill are shown in figure 2; this map was modified from previously published maps of the depth to bedrock from land surface (Canace and others, 1993). These depths were estimated from the results of seismic-refraction studies conducted along several cross-sections in the valley. The depth to bedrock is greatest in the center of each valley, where it is typically between 100 and 200 ft below land surface. The valley fill thins at the valley flanks, where it can be less than 20 ft thick. Locally, the thickness of valley fill exceeds 200 ft in Roxbury Township and 300 ft in Mountain Lakes Borough. The delineation of valley-fill deposits in the study area (fig. 2) is based on a previous investigation of the upper Rockaway River Basin (Schaefer and others, 1993).

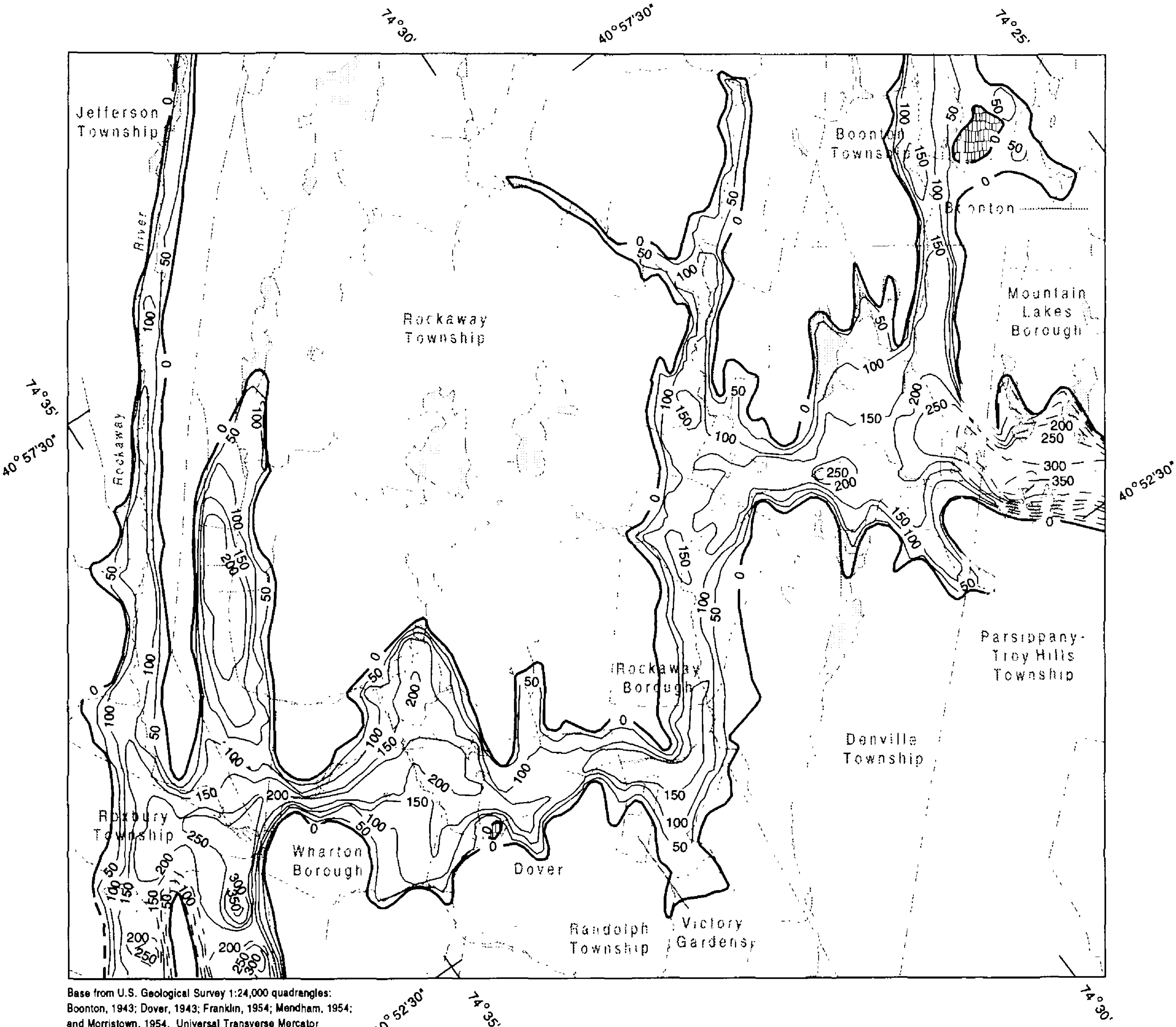
Description and Hydraulic Characteristics

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). The extensive sand and gravel deposits contain significant quantities of ground water. The till is commonly a poorly sorted mixture of boulders, gravel, sand, and clay that was transported within the ice mass during its advance and was deposited during its recession. The valley-fill deposits in the study area are grouped into three units: (1) an uppermost unit of sand and gravel; (2) a clay, silt, and fine-sand unit and, in some places, till; and (3) a basal sand and gravel unit (Canace and others, 1993). These glacial deposits are characterized by different hydraulic properties. Typically, the horizontal hydraulic conductivity of sand and gravel deposits is higher than that of silt and clay deposits or unsorted till deposits (Freeze and Cherry, 1979, p. 29). 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 20 to 70 ft/d for till (Geraghty and Miller, 1968 and 1978; Moretrench American Corporation, 1975; Summers and others, 1978; Canace and others, 1983; Dan Raviv Associates, Inc., 1984; Hill, 1985; Scientific Applications International Corporation, 1986). These ranges of horizontal hydraulic conductivity were calculated from values of transmissivity reported in these publications by dividing the transmissivity values by the aquifer-thickness values obtained from the well record or from reported test data. Values of transmissivity from six selected aquifer tests conducted in the study area and reported in these publications are summarized in table 1.

Information on the hydraulic properties of the fine material of glaciolacustrine origin that comprises the confining unit is limited. An average value of 3.3×10^{-2} ft/d for the vertical hydraulic conductivity of this layer in the vicinity of water-supply well number 3 (27-136) for Denville Township, which is located in Randolph Township (see fig. 7), was reported by Dan Raviv Associates, Inc. (1984). Vertical hydraulic conductivities of low-permeability layers south of Picatinny Lake in Rockaway Township (fig. 1) range from 0.01 to 0.6 ft/d (L.M. Voronin, U.S. Geological Survey, written commun., 1990).

Information on the vertical hydraulic conductivity of streambed material in the study area also is limited. Dysart (1988) used isotope data to calculate a value of 1.6 ft/d for the vertical hydraulic conductivity of streambed material in a 2,000-ft-long reach of the Rockaway River in the Town of Dover. Lapham (1989) estimated a value between 2.2 and 2.5 ft/d for the same reach. His estimates of the effective vertical hydraulic conductivity of the sediments were determined by using temperatures measured beneath the stream.

Yields from wells completed in the valley-fill deposits in the study area range from less than 20 gal/min for some domestic wells to more than 1,500 gal/min for a production well screened in glacial outwash in the Town of Dover. Yields are reported in well records completed during well development at the time of drilling. The wide range of values for well



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

EXPLANATION

Outcrop of bedrock

— 350 — — THICKNESS CONTOUR--Shows thickness of the valley fill. Dashed where approximately located. Contour interval 50 feet. Datum is sea level

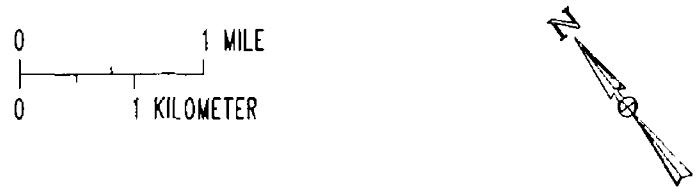


Figure 2. Approximate extent and thickness of the valley-fill deposits in the study area.

Table 1. Transmissivity and storage values from selected aquifer tests conducted in the valley-fill aquifers in the study area

((gal/d)/ft, gallons per day per foot; –, not available)

New Jersey well number	Source of data	Mean transmissivity ((gal/d)/ft)	Specific yield of storage coefficient	Location and description of test
		Upper aquifer		
27-029	Moretrench American Corporation, 1975	139,000	–	48-hour test on production well 6 in the Town of Boonton
27-291	Geraghty and Miller, Inc., 1978	280,000	–	72-hour test on production well 5 in the Town of Dover
27-915	[1]Hill, 1985	233,000	–	48-hour test on test well 3 in Wharton Borough
		Lower aquifer		
27-027	Canace and others, 1983	127,000	4.9×10^{-3}	24-hour test on test well 9 in Jefferson Township
27-136	Dan Raviv Associates, 1984	41,000	3×10^{-4}	72-hour test at Denville Township production well 3 in Randolph Township
27-357	[2]Dan Raviv Associates, 1984	93,800	4.6×10^{-2}	Test on the Town of Dover production well 4

[1] Test conducted by Geraghty and Miller, Inc., 1971

[2] Test conducted by Township of Dover, 1982

yields probably results from the high lateral and vertical variability of the grain-sized distribution of the glacial sediments. The average yield of water-supply wells in the study area is about 500 gal/min.

Lithology varies both laterally and vertically over short distances throughout the study area as a result of the deposition, erosion, and redeposition of materials by glacial and fluvial action. Because most of the valley-fill deposits are discontinuous, definition of the hydrogeological units is difficult. In general, the upper sand and gravel unit, hereinafter called the upper aquifer, constitutes an unconfined aquifer; the middle unit functions as a confining unit; and the basal sand and gravel unit, hereafter called the lower aquifer, is a confined aquifer. The upper and lower aquifers together are 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 interpretation of geologic well logs, the altitude of the water level, and well depth (table 2). Wells screened in surficial sand and gravel deposits are designated as being screened in the upper aquifer. Wells screened in areas overlain by silt or clay and, in some areas, till, generally are considered to be screened in the lower aquifer.

The upper aquifer consists mostly of surficial outwash deposits of sand and gravel as much as 50 ft thick. Extensive outwash deposits are present near the Rockaway River in Jefferson, Denville, and Boonton Townships, Dover, and in parts of Wharton Borough. In the vicinities of Roxbury Township and Mountain Lakes Township this aquifer can consist of till of the terminal moraine which contains some stratified sand and gravel (Stanford, 1989a and 1989b). This aquifer contributes significantly to the public water supply of Wharton Borough and the Town of Dover.

The upper aquifer is underlain in places by a confining unit that consists of fine-grained lakebottom sediments; in other places it can be underlain by till or bedrock. The thickness and extent of the confining unit varies throughout the study area; the average thickness is about 50 ft. The confining unit is leaky in parts of the study area, such as in Green Pond valley. In parts of Denville Township and Mountain Lakes Borough, it may consist of till that contains clay as well as sandy material.

The lower aquifer consists of coarse sand and gravel deposited at the bottom of glacial lakes; in some areas, these deposits may be fluvial in origin (Stanford, 1989a). This aquifer is locally confined. Interfingering of deposits has resulted in the presence of water-bearing layers between less permeable units in which ground water flows around the less permeable sediments. In areas where the confining unit is discontinuous or leaky, the lower aquifer is hydraulically connected to the upper aquifer. The thickness of the lower aquifer ranges from about 30 to about 80 ft in the study area (Canace and others, 1993). This aquifer is absent in parts of Dover and Boonton Township.

Because the confining unit varies in extent and is poorly defined in some areas, partially confined or semiconfined conditions can prevail. Semiconfined aquifers are common in former lake basins where a permeable stratum is overlain by a semipervious layer (Todd, 1980, p. 45). Water in wells screened below a unit of very fine sand and till in Berkshire Valley (Canace and others, 1983), at the Boonton Township well field (Moretrench American, 1975), and at the Town of Dover water-supply well number 4 (Dan Raviv Associates, Inc., 1984) is semiconfined. These wells are considered to be screened in the lower aquifer for the purposes of this report.

Ground-Water Levels and Directions of Flow

A generalized hydrogeologic section showing ground-water flow in the valley-fill aquifers is shown in figure 3. Precipitation that falls on the valley-fill sediments infiltrates into the ground-water flow system, flows overland to streams, or is taken up as evapotranspiration. The upland areas consist of bedrock ridges mantled by till. The till generally is less than 20 ft thick, but may be as thick as 150 ft in places, and consists of unsorted glacial material in a silty, fine-sand to medium-sand matrix (Stanford, 1989a, 1989b). Precipitation that falls on upland areas can infiltrate to the subsurface or become upland surface runoff. The upland surface runoff can flow to upland tributary streams or toward the valley-fill sediments as unchanneled upland runoff, which infiltrates into the upper aquifer at the valley walls. Precipitation that percolates into the upper aquifer can discharge to streams, discharges through wells, percolates into the lower aquifer, or is taken up as ground-water evapotranspiration. Subsurface flow also can be derived from precipitation that falls on upland areas and percolates through the till to enter fractures in the bedrock. The water moves downgradient through the fractures and flows to the valley-fill aquifers at the valley walls and floor. The lower aquifer also 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 aquifer discharges through wells or eventually flows upward and discharges to the Rockaway River. A small amount of water can exit or enter the aquifers to or from the underlying bedrock.

Unstressed Conditions

The first production wells in the study area were in operation in the early 1920's in the Town of Dover, Denville Township, and Rockaway and Mountain Lakes Boroughs. Water levels in the years before 1922 represent unstressed conditions; however, no water-level data are available for the study area during this period. The unstressed flow system can be described by the earliest water levels measured at wells not located near a production well. These water levels typically were recorded at the time of drilling or well development and span the 34-year period from 1922-55. Consequently, they do not represent the unstressed aquifer system, but are considered a close approximation because withdrawals from domestic wells were assumed to have been small. Water-level altitudes were estimated from a topographic map because an exact altitude was determined at only a few of these wells. These water levels are accurate to within 20 ft.

The altitudes of the water table in the upper aquifer and the potentiometric surface of the lower aquifer in 1922-55 are shown in figures 4 and 5, respectively. Contours for the upper aquifer indicate that the water table is a subdued reflection of the topography and that ground water flowed from areas of recharge at the surface of the valley fill or along the sides of the valleys to areas of discharge to streams. Ground water in the Lamington River Basin may have discharged to the Rockaway River Basin, as it does currently (R.S. Nicholson, U.S. Geological Survey, written commun., 1990). Ground water in the Whippany River Basin is assumed to have discharged to surface-water bodies within that basin. Water levels in the lower aquifer in the Rockaway River Basin indicate that ground water flowed downvalley and toward the center of the valley, where flow was upward, and discharged to the Rockaway River. A ground-water divide was probably located in the vicinity of the boundary between the Rockaway and Whippany River Basins. Because predevelopment water-level data were not available for this area, however, the exact location of the divide could not be determined. Predevelopment water-level data were not available for the area near the boundary between the Lamington and Rockaway River Basins; ground water in the lower aquifer in the Lamington River Basin near this boundary may have flowed toward the Rockaway River Basin. The lower aquifer was recharged by downward flow of water through the leaky confining unit or along valley flanks where the confining unit is thin or absent. Vertical

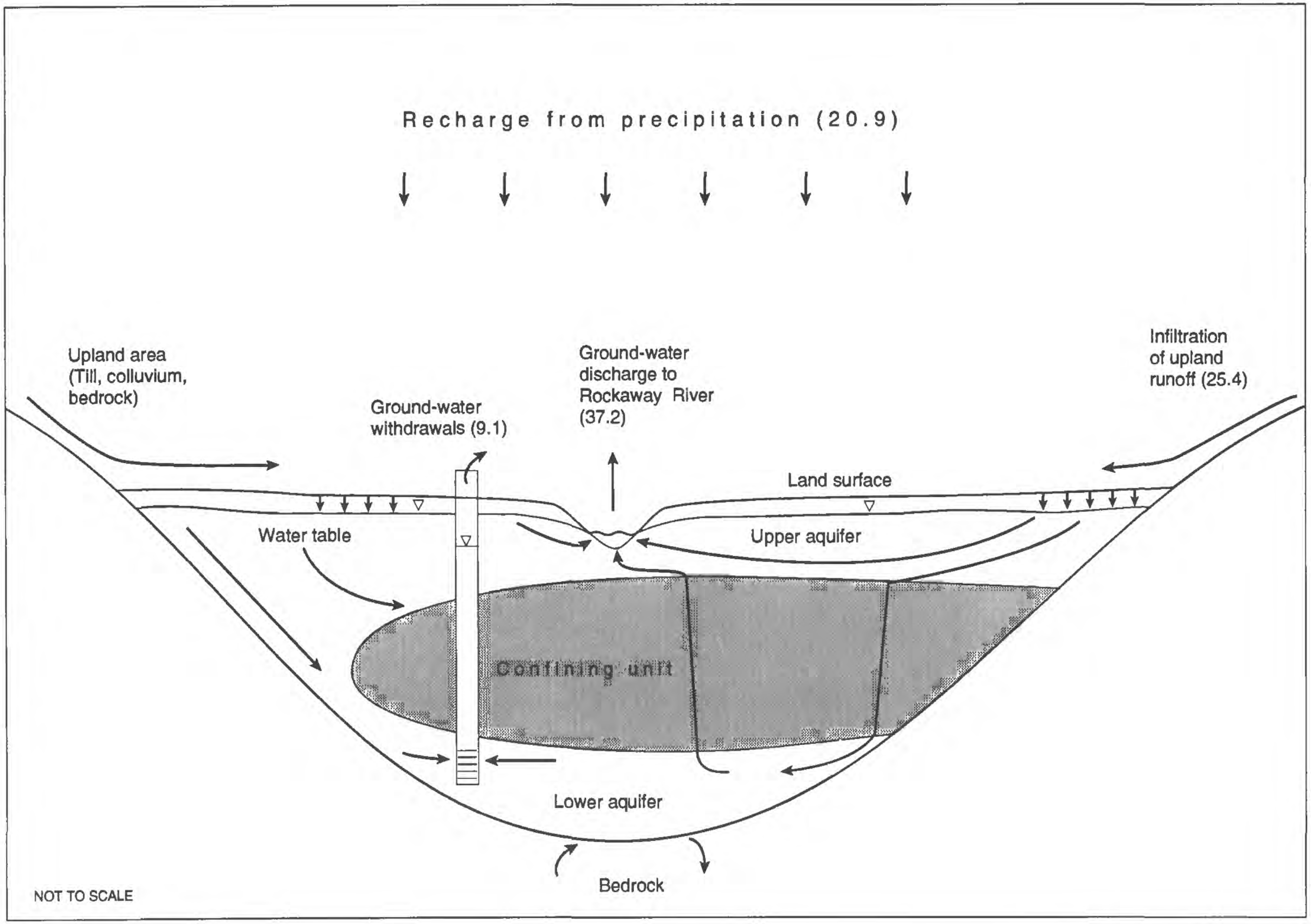
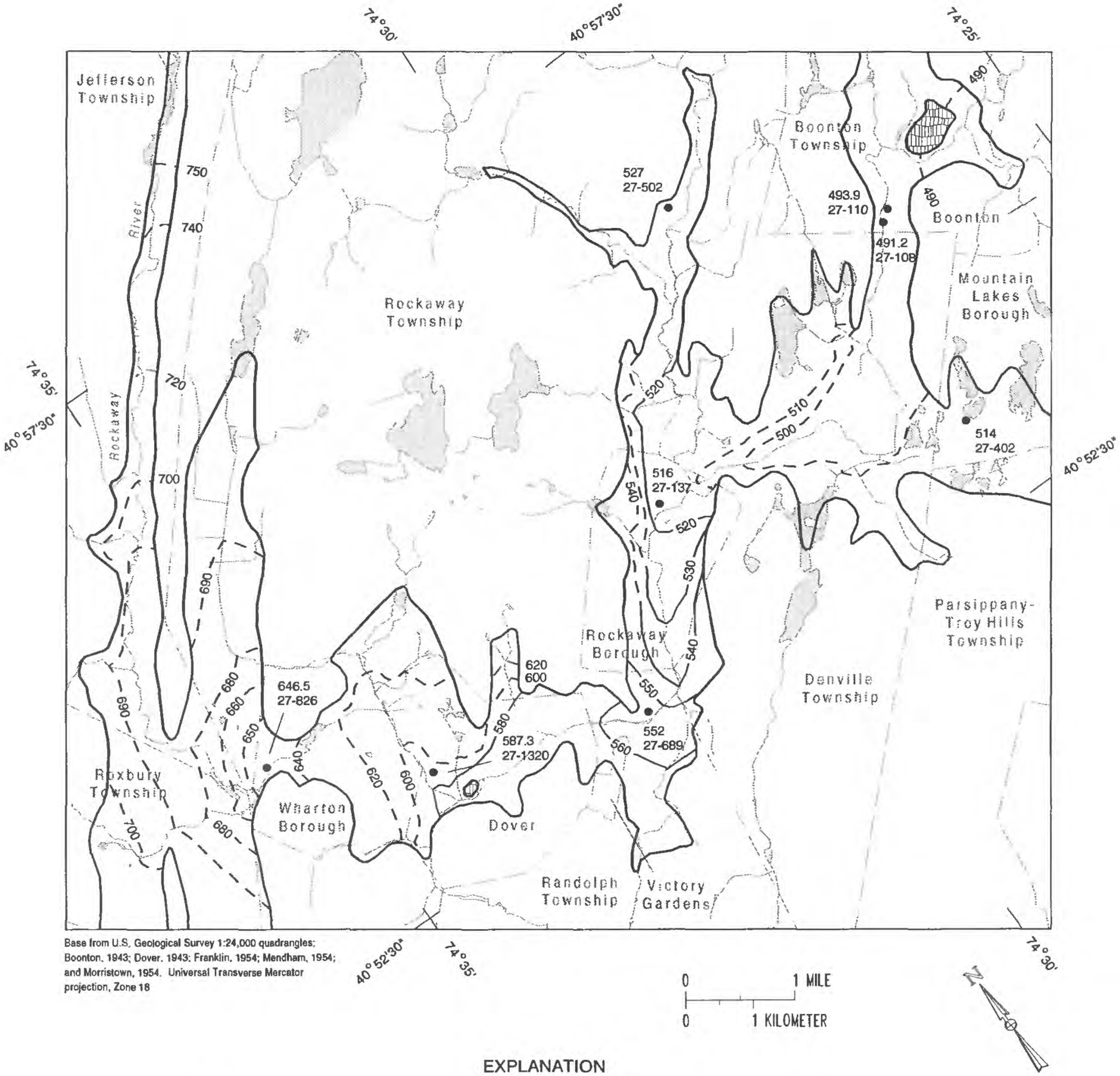


Figure 3. Generalized hydrogeologic section showing ground-water flow in the valley-fill aquifers and estimated ground-water budget for 1986, in million gallons per day.



EXPLANATION

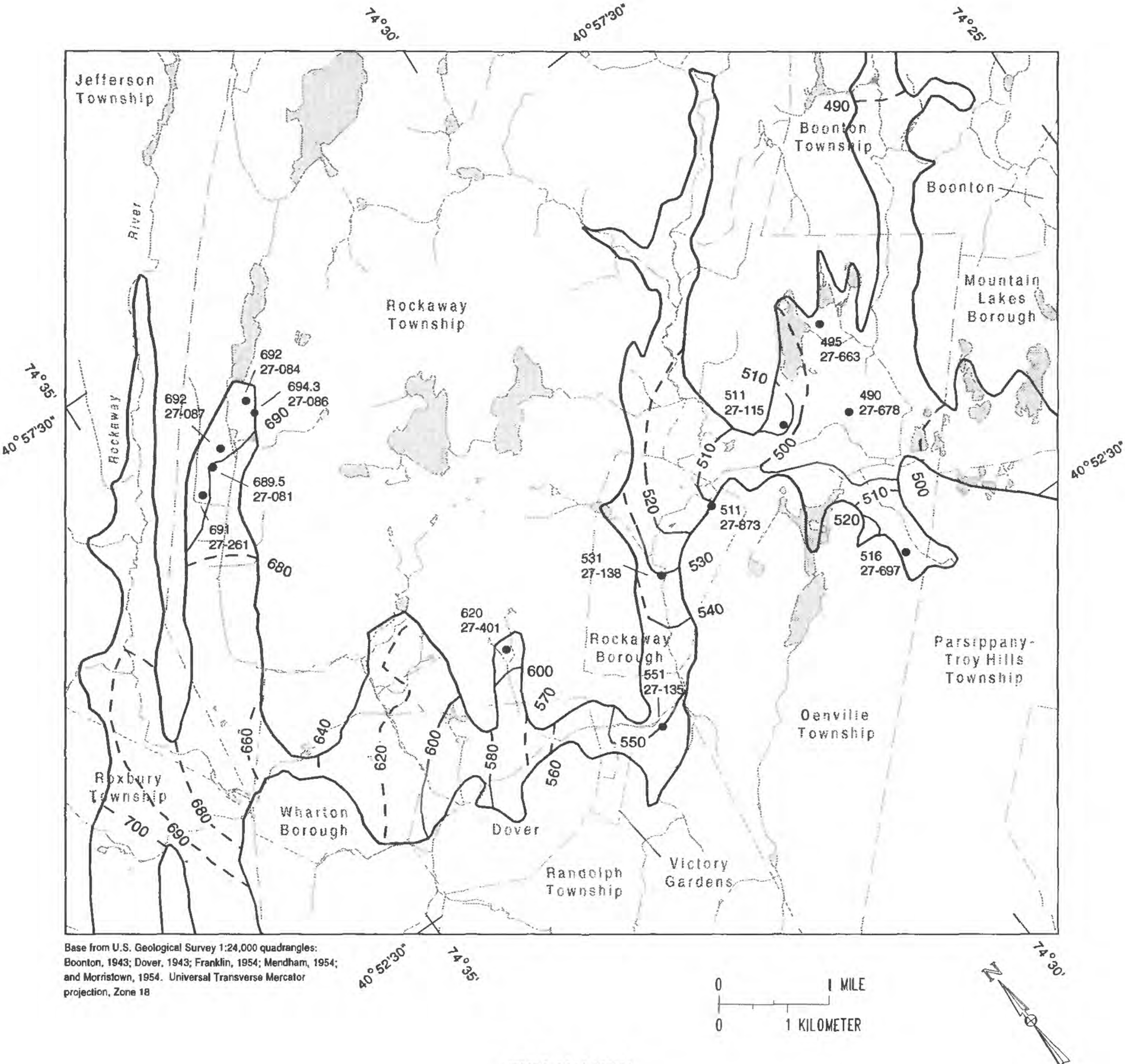
Outcrop of bedrock

— 530 – – WATER-TABLE CONTOUR--Shows altitude of water table. Dashed where approximately located. Contour interval is variable. Datum is sea level

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

• 514 27-402 Location of well. Upper number is altitude of water table, in feet above sea level; lower number is well number

Figure 4. Water-table altitude in the upper aquifer interpreted from static water levels measured during 1922-55.



EXPLANATION

— 620 — — POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Contour interval is variable. Datum is sea level

——— Approximate extent of the lower aquifer in the valley-fill deposits

● 490 27-678 Location of well. Upper number is altitude of potentiometric surface, in feet above sea level; lower number is well number

Figure 5. Altitude of potentiometric surface of the lower aquifer interpreted from static water levels measured during 1922-55.

gradients between the upper and lower aquifers under unstressed conditions were difficult to determine because available water-level data are incomplete and measurements were not made synoptically. Because the confining unit is discontinuous and leaky in some places, the difference between water levels in the upper and lower aquifers is assumed to have been small in most areas. Where the confining unit is thick and extensive, as in Denville Township, Mountain Lakes Borough, and Roxbury Township, a larger vertical gradient between the two aquifers would be expected. Static water levels from the 1940's to the early 1960's indicate that flowing wells were present near the boundary between Rockaway Township and Rockaway Borough (wells 27-058, 27-138, and 27-873), and in Randolph Township (well 27-135).

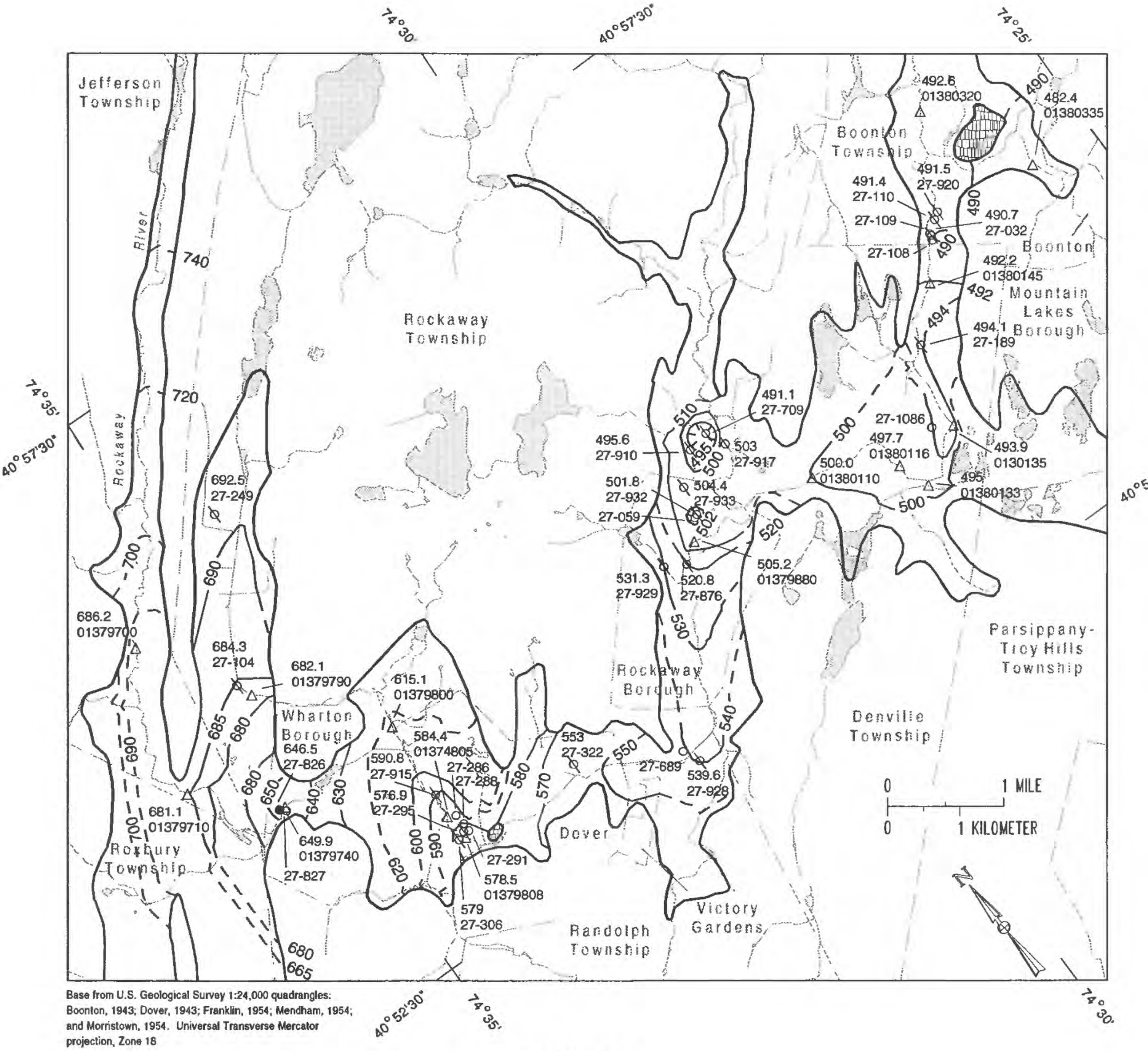
Stressed Conditions

Representations of the water-table and potentiometric surfaces in the upper and lower aquifers under stressed conditions (figs. 6 and 7), respectively, were prepared by measuring static water levels in 41 observation and industrial wells within the study area during June 1986. These water levels are assumed to represent average annual water levels. If the well was a production well or was located near a pumping center, the measurement was made at least 1 hour after the pump was shut off to allow time for recovery. A seepage run was completed at 15 surface-water sites before water levels were measured. A seepage run consists of discharge measurements made along a river over a short period of time to identify losing and gaining reaches. Surface-water elevations measured during the seepage run were incorporated into the water-table map (fig. 6). Most of the surface-water elevations were determined from a leveled reference point and are accurate to within 0.1 ft.

All wells in figures 6 and 7 (except well 27-826) were surveyed to maximize the accuracy of the water-level altitudes. These water levels are accurate to within 0.1 ft. The altitude for well 27-826 was estimated from a topographic map and is accurate to within 20 ft. Surface-water elevations used in contouring the water table (fig. 6) were determined from a reference point surveyed at each streamflow-gaging station. Detailed information on local ground-water flow patterns is not available for some parts of the study area because water-level data are incomplete.

The water table follows the topography of the land surface, with steeper gradients at the valley sides (fig. 6). Ground water flows downvalley and toward the center of the valley, where it discharges to the Rockaway River. The average depth to water in the upper aquifer over the study area ranges from about 1 to 14 ft below land surface. Cones of depression are apparent around pumping centers in Boonton and Rockaway Townships and Rockaway Borough; water levels in these areas are about 10, 48, and 25 ft below land surface, respectively. Ground-water flow in the upper aquifer at Boonton Township is toward the Boonton Reservoir, outside the study area, and is calculated to be about 0.02 Mgal/d. The glacial sediments in this area are composed of sand and gravel and are about 25 ft thick; the lower aquifer is thin or absent in this area.

The potentiometric surface of the lower aquifer (fig. 7) indicates a downvalley gradient. Ground water in this aquifer eventually discharges to the Rockaway River or is diverted by pumping. The average depth to water over the study area is about 5 to 35 ft below land surface. The largest drawdowns are measured in Rockaway Township near production well 7 (27-080), which has been in operation since 1969, and in Denville Township near production well 5 (27-035), which has been in operation since 1961. Cones of depression are evident around these two pumping centers. Water levels around the pumping areas of Rockaway



EXPLANATION

Outcrop of bedrock

—620— — WATER-TABLE CONTOUR--Shows altitude of water table. Dashed where approximately located. Contour interval is variable. Datum is sea level

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

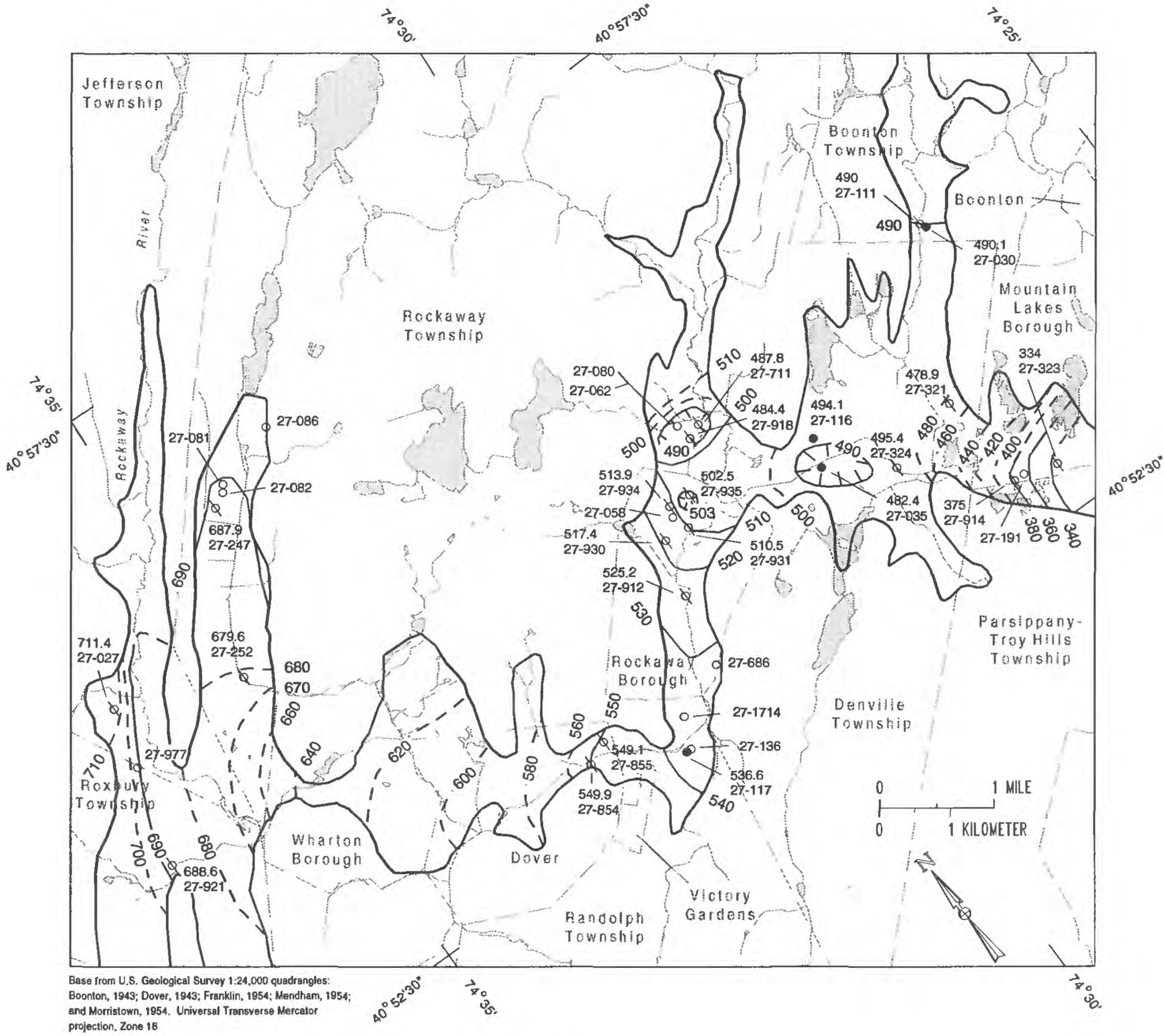
491.1 27-709 Location of observation well. Upper number is altitude of water table, in feet above sea level; lower number is well number

△ 682.1 01379790 Location of stream-stage measurement site. Upper number is elevation of stream, in feet above sea level; lower number is surface-water station number

○ 27-827 Location of production well and well number

● 646.5 27-826 Location of production well with water-level measurement. Upper number is altitude of water table, in feet above sea level; lower number is well number

Figure 6. Altitude of the water table in the upper aquifer interpreted from ground-water levels and stream stages measured during June 1986.



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

EXPLANATION

—620— — POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased well. Dashed where approximately located. Contour interval is variable. Datum is sea level

Approximate extent of the lower aquifer in the valley-fill deposits

686.6 27-921 Location of observation well. Upper number is altitude of potentiometric surface, in feet above sea level; lower number is well number

27-686 Location of production well and well number

536.6 27-117 Location of production well with water-level measurement. Upper number is altitude of potentiometric surface, in feet above sea level; lower number is well number

Figure 7. Altitude of the potentiometric surface of the lower aquifer interpreted from water levels measured during June 1986.

Township are more than 30 ft below land surface, whereas water levels distant from these pumping centers are about 10 ft below land surface. Water levels at well 27-035 in Denville Township are more than 25 ft below land surface.

The lowest water levels in the study area are found in the lower aquifer in Mountain Lakes Borough (fig. 7), where water levels are from about 130 to 170 ft below land surface. The glacial deposits here are more than 300 ft thick at the center of the valley, and a thick confining unit consisting of fine sand and clay overlies the lower aquifer. The low water levels are assumed to result from pumping effects at both the Mountain Lakes Borough water supply well (well 27-191) and in Parsippany-Troy Hills Township. Ground-water withdrawals in 1986 at a pumping center at Parsippany-Troy Hills (about 1 mi outside the study area) were about 2 Mgal/d. Ground water in the lower aquifer near Mountain Lakes Borough does not discharge to the Rockaway River, but a ground-water divide probably exists in the Rockaway River Basin near well 27-321 and the boundary between Mountain Lakes Borough and Denville Township. This location of the ground-water divide in the lower aquifer under stressed conditions differs from that under unstressed conditions (fig. 5). Flow in the lower aquifer from Mountain Lakes Borough to Parsippany-Troy Hills Township is calculated to be about 0.5 Mgal/d.

Water-level data from an investigation in the area of the Lamington River Basin (fig. 1) (R.S. Nicholson, U.S. Geological Survey, written commun., 1990) indicate that ground water in the glacial sediments outside the southwestern surface-water drainage boundary of the Lamington River Basin flows toward the Rockaway River Basin, and that a ground-water divide that does not coincide with the surface-water divide probably is present outside the study area in the Lamington River Basin. Ground-water flow from outside the basin was calculated by using Darcy's Law and average values of horizontal hydraulic conductivity and thickness for the upper and lower aquifers in that area. The hydraulic gradient was determined from water levels in wells in the area. Flow into the upper aquifer from the valley-fill deposits in the Lamington River Basin was calculated to be less than 0.1 Mgal/d. The upper aquifer is approximately 40 ft thick. The hydraulic gradient was calculated to be about 16 ft/mi. Flow to the lower aquifer from the glacial sediments outside the basin was calculated to be less than 0.01 Mgal/d. The lower aquifer is about 45 ft thick. The hydraulic gradient was determined to be less than 5 ft/mi.

The effects of seasonal fluctuations in water levels on the ground-water flow pattern cannot be determined from steady-state simulations, but can be determined from water-level measurements. Results of simulation of ground-water flow in the glacial deposits at Picatinny Arsenal in the Green Pond Brook valley (fig. 1) indicate that the direction of ground-water flow changes in response to seasonal fluctuations in the rate of ground-water recharge to the upper aquifer and that ground-water flow in this area is controlled by the distribution of ground-water recharge and the permeability of the glacial sediments and the bedrock (L.M. Voronin, U.S. Geological Survey, written commun., 1991). Both water-level hydrographs and bimonthly water levels measured from 1985 to early 1987 (Schaefer and others, 1993) show declines in water levels from late June to early September. The average decline in water level was about 2 ft, but declines of more than 7 ft were measured near pumping centers. Precipitation data for 1985-87 (National Oceanic and Atmospheric Administration, 1985, 1986, 1987) indicate that monthly precipitation remained fairly constant during the 2-year interval. Withdrawal data reported by local municipalities indicate that seasonal fluctuations in withdrawals are not significant, but withdrawals increase at some industrial and commercial sites during the summer months for lawn care or air-conditioning. Water levels remained low in October, probably as a result of the effects of evapotranspiration during the summer.

Vertical gradients between the upper and lower aquifers were difficult to measure because of the scattered locations of wells in the well network and the relative lack of paired wells. Water levels in June 1986 (fig. 6) indicated that heads in the upper aquifer were, in general, higher than those in the lower aquifer (fig. 7); therefore, the lower aquifer is recharged by leakage from the upper aquifer. Water levels measured (Schaefer and others, 1993) in paired wells at Picatinny Arsenal (wells 27-104 and 27-252) and in Rockaway Township (wells 27-709 and 27-711) indicate that vertical gradients are downward from the upper to the lower aquifer. In some areas the downward movement may be the result of pumpage from the lower aquifer, as in Rockaway Township.

Flow Budget

This section presents a discussion of the components of the flow budget, or the rates of recharge and discharge to the aquifers in the study area (fig. 3). Because the budget is calculated for steady-state conditions the change in storage is assumed to be zero.

Results of studies of several areas in the glaciated northeastern United States indicate that a significant percentage of the natural recharge to glacial valley aquifers is derived from upland runoff (Morrissey and others, 1988). 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. Underflow from the bedrock is assumed to be small because the bedrock is much less permeable than the valley-fill sediments (Gill and Vecchioli, 1965). Natural leakage from streams to the valley-fill aquifers occurs as upland tributary streams enter larger valleys that are underlain by stratified-drift sediments and lose water to the valley-fill aquifers by infiltration through streambeds. No measurements of discharge between reaches of upland tributaries are available, however. Ground-water withdrawals from the upland areas are considered negligible compared to the withdrawals from the valley-fill deposits. The distribution of recharge from the upland areas varied over the study area. The calculation of the distribution of this recharge component is discussed further in the model-input section of this report.

Ground-water recharge is the principal source of inflow to the valley-fill aquifers. A calculated ground-water-recharge rate of 1 (Mgal/d)/mi^2 has been reported for the valley-fill deposits in New Jersey (Halasi-Kun, 1972, 1979; R.S. Nicholson, U.S. Geological Survey, written commun., 1993). This rate is similar to the rate of 22 in/yr over the 20-mi^2 area of valley-fill deposits in the upper Rockaway River valley used in this report. A ground-water-recharge rate of 0.3 (Mgal/d)/mi^2 calculated from stream base-flow data has been reported for the fractured Precambrian crystalline rocks that underlie the upland areas in New Jersey (N.J. Department of Environmental Protection, 1974); however, the ground-water-recharge rate for the uplands areas of the upper Rockaway River valley is assumed to be 0.35 (Mgal/d)/mi^2 to include an estimate of ground-water withdrawals from the fractured rock. This rate is equal to about 5.6 in/yr over the 96-mi^2 upland area. The total long-term ground-water recharge rate to the valley-fill aquifers, then, is 46.3 Mgal/d, or the sum of the recharge to the valley-fill deposits (22 in/yr over 20 mi^2, or 20.9 Mgal/d) and the recharge to the fractured rock in the upland areas (5.6 in/yr over 96 mi^2, or 25.4 Mgal/d).

Ground-water discharge from the valley-fill aquifers can be calculated from stream base flow measured on June 3, 1986, and from average ground-water withdrawals from the valley-fill aquifers during 1986. On June 3, 1986, a gain in base flow of 57.6 ft^3/s (37.2 Mgal/d) was measured over a 91.9-mi^2 area of the upper Rockaway River drainage basin between streamflow-gaging station 01379690, located downstream from Longwood Lake (fig.1), and station 01380335, located about 1 mi above the Boonton Reservoir. Average ground-water withdrawals in 1986 were 9.1 Mgal/d, this amount is considered to have been used consumptively because all treated sewerage effluent is discharged into the Rockaway River downstream from the Boonton Reservoir. The total ground-water discharge is equal to the sum of the gain in stream base flow (37.2 Mgal/d) and the ground-water withdrawals (9.1 Mgal/d), or 46.3 Mgal/d. This rate equals the rate of ground-water recharge calculated above.

Aquifer/Stream-System Interaction

Low-flow measurements were made at various sites along the tributaries of the Rockaway River during October 1984, September 1985, and June 1986 (fig. 8). The measurements and associated gaging stations are listed in table 3 (Bauersfeld and others, 1985, 1986, 1987). The discharge values are direct measurements made during seepage runs and are assumed to approximate base flow. The values indicate that along the course of the Rockaway River some reaches lose water to the aquifer, whereas other reaches gain water from the aquifer.

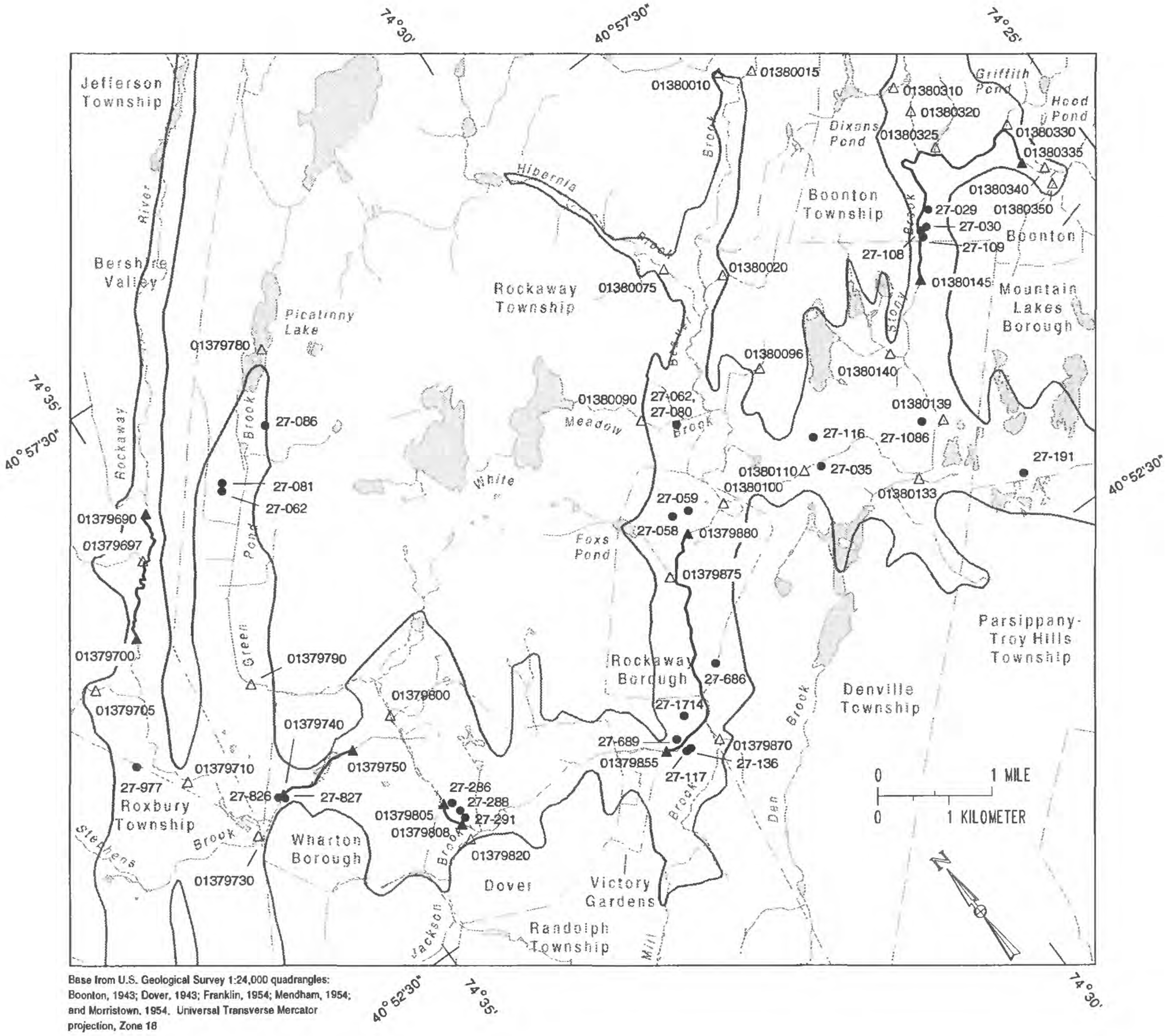
Losing reaches along the course of Rockaway River are found in areas where production wells screened in the upper aquifer are located near the river. One of these reaches is in the Town of Dover near production wells 1 and 3 (27-286 and 27-288), which are located between streamflow-gaging stations 01379805 and 01379808 (fig. 8) and are screened in glacial deposits composed of outwash sands and gravels. The average rate of withdrawals at this well field during 1986 was 1.85 Mgal/d. Measured streamflow loss between these gaging stations on June 3, 1986, was 0.5 ft^3/s (0.3 Mgal/d). Losses also were measured on October 16-17, 1984, and September 19, 1985. Geraghty and Miller (1969) documented the presence of a hydraulic connection between the glacial deposits and the Rockaway River at production well 3 that results in the sustained high yields of these wells.

Induced seepage from the river also has been measured in Wharton Borough in the vicinity of production wells 1 and 2 (27-826 and 27-827), located between streamflow-gaging stations 01379740 and 01379750 (fig. 8). Because the upper aquifer at Wharton Borough consists of medium-grained sand to coarse gravel, a good hydraulic connection exists between the river and the aquifer there. The average rate of withdrawals from these wells during 1986 was 0.69 Mgal/d. The measured loss from the river between these stations on June 3, 1986, was 3.9 ft^3/s (2.6 Mgal/d). A small loss in streamflow (0.6 ft^3/s) was measured on September 19, 1985, but a small gain (0.2 ft^3/s) was measured on October 16-17, 1984. These small differences in measured streamflow may result from inaccuracies in discharge-measurement techniques, which have a standard error of about 2 to 6 percent (Sauer and Meyer, 1992).

SIMULATED GROUND-WATER FLOW

Model Design

A ground-water-flow model was constructed by using the McDonald and Harbaugh (1984) ground-water flow program. The model design incorporates the assumptions that the aquifers are isotropic and the bedrock is impermeable. Flow was assumed to be horizontal in the aquifers and vertical in the confining unit. The ground-water-flow model allows for simulations of areal recharge, stream/aquifer interactions, discharging wells, specified-flux boundaries, and constant-head boundaries. Ground-water evapotranspiration was not simulated explicitly because of the unavailability of data, but was incorporated in the estimate of recharge.



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

EXPLANATION

- Approximate extent of the valley-fill deposits, modified from Canace and others, 1993, and Stanford, 1989a, 1989b
- △ 01379730 — Locations of stream-flow-gaging stations or low-flow partial-record station and number
- Gaining reach of the Rockaway River during June 3, 1986
- Losing reach of the Rockaway River during June 3, 1986
- ● 27-977 — Location and number of production well

Figure 8. Locations of losing and gaining reaches of the Rockaway River during June 3, 1986, and pumped wells in the study area.

Table 3. Discharge measurements from seepage runs conducted on the Rockaway River during October 16-17, 1984, September 19, 1985, and June 3, 1986

(mi^2, square miles; ft^3/s, cubic feet per second; --, no data)

Station number	Station name	Station type[1]	Drainage area (mi^2)	Base flow (ft^3/s) 10/16-17/84	9/19/85	6/3/86
01379690	Rockaway River near Route 15 at Berkshire Valley	M	23.1	6.48	9.87	25.9
01379697	Rockaway River tributary 9 near mouth at Berkshire Valley	M	.86	0	0	.1*
01379700	Rockaway River at Berkshire Valley	G	24.4	6.68	11.8	23.8
01379705	Rockaway River tributary 1 near Berkshire Valley	M	1.27	--	--	.1*
01379710	Rockaway River near Wharton	M	27.4	7.82	8.90	27.0
01379730	Stephens Brook at Wharton	M	1.73	--	--	1.0*
01379740	Rockaway River at West Central Avenue at Dover	M	30.3	10.4	11.8	36.1
01379750	Rockaway River at Dover	L	30.8	11.0	11.6	32.2
01379780	Green Pond Brook below Picatinny Lake at Picatinny Arsenal	G	9.16	.46**	1.2**	5.6**
01379790	Green Pond Brook at Wharton	M	12.6	3.3**	3.6**	9.3**
01379800	Green Pond Brook at Dover	M	15.1	3.59	4.57	10.8
01379805	Rockaway River above Dover well field at Dover	M	46.3	16.2	18.6	45.0
01379808	Rockaway River below Dover well field at Dover	M	47.1	15.7	16.5	44.5
01379820	Jackson Brook at mouth at Dover	M	4.87	2.83	1.89	3.97
01379855	Rockaway River at Rockaway Road at Randolph	M	56.1	22.5	23.9	53.7
01379870	Mill Brook at Randolph	M	4.84	2.96	2.29	4.41
01379875	Foxs Pond outlet at Rockaway	M	1.39	.01	.01	.37
01379880	Rockaway River at Rockaway	M	64.3	25.4	23.5	56.4
01380010	Beaver Brook at Meriden	M	6.80	2.00	1.88	1.90
01380015	Beaver Brook tributary 3 at Meriden	M	.25	.04	.04	0.9
01380020	Beaver Brook, tributary 2 at Ford Road at Beach Glen	M	.41	.02	0	.06
01380075	Hibernia Brook at Beach Glen	M	7.73	1.09	.83	2.64
01380090	White Meadow Brook near Denville	M	3.35	.32	.34	.09
01380095	Beaver Brook tributary 1 near Denville	M	.16	.11	.01	.03
01380100	Beaver Brook at Rockaway	M	22.7	2.64	2.48	7.91

Table 3. Discharge measurements from seepage runs conducted on the Rockaway River during October 16-17, 1984, September 19, 1985, and June 3, 1986--Continued

(mi^2, square miles; ft^3/s, cubic feet per second; --, no data)

Station number	Station name	Station type[1]	Drainage area (mi^2)	Base flow (ft^3/s) 10/16-17/84	9/19/85	6/3/86
01380110	Rockaway River at Savage Avenue at Denville	M	87.6	27.8	27.5	67.0
01380133	Den Brook at Denville	M	17.5	--	--	3.48
01380135	Rockaway River at Pocono Road at Denville	M	96.7	30.8	39.6	70.0
01380140	Rockaway River tributary 3 at Denville	M	1.80	.11	.34	.23
01380145	Rockaway River at Bush Road at Denville	M	99.5	30.8	41.7	86.5
01380310	Dixons Pond outlet stream at Boonton	M	3.05	.08	.12	.37
01380320	Stony Brook at Boonton	M	12.7	0	0	2.65
01380325	Rockaway River tributary 7 at Powerville	M	.44	.10*	.03*	0
01380330	Griffith Pond outlet at Powerville	M	.82	.03	.02	.20
01380335	Rockaway River at North Main Street at Powerville	M	115	35.9	36.7	83.5
01380340	Hood Pond outlet at Powerville	M	.18	.002	0	.05
01380350	Rockaway River tributary 1 at Powerville	M	.79	.07	.06	.22
01380500	Rockaway River above Reservoir at Boonton	G	116	36**	39.6	74.6

[1] Station type: L, low-flow partial-record station; G, gaging station; M, miscellaneous discharge station

* Estimate

** Value is mean for month from continuous-record streamflow-gaging station

Approach

The flow model was used to simulate ground-water flow in the valley-fill aquifers under both unstressed and stressed steady-state conditions. Simulation results were used to show the effects of ground-water withdrawals on the ground-water flow system and to compare base flow in the Rockaway River under unstressed and stressed conditions. The calibrated steady-state model was used to evaluate the effects of predicted water use on the flow system during 1986-2000 and 1986-2040. Historical water-level, pumpage, and streamflow data for the study area are limited. The lack of long-term hydrographs and historical water levels precluded simulation of ground-water flow under transient conditions.

The flow model was calibrated to average annual unstressed (nonpumping) and stressed (pumping) steady-state conditions. The model first was calibrated to unstressed steady-state conditions by comparing simulated water levels to measured predevelopment water levels. No predevelopment streamflow data for unstressed conditions are available for the study area. Recent (1986) stressed steady-state conditions were simulated by including average pumpage for 1986; ground-water altitudes measured in observation and production wells during June 1986, which are considered to represent average water levels for the year; and base-flow measurements from three seepage runs made during 1984-86. Conditions during 1986 were considered to approximate steady-state conditions because most water levels measured during 1986 did not fluctuate more than 2 ft, except in areas of pumpage in Rockaway Township, Rockaway Borough, Denville Township, and Mountain Lakes Borough, where water-level fluctuations were as great as 7 ft. Hydrographs of water levels in eight wells screened in the valley-fill sediments (Schaefer and others, 1993) do not show declines in water levels resulting from pumpage during 1985-87, except those for well 27-323 (located outside the Rockaway River Basin) and well 27-709 (located in Rockaway Township). Annual precipitation at the three rain-gaging stations located in or near the basin (fig. 1) was 52.3 in/yr in 1986; this value is near the long-term (1951-80) average of 49.7 in/yr (Schaefer and others, 1993).

Differentiation of hydrogeologic units was difficult in some areas because lithology varies laterally and vertically over short distances, and geologic and water-level data are limited. The three-layer ground-water flow system previously discussed was simulated by using two layers. The upper layer (layer 1) was simulated as an unconfined aquifer consisting mainly of glacial outwash and deposits and till of the terminal moraine. The water-bearing units below the upper layer were simulated as a composite lower layer (layer 2) to represent the interfingering of deposits of different lithologies, which results in a complex nondistinct hydrogeologic unit.

The confining layer regulates vertical flow between the upper and lower layers. Units of very fine sand, silt, or clay, and units containing mostly silt and clay in a sandy matrix, were simulated as part of the confining layer. The confining layer was not simulated explicitly as a model layer, but was represented by the vertical leakance between the two aquifer layers. Vertical leakance is defined as the vertical hydraulic conductivity divided by the thickness of the confining unit. Leakage between layers depends on the head in each layer as well as the values specified for vertical leakance.

Grid

The finite-difference grid used to simulate the valley-fill deposits consists of 85 rows, 96 columns, and 2 layers (figs. 9 and 10). The grid is oriented northeast-southwest, parallel to the trend of the bedrock ridges. The grid spacing is uniform and each cell is 500 ft on each side. This nodal spacing was chosen in order to simulate a 1,500-ft-wide constriction at Wharton

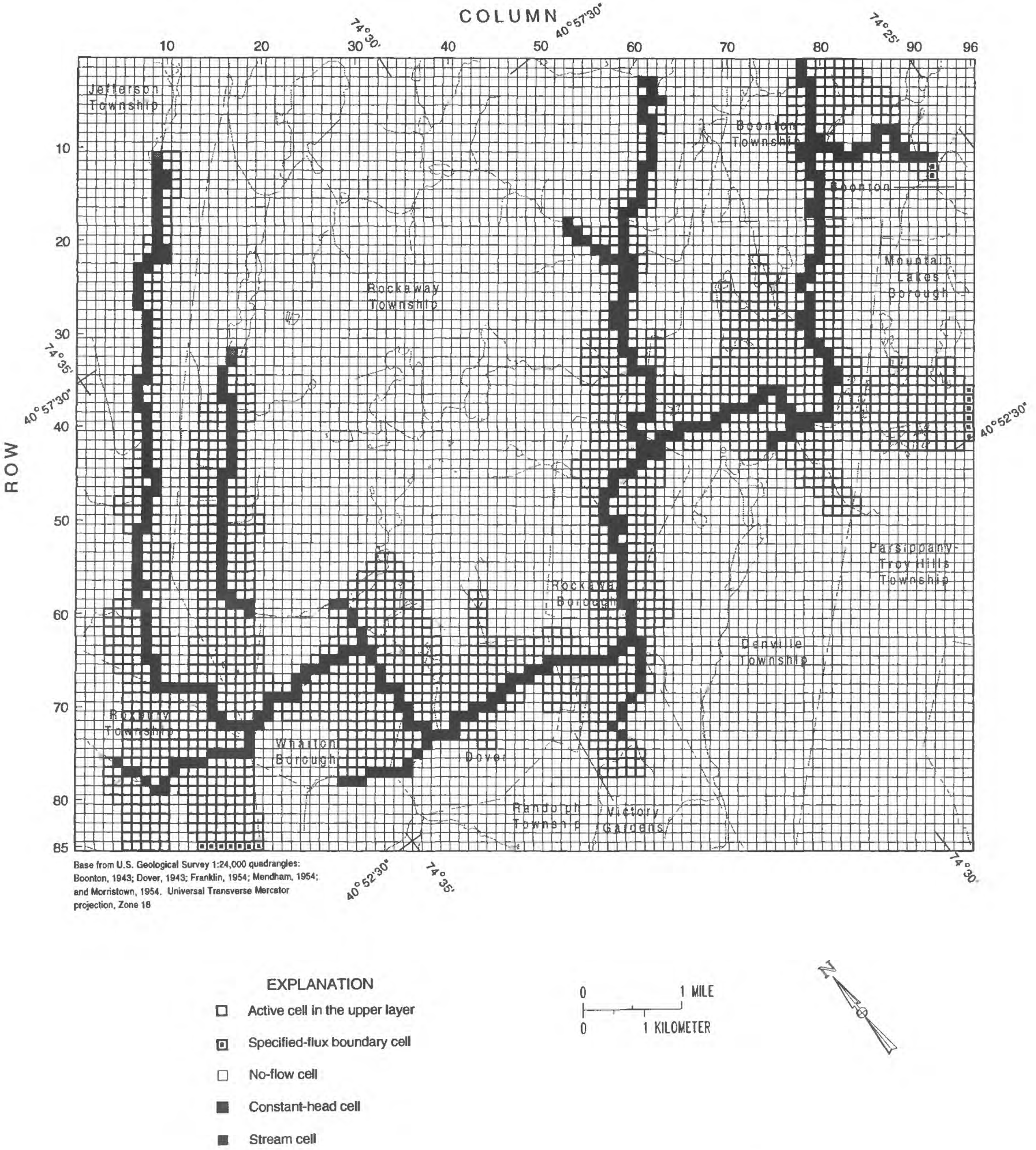


Figure 9. Finite-difference grid for the upper modeled layer.

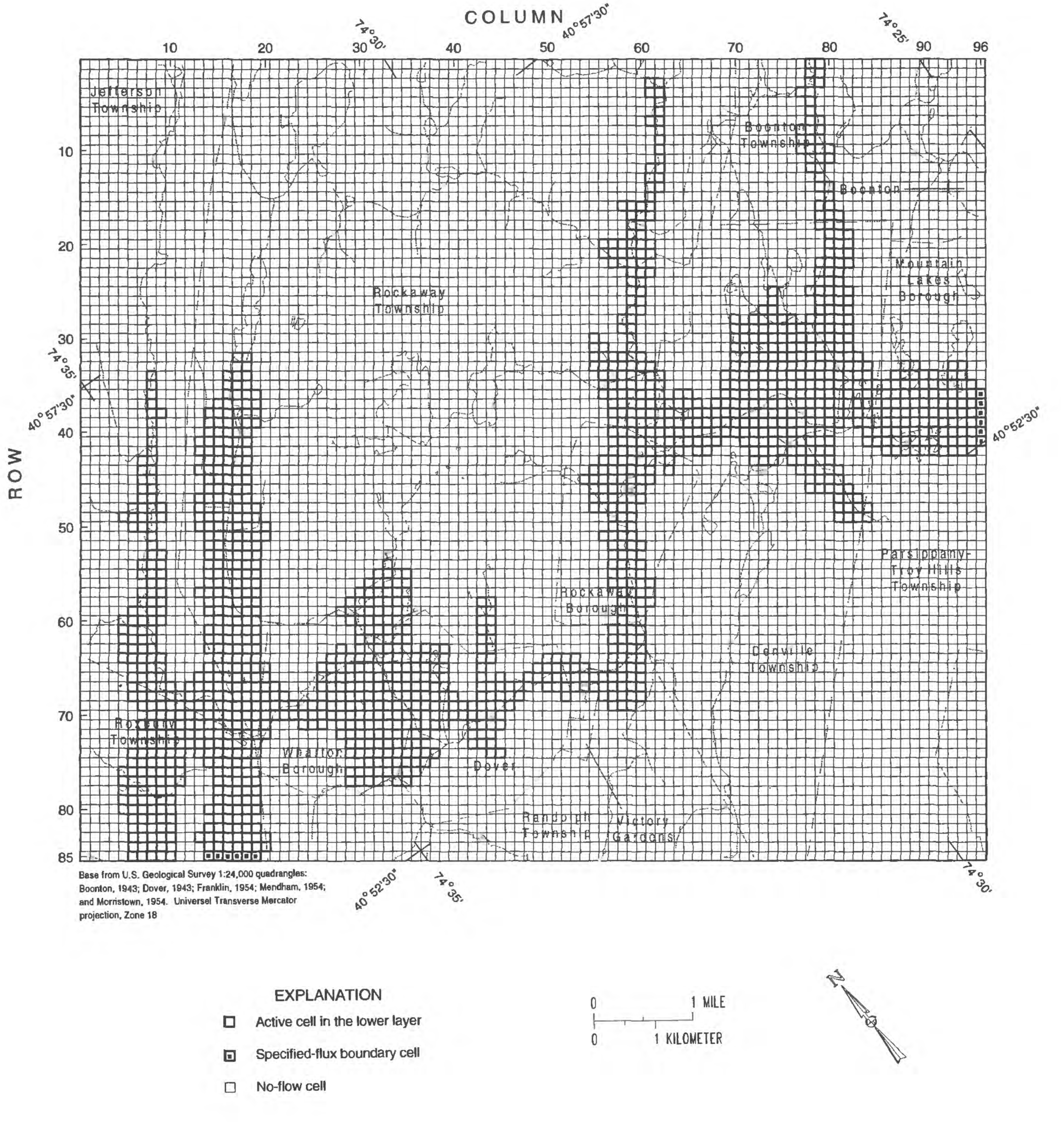


Figure 10. Finite-difference grid for the lower modeled layer.

Borough. A minimum of three nodes across this narrow constriction was assumed to be necessary for adequate simulation. A uniform grid and nodal spacing of 500 ft was considered to be acceptable for simulating the regional ground-water flow system.

The active cells in the grid (fig. 9) generally correspond to the areal extent of the valley-fill aquifers within the modeled area; however, in some areas the valley-fill deposits were not simulated because of the limited saturated thickness. In other areas, surficial till deposits were incorporated in active cells to allow for recharge from adjacent upland areas. The valley-fill deposits above Longwood Lake (fig. 1) were not simulated because of their limited narrow extent and because ground-water withdrawals from this area are not significant. A section of the Lamington River Basin was included because ground-water flow in the glacial sediments in this area is toward the Rockaway River Basin. The model boundary at Mountain Lakes Borough is extended beyond the Rockaway River Basin boundary because of major withdrawals from the valley-fill deposits in this part of the study area. Although the upper aquifer in Mountain Lakes Borough discharges outside the Rockaway River Basin, it was included in the model to allow for the simulation of recharge to the upper and lower aquifers there.

Boundary Conditions

The types of boundaries used in the model are constant-head, no-flow, specified-flux, and head-dependent (figs. 9 and 10). Constant heads are used to represent lakes in some areas. A no-flow boundary was imposed on the boundary beneath layer 2 and along the perimeter of the valley fill, except where head-dependent boundaries were used. The no-flow boundary denotes the contact of the valley-fill deposits with the surrounding and underlying bedrock. A no-flow boundary was assigned from column 6 through column 10 in row 85 (fig. 9). This area is assumed to coincide with the drainage divide between the Rockaway River and the Lamington River. Columns 10 and 14 were separated by a no-flow boundary representing an impermeable bedrock ridge. The upper model boundary is a specified-flux boundary representing recharge to the water table at all active nodes in layer 1.

Head-dependent boundaries were assigned by use of the general-head-boundary package of the modular model (McDonald and Harbaugh, 1984) in areas where ground water flows to or from the glacial sediments outside the modeled area. This allows ground water to flow in or out of the modeled area depending on the difference between the fixed general head and the aquifer head, and on the hydraulic conductance across the boundary. These boundaries were imposed (1) at the southwestern boundary of the model at Roxbury Township; (2) near Stony Brook valley between Boonton Township and the Town of Boonton, where the Rockaway River flows out of the modeled area; and (3) at Mountain Lakes Borough just outside the southeastern Rockaway River Basin boundary. The general head imposed at Mountain Lakes Borough simulates the effects of pumpage at the Parsippany-Troy Hills pumping center on ground-water flow in the valley-fill deposits in the study area. An average water level in wells at the Parsippany-Troy Hills pumping center was used for both model layers.

Model Input

Aquifer properties are assigned to each cell; each assigned value reflects the average value for that cell. The initial heads for the simulation of unstressed conditions were obtained from estimates of water-table altitudes relative to land-surface elevations. The initial heads for the simulation of stressed conditions were determined from the calibrated steady-state heads resulting from the calibration of unstressed conditions, and the initial heads in the predictive simulations were the calibrated steady-state heads resulting from the simulation of stressed conditions. Pumpage stress and streamflow values were assigned to appropriate cells.

Aquifers and Confining Units

Hydraulic properties assigned to the upper layer were the altitude of the bottom of the upper layer and horizontal hydraulic conductivity. The value for the altitude of the bottom of the upper layer was determined by subtracting the thickness of the upper layer from land-surface elevation for each active node in the upper layer. The ratio of vertical hydraulic conductivity to thickness of the confining unit was used to represent vertical leakance. The thickness of the lower aquifer was incorporated into the model by assigning a transmissivity value to each node where the lower layer is present. The thicknesses of the upper and lower layers and the confining material (figs. 11-13) between the layers were determined from drillers' logs of wells and borings in the study area and from geologic sections in previously published reports (Stanford, 1989a and 1989b; Canace and others, 1993).

Initial estimates of hydraulic conductivity for the upper and lower layers were compiled from data reported in previously published reports (Gill and Vecchioli, 1965; Geraghty and Miller, 1968 and 1978; Moretrench American Corporation, 1975; Summers and others, 1978; Canace and others, 1983; Dan Raviv Associates, Inc., 1984; Hill, 1985; Scientific Applications International Corporation, 1986). For areas where information was not available, hydraulic conductivity was estimated from aquifer properties at sites with similar geologic materials.

The vertical leakance was obtained by dividing the vertical hydraulic conductivity by the thickness of the confining unit for each cell that contains this unit. Initial estimates of vertical hydraulic conductivity were made on the basis of previously reported values (Dan Raviv Associates, Inc., 1984; L.M. Voronin, U.S. Geological Survey, written commun., 1991). In areas where a confining layer could not be defined, initial values of vertical hydraulic conductivity were calculated by dividing the hydraulic conductivity of the upper layer by 50 if the upper aquifer consisted of sand and gravel, or by 100 if the upper aquifer consisted of till or fine sand.

Recharge

Assigned recharge values incorporate precipitation that infiltrates the valley fill; infiltration of unchanneled runoff from the surrounding upland till; streamflow loss from small, upland-draining tributaries; and lateral inflow from surrounding surface-water basins. A value of recharge to the valley-fill deposits of 46.3 Mgal/d was nonuniformly distributed to active cells in layer 1. This value is the sum of the gain in base flow over the drainage area of the valley-fill deposits (37.2 Mgal/d) on June 3, 1986, plus the ground-water withdrawals from the valley-fill deposits (9.1 Mgal/d). Less recharge was applied to model cells where the stratified drift is absent or where surficial lacustrine or till deposits of low permeability overlie stratified drift than to model cells where stratified drift is present (fig. 14). More recharge is applied to model cells representing the valley edges and more recharge is applied to some model cells underlying areas where stream tributaries from the upland area are present than to model cells representing other areas of the outcrop of the valley-fill deposits. The additional recharge from upland areas includes seepage losses from upland-draining tributaries, infiltration of unchanneled overland runoff, and subsurface flow.

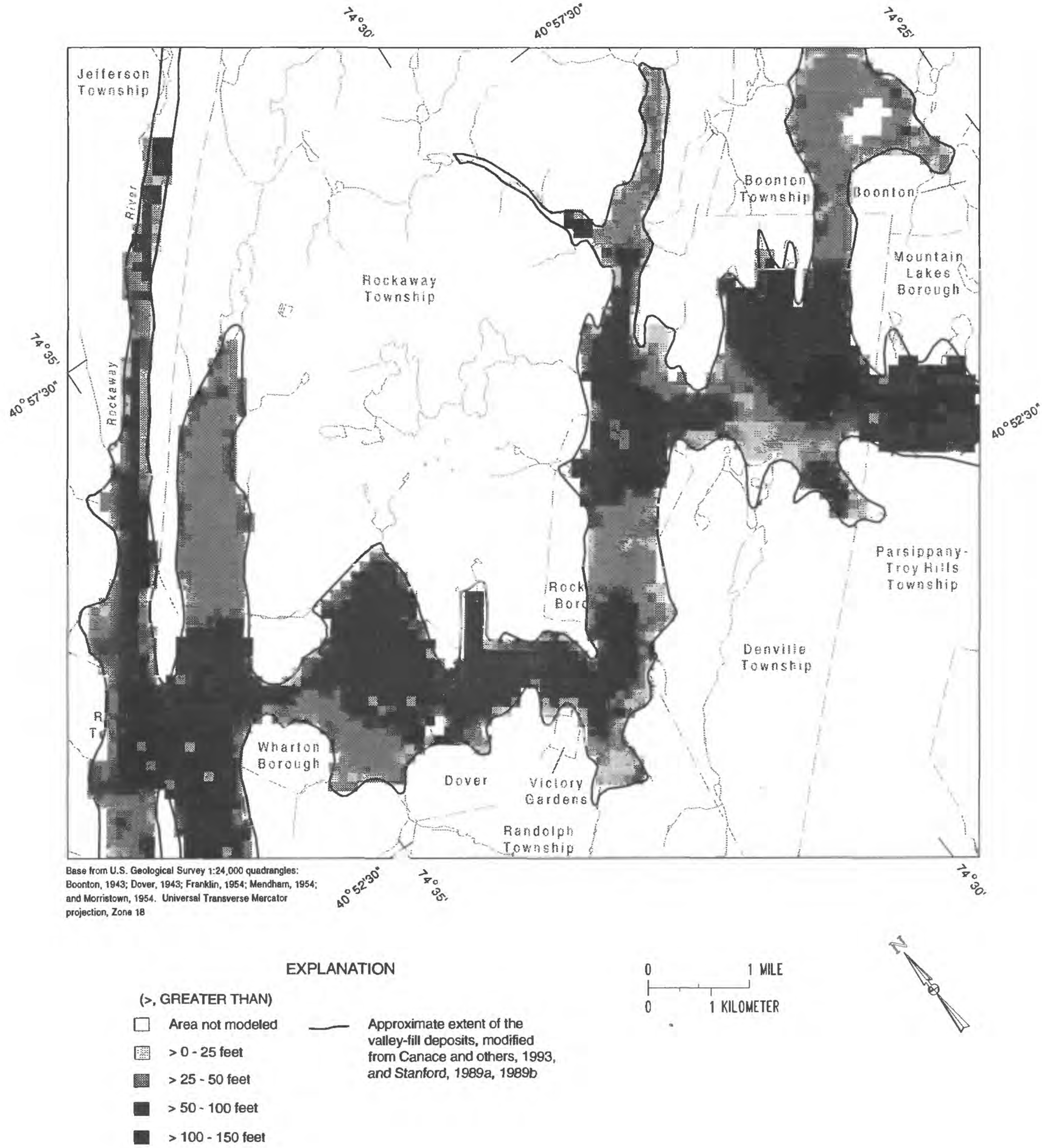


Figure 11. Discretized thickness of the upper layer in the modeled area.

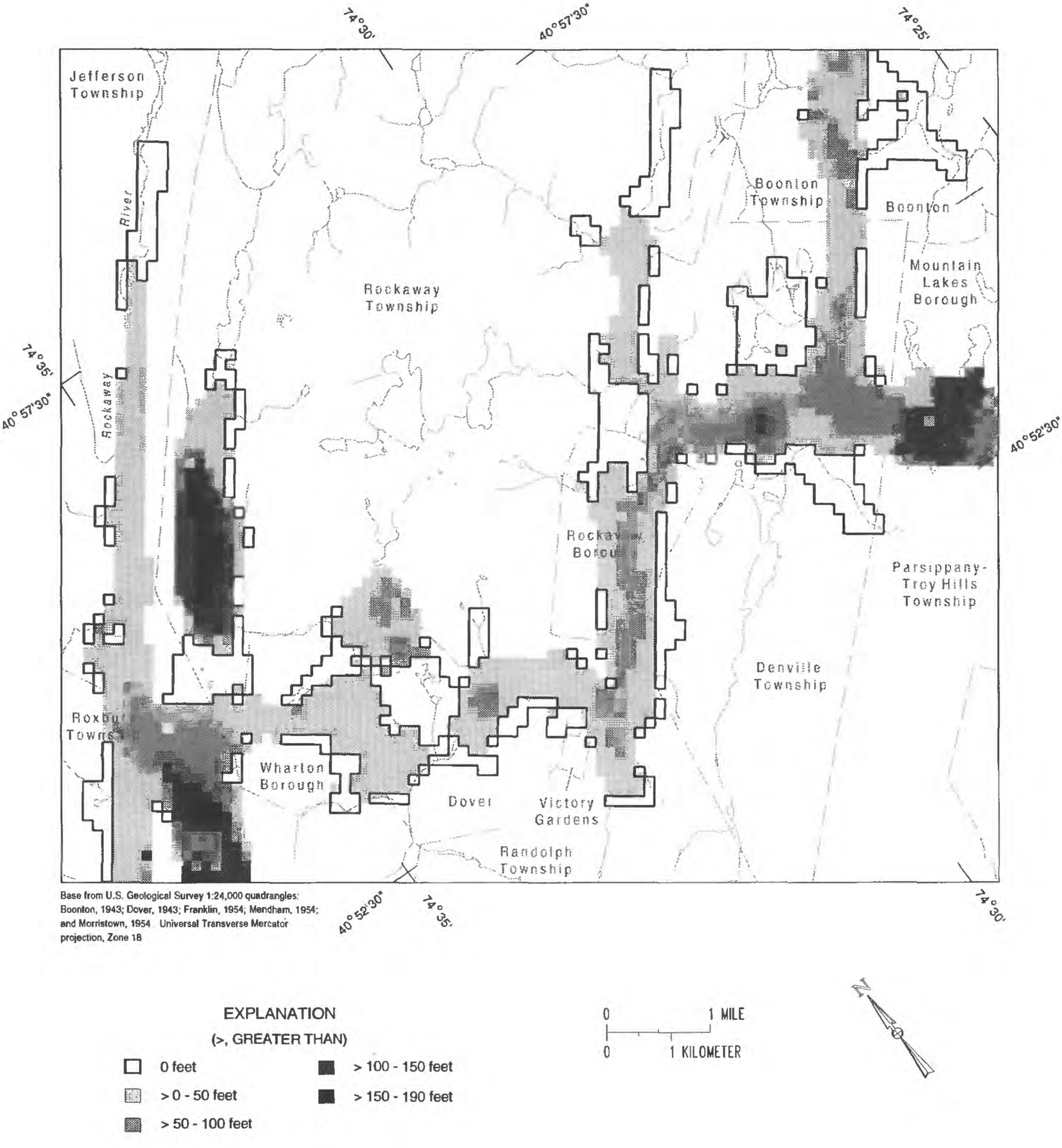


Figure 12. Discretized thickness of the confining unit between the upper and the lower layers in the modeled area.

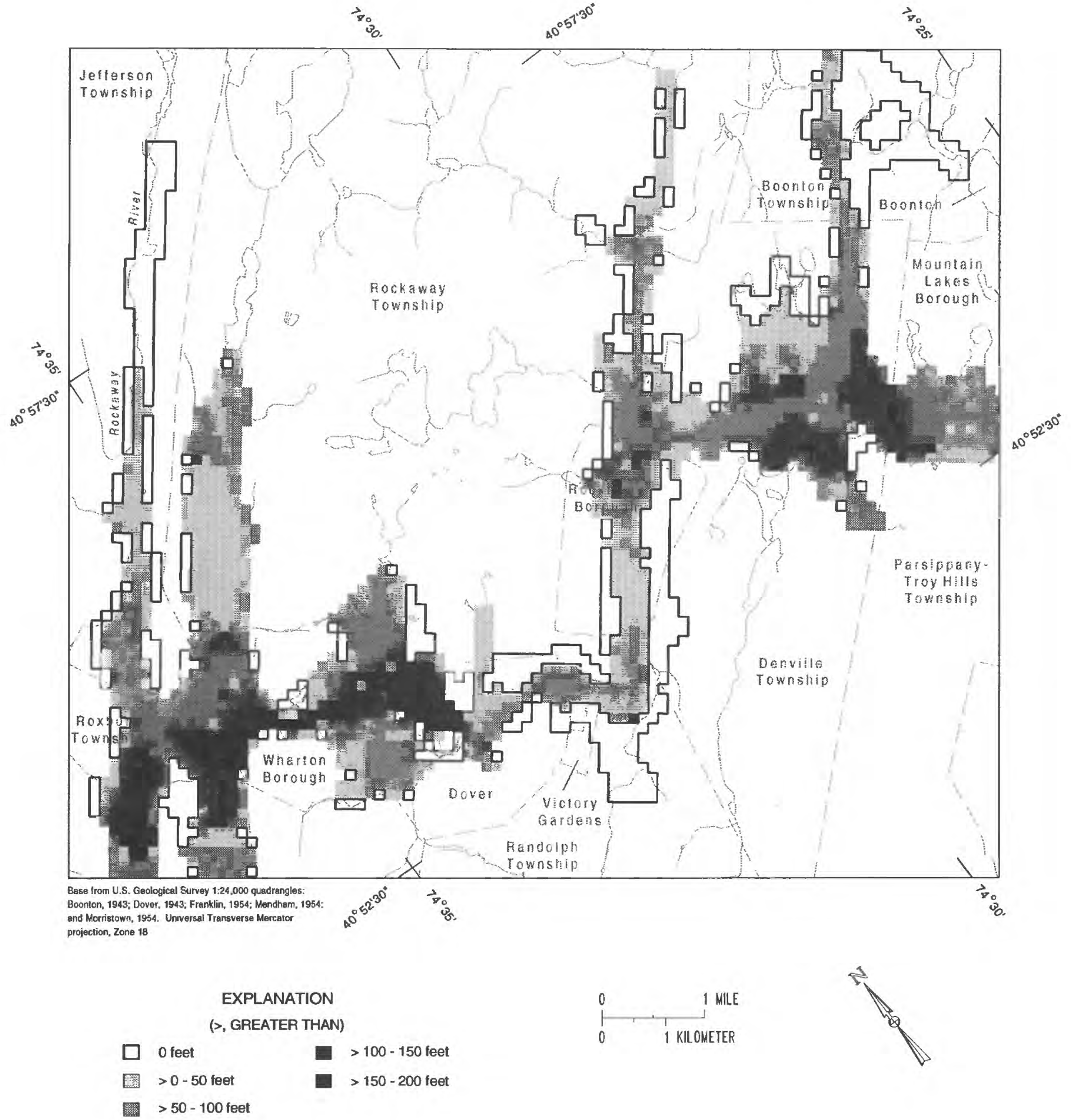


Figure 13. Discretized thickness of the lower layer in the modeled area.

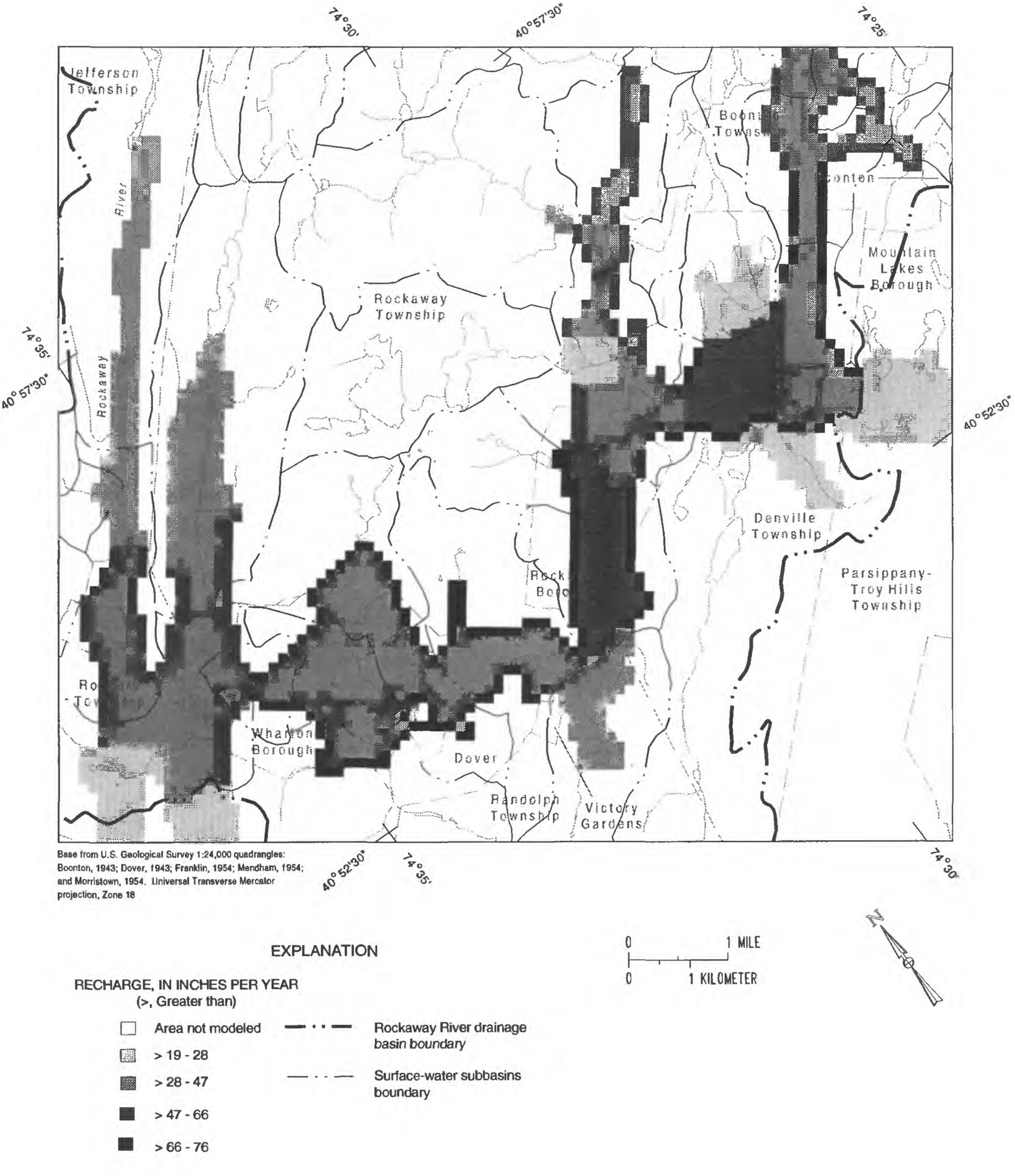


Figure 14. Discretized distribution of ground-water recharge to the upper layer in the modeled area and surface-water subbasins in the Rockaway River drainage basin in the study area.

The recharge from the upland areas was distributed to each section of the study area by (1) dividing the study area into surface-water subbasins (fig. 14), (2) determining the upland area that contributes runoff to the valley in each subbasin, (3) multiplying the contributing upland area by the average unit-area base flow and, (4) dividing this flow by the number of perimeter cells surrounding the valley-fill area in the subbasin and distributing it to them.

The percentage of upland area contributing recharge to the valley-fill deposits is a function of upland drainage patterns, grain-size distribution of the glacial cover, valley width, and slope. Upland recharge applied to perimeter cells in subbasins where ridges slope directly toward the valley was greater than recharge applied where ridges slope toward a surface-water discharge point, depending on the type of glacial cover. If the upland area drained directly to a stream, only a small amount of water was assumed to be available to infiltrate at the valley floor. If the subbasin contained few upland drainage sinks, however, a greater percentage of recharge from this area was applied to the valley-perimeter cells.

Streams

Streams in the valley-fill area are simulated as head-dependent flux boundaries at designated cells in the upper layer. Simulated streams include the Rockaway River, Green Pond Brook, Beaver Brook, and Stony Brook, and small sections of Stephens, Jackson, Mill, and Den Brooks (fig. 8). Smaller upland tributaries whose low-flow discharge was less than 1 ft^3/s, or for which discharge data were unavailable but whose low-flow discharge was assumed to be less than 1 ft^3/s, were simulated as specified-flux boundaries by incorporating them as part of the recharge flux. A section of Green Pond Brook that flows through an upland area downstream from streamflow-gaging station 01379790 (fig. 8) was not simulated because valley-fill deposits are absent in this area.

Stream leakance is a function of the head difference between the stream stage and ground-water head beneath the stream, and the streambed conductance. Stream characteristics assigned to each cell representing a stream are (1) stage, (2) elevation of the streambed, (3) thickness of the streambed, (4) vertical hydraulic conductivity of the streambed, and (5) area occupied by the stream in a cell. Stream stage was measured at low-flow-measurement sites along the Rockaway River during June 1986. Stream stage between these sites was interpolated from measured stages. Streambed conductance along a reach is the product of the vertical hydraulic conductivity of the streambed material and the area of the streambed divided by the thickness of the streambed material (McDonald and Harbaugh, 1984, p. 213-214). To calculate the area, stream length per model cell was estimated from U.S. Geological Survey topographic maps. The average width for each major tributary was estimated from the low-flow measurements made on June 3, 1986, and was estimated to be 30 ft for Green Pond Brook, 45 ft for Beaver Brook, 30 ft for the Rockaway River from Longwood Lake to Dover, and 50 ft for the Rockaway River from Dover to above the Boonton Reservoir. A streambed thickness of 3 ft was used (Lapham, 1989). Initial values of the streambed hydraulic conductivity were based on values reported in Dysart (1988) and Lapham (1989).

Ground-Water Withdrawals

Average ground-water withdrawals from the valley-fill deposits in 1986 were incorporated into the model for the steady-state simulation of stressed conditions (table 4). The well locations are shown in figure 8. Private and small industrial wells in the study area were not included if the total annual withdrawals were less than 500,000 gal/yr, or if pumping was

Table 4. Ground-water withdrawals from the valley-fill aquifers in the study area in 1986 and projected withdrawals for 2000 and 2040

(Mgal/d, million gallons per day; –, well not used)

New Jersey well number	Owner	Well number or name	Location in model			Withdrawals		
			Layer	Row	Column	1986 (Mgal/d)	Projected 2000 (Mgal/d)	Projected 2040 (Mgal/d)
27-108 & 109	Boonton Water	1&2	1	17	80	0.19	0.21	0.24
27-030	Dept.	5	2	16	80	.24	.3	.3
27-029		6	1	15	80	.03	.03	.04
27-136	Denville Township	3	2	65	59	.48	.59	.6
27-116	Water Dept.	4	2	36	70	.13	.16	.16
27-035		5	2	39	71	1.04	1.28	1.3
27-117		6	2	65	58	.02	.03	.02
27-286	Dover Water Dept.	1	1	70	37	1.66	1.84	2.07
27-288		3	1	71	37	.19	.21	.24
27-291		5	1	72	38	.89	.98	1.11
27-189	Mountain Lakes	4	1	27	79	–	[1].01	[1].01
27-191	Water Dept.	5	2	39	89	.67	.69	–
27-137	Rockaway Water	1	2	44	58	–	.31	.39
27-058	Dept.	5	2	44	57	[2].47	.31	.39
27-059		6	1	43	58	.81	1.06	1.32
27-062	Rockaway Township	6	2	35	57	.11	–	–
27-080	Water Dept.[3]	7	2	35	57	.92	–	–
27-977	Roxbury Township Water Dept.	Evergreen Acres	2	67	7	.005	.006	.006
27-826 & 827	Wharton Water	1&2	1	70	21	.69	.73	.73
27-353	Dept.[4]	3	1	69	35	–	–	.13
27-689	Austenal Labora-	1	1	64	57	.1*	**	**
27-1714	tory, Inc.	2	2	62	58	.09*	**	**
27-686	McWilliams Forge, Inc.	339	2	57	61	.09	**	**
27-081	US Army-Picatinny	129	2	41	15	.07	**	**
27-082	Arsenal	310	2	42	15	.06	**	**
27-086		410	2	36	19	.13	**	**
27-1086	St. Clare's Hospital		1	35	80	.09*	–	–
					1986 TOTAL	=9.1		

[1] Standby well. Projected increases were based on withdrawals during 1983-86.

[2] Well number 1 was in use again in 1987. The projected increase was divided equally between well 1 and well 5.

[3] Projected increased withdrawals for Rockaway Township will be pumped from wells at proposed sites.

[4] Well number 3 was in use again in 1988. Projected increases for 2040 were assigned to well 27-353.

* Estimated by owner.

** No change in withdrawals simulated.

intermittent, such as during the summer for lawn care or air-conditioning. Withdrawal data were obtained directly from municipal water authorities and industrial-well owners. Total ground-water withdrawals from these wells were 9.1 Mgal/d in 1986.

Model Calibration

The model was run with and without withdrawals and allowed to reach steady-state conditions. Model calibration consisted of adjusting model parameters until (1) measured water levels were within 10 to 15 ft of simulated heads and the configurations of the simulated potentiometric surfaces were similar to those of the interpreted surfaces contoured from water-level measurements, (2) simulated stream seepages approximated from seepages measured at low-flow sites along the Rockaway River, (3) simulated vertical head gradients matched measured vertical head gradients, and (4) estimated fluxes across the boundaries were considered reasonable. The aquifer characteristics adjusted include conductances at boundaries, horizontal hydraulic conductivity of the layers, and vertical leakance between the layers. Values of streambed conductance under stressed steady-state conditions were adjusted by varying the hydraulic conductivity of the streambed to match simulated stream seepage with stream seepage observed during three seepage runs conducted during 1984-86. An initial simulation period of 5 years was used. In most areas, except in Mountain Lakes Borough, steady-state conditions were achieved in less than 5 simulated years. The absence of steady-state conditions in this area is verified by a decline in water levels in well 27-323 in Mountain Lakes Borough (Schaefer and others, 1993). Because steady-state conditions were not achieved everywhere in the study area within 5 simulated years, a simulation period of 7 years was used. Steady-state conditions were achieved everywhere in the study area in 7 simulated years.

Hydraulic Characteristics

The results of model calibration of the horizontal hydraulic conductivities of the upper and lower layers and the vertical hydraulic conductivity of the confining layer are shown in figures 15 through 17.

Horizontal hydraulic conductivity of layer 1 (fig. 15) ranges from about 10 ft/d to 350 ft/d. Low values of hydraulic conductivity correspond to surficial deposits of fine sand and silt or till present in Mountain Lakes Borough and Denville and Rockaway Townships (Stanford, 1989a, 1989b). High values of hydraulic conductivity correspond to 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).

Vertical hydraulic conductivity of the confining layer (fig. 16) ranges from about 10 to 9×10^{-6} ft/d. Low values of vertical hydraulic conductivity correspond 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. High values of hydraulic conductivity correspond to areas where the confining unit is poorly defined, but consists of mostly silt or clay in a fine-to-medium sandy matrix.

The horizontal hydraulic conductivity of layer 2 (fig. 17) ranges from about 5 ft/d to 180 ft/d. The transmissivity of the lower aquifer is higher in the center of the valley because the valley-fill deposits are thicker there.

The vertical hydraulic conductivity of the streambed material ranges from about 0.4 ft/d to 20 ft/d. High values (more than 5 ft/d) were used in areas where sand and gravel deposits are in good hydraulic connection with the river, as in Wharton Borough and Dover. A

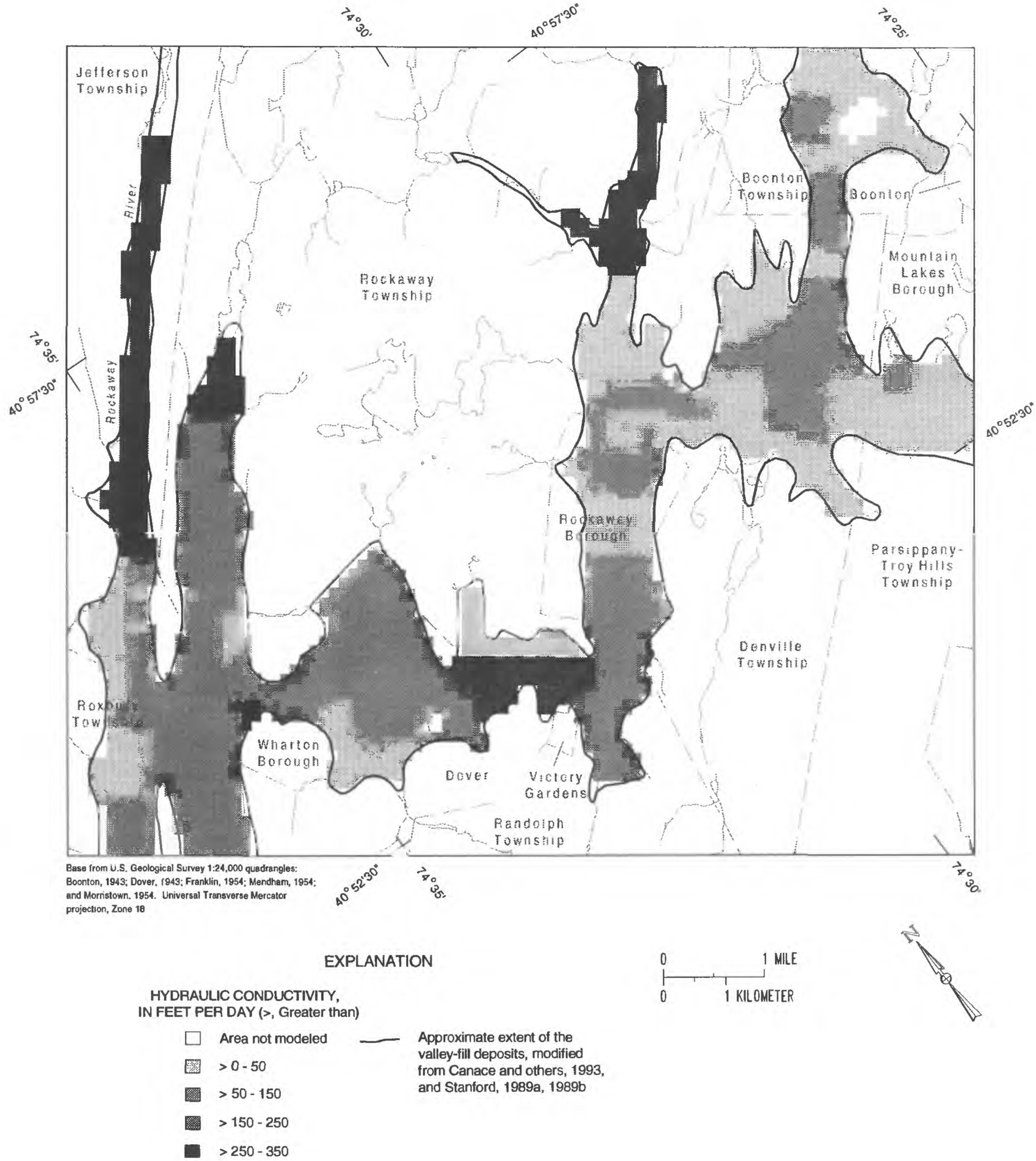


Figure 15. Discretized values of horizontal hydraulic conductivity of the upper layer in the modeled area.

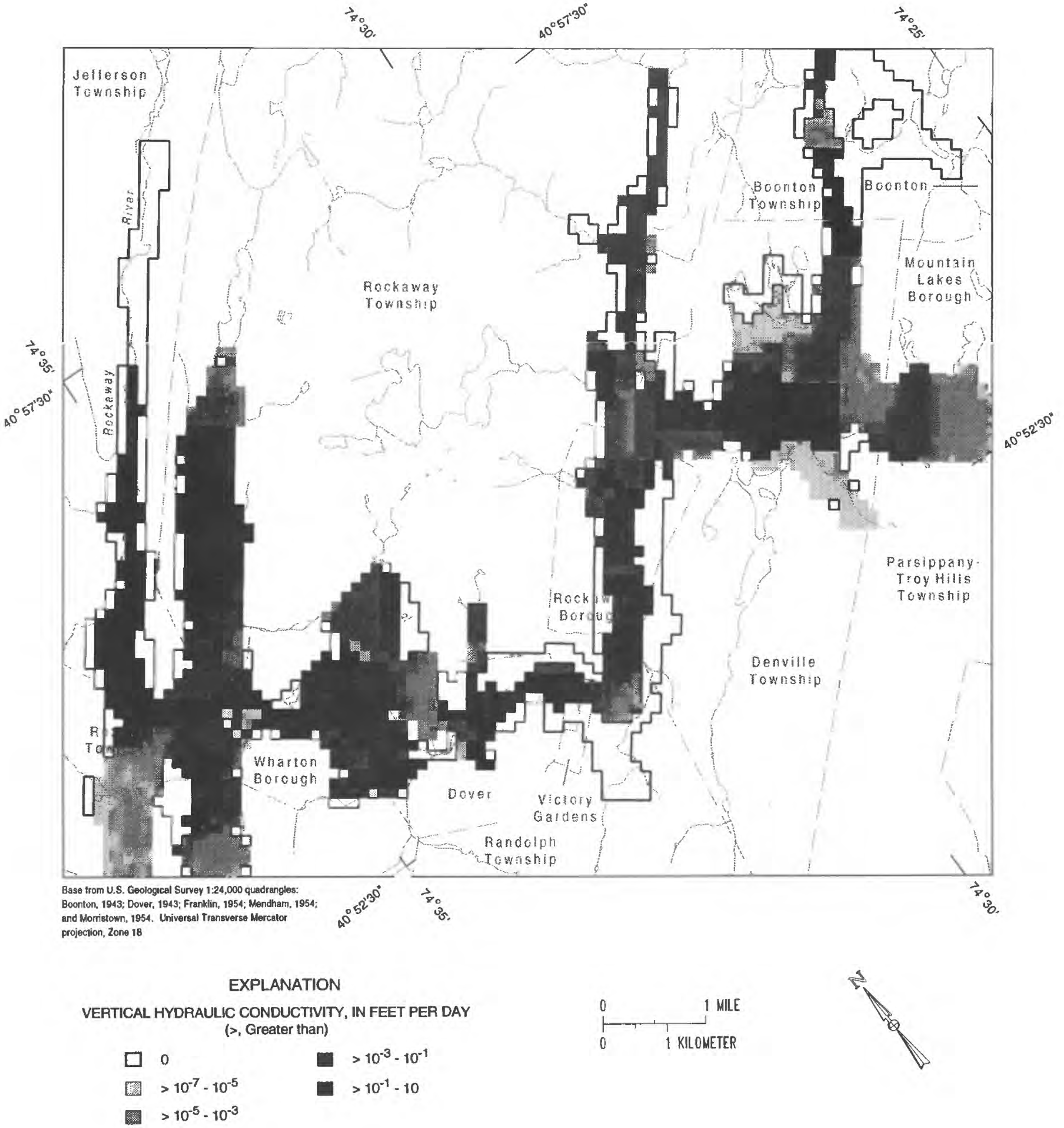


Figure 16. Discretized values of vertical hydraulic conductivity of the confining layer between the upper and lower layers in the modeled area.

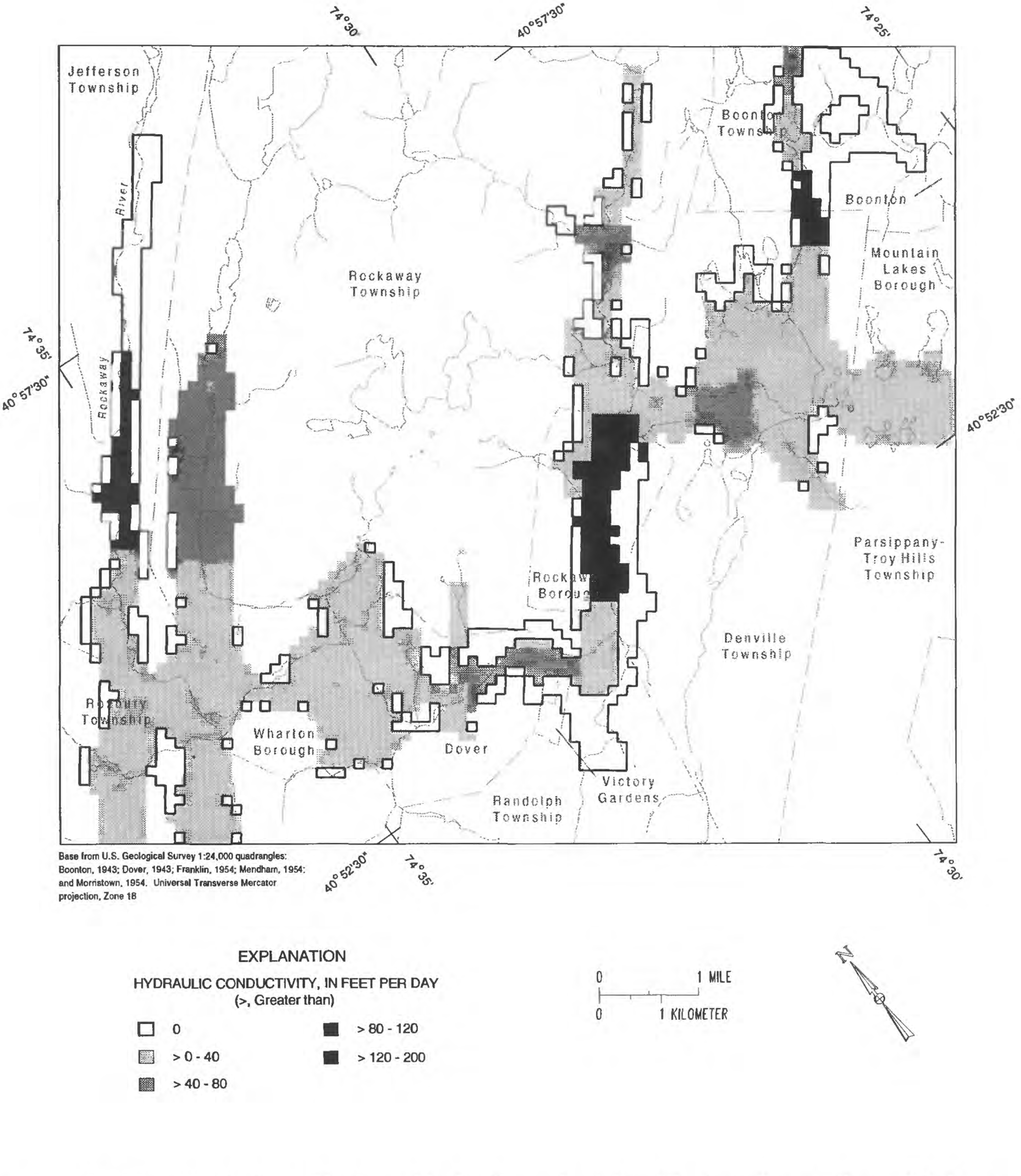


Figure 17. Discretized values of horizontal hydraulic conductivity of the lower layer in the modeled area.

high value of 20 ft/d was assigned for streambed hydraulic conductivity above Wharton Borough to account for water that flows from the upland section of Green Pond Brook that was not represented physically in the model (fig. 8).

Simulation of Unstressed Conditions

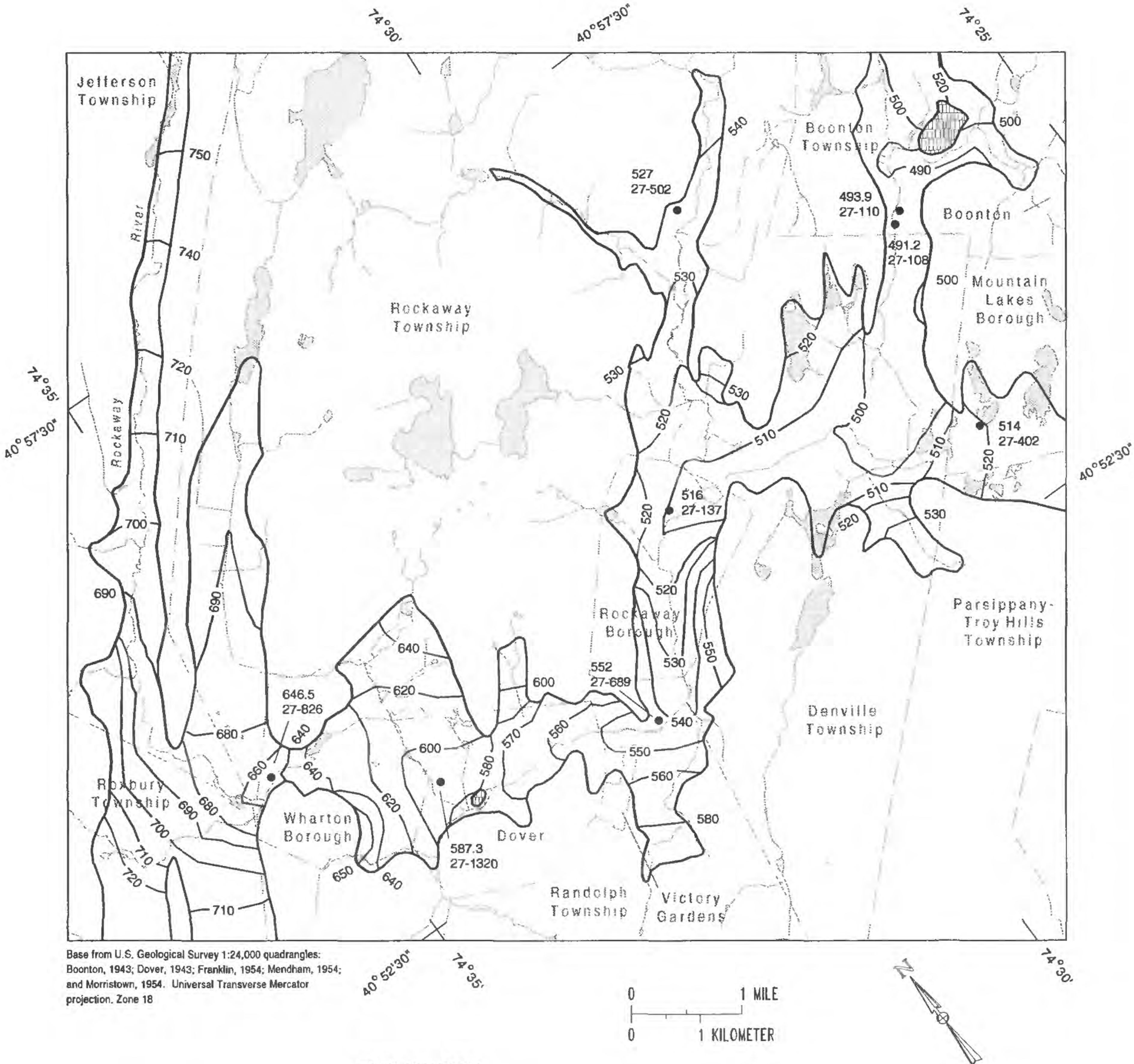
Water levels resulting from simulation of unstressed conditions (figs. 18 and 19) indicate that predevelopment ground-water flow directions were similar to present ground-water flow directions (figs. 6 and 7), except in areas of pumpage and in the lower aquifer in Mountain Lakes Borough. The mainstem of the Rockaway River was expected to be a gaining reach under unstressed conditions. Most simulated prepumping water levels are within 15 ft of measured water levels (table 5). Because predevelopment water levels were limited in number and spanned a period of 34 years, relatively large differences between simulated and observed water levels were expected. Differences also can result from the contrast between the model's averaging of water levels in a cell to obtain the water level at a node, and the measurements of observed water levels at specific locations within a cell. Moreover, deficiencies and simplifications in the model can result in additional differences between observed and simulated water levels.

The simulated predevelopment water levels (figs. 18 and 19) show that ground water flowed from the valley sides and downvalley toward the river or tributary at the center of the valley. The altitude of the water table in the upper layer was controlled predominantly by the simulated stream stages. Ground water in both the upper and lower aquifers flowed into the Rockaway River Basin from the Lamington River Basin. A ground-water divide was present in the lower aquifer in Mountain Lakes Borough, on one side of the divide, ground water discharged to the Rockaway River Basin; on the other side of the divide, ground water flowed toward Parsippany-Troy Hills Township.

Simulation of Stressed Conditions

Simulated steady-state hydraulic heads under stressed conditions in 1986 in the upper and lower aquifers are shown in figures 20 and 21, respectively. Most of the simulated water levels in 41 wells were within 10 ft of the measured water levels (table 6); the difference was greater in one well (27-323) screened in the lower aquifer. Differences between simulated and measured water levels may result from the measurement of water levels during recovery following shutdown of nearby pumped wells. In addition, differences between measured and simulated heads can result, in part, from the relatively large grid spacing of 500 ft. Consequently, the nodal spacing may not be sufficiently small in some areas to represent changes in water levels caused by pumpage stresses. The water level in an observation well is a point measurement, whereas the water level simulated at a model node is an average for that cell.

The well (27-323, table 6) that did not meet the calibration criteria of 10 ft is screened in the lower aquifer in the Mountain Lakes Borough (fig. 7). The simulated head is about 24 ft higher than the measured water level. Because the thickness and extent of the lower aquifer in this area are poorly known and predevelopment and current water-level data are limited, the model may not be an accurate representation of the flow system in this area. Also, the lower aquifer in this area consists of thick deposits in a narrow preglacial valley, and the nodal spacing may be too coarse to simulate variations in the aquifer thickness and water-level gradient accurately.



EXPLANATION

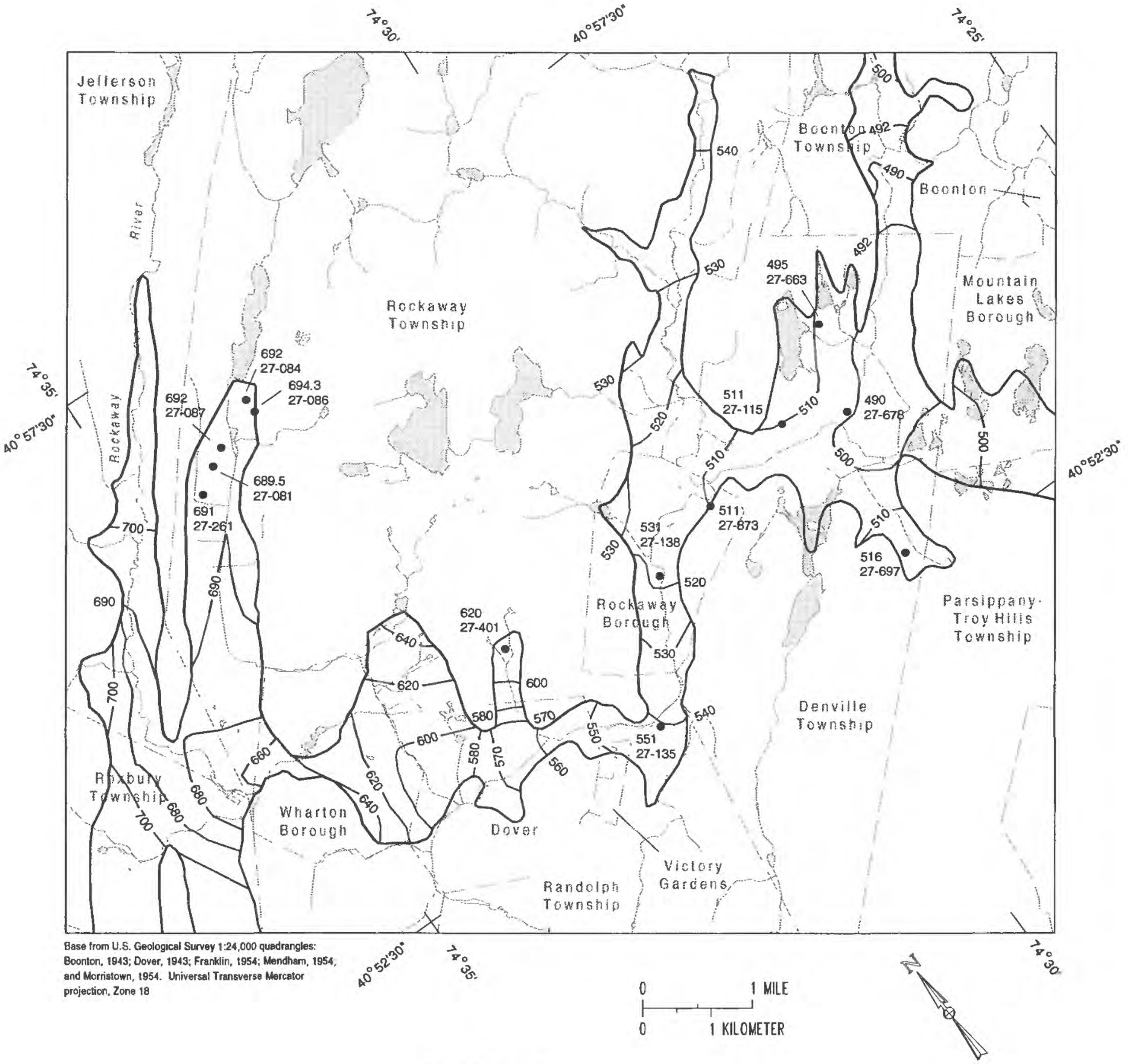
Outcrop of bedrock

— 530 — SIMULATED WATER-TABLE CONTOUR--Shows altitude of water-table. Contour interval is variable. Datum is sea level

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

● 514 / 27-402 Location of well. Upper number is altitude of simulated water table, in feet above sea level; lower number is well number

Figure 18. Simulated water levels in the upper layer under unstressed conditions.



EXPLANATION

— 620 — SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude of simulated potentiometric surface. Contour interval is variable. Datum is sea level

Approximate extent of the lower aquifer in the valley-fill deposits

● 490 27-678 Location of well. Upper number is altitude of simulated potentiometric surface, in feet above sea level; lower number is well number

Figure 19. Simulated water levels in the lower layer under unstressed conditions.

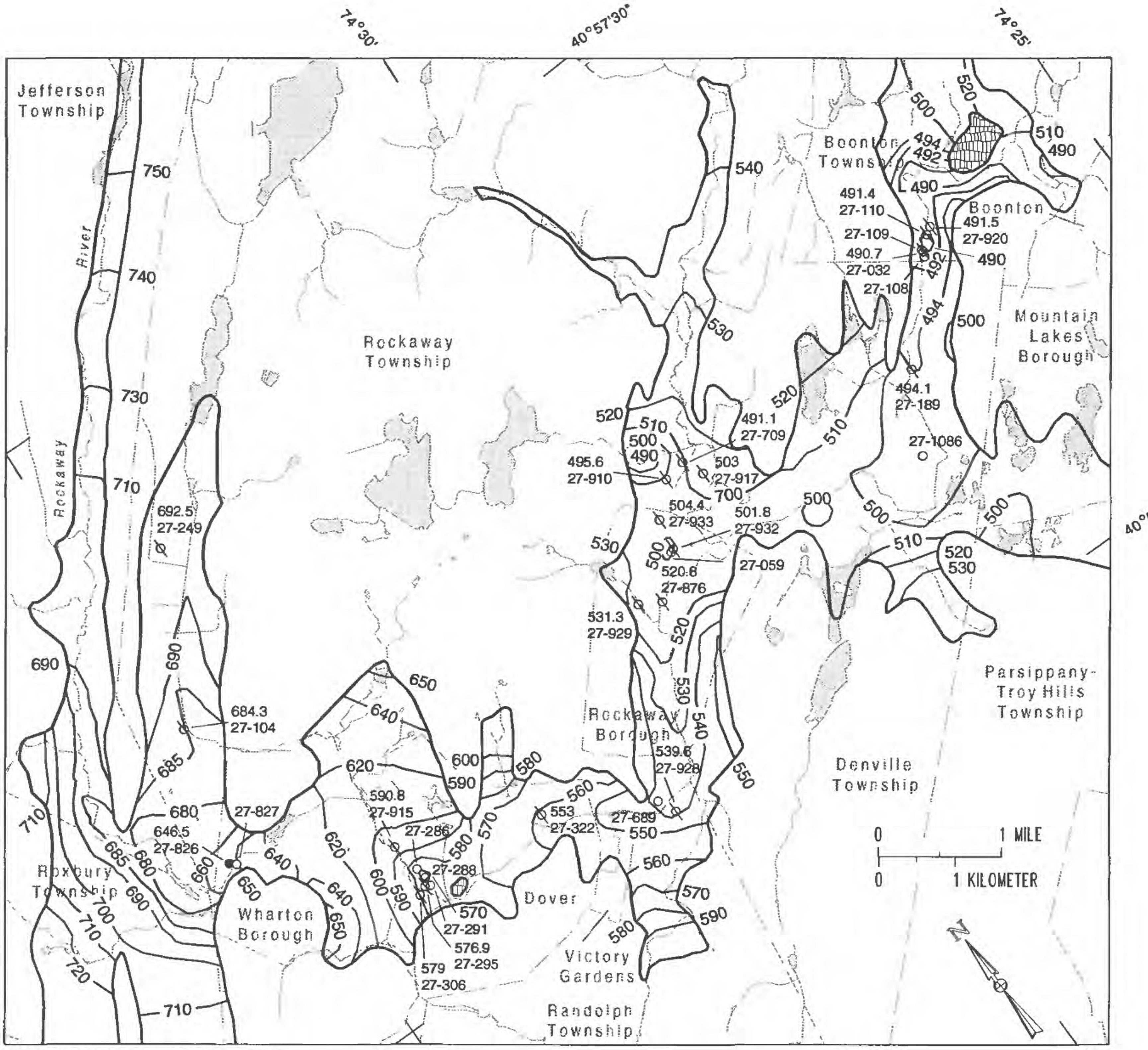
Table 5. Measured and simulated water-level altitudes for unstressed steady-state conditions

(Water-level altitudes in feet; +, water level above land surface (flowing well))

New Jersey well number	Well name	Location in model: Row	Location in model: Column	Date of static water-level measurement	Depth below land surface	Measured water-level altitude[1] (in feet above sea level)	Simulated water-level altitude (in feet above sea level)	Difference[2] (in feet)
				Upper aquifer				
27-108	BWD 1	17	80	7/31	13.7	491.2	492.0	0.8
27-110	BWD 3	16	80	8/46	4.0	493.9	491.8	-2.1
27-137	RWD 1	44	58	9/22	4.0	516	511.2	-4.8
27-402	Onorati 1	36	88	2/52	6.0	514	518.9	4.9
27-502	Jayne 1	16	59	3/52	3.0	527	534.2	7.2
27-689	Austenal 1	64	57	6/54	8.0	552	541.5	-10.5
27-826	WWD 1	70	21	9/53	9.0	646.5	650.9	9.4
27-1320	DOVWD 1-Abandoned	70	37	9/25	2.7	587.3	586.3	-1.0
				Lower aquifer				
27-081	US Army-Picatinny 129	41	15	2/48	14.5	689.5	696.0	6.5
27-084	US Army-Picatinny 430A	34	18	8/43	9.0	692	699.1	7.1
27-086	US Army-Picatinny 410	36	19	10/42	17.0	694.3	696.7	.4
27-087	US Army-Picatinny 305A	39	16	/38	4.0	692	695.4	3.4
27-115	DTWD 1	36	70	5/28	9.0	511	508.1	-2.9
27-135	DTWD 2	65	58	10/31	+1.0	551	541.3	-9.7
27-138	RWD 3	51	58	2/43	+1.0	531	518.8	-12.2
27-261	US Army-Picatinny DH-8	44	14	3/47	9.0	691	696.4	5.4
27-401	Brown 1	58	43	12/51	10.0	620	617.9	-2.1
27-663	Bernstorf 1	27	73	6/52	40.0	495	509.8	14.8
27-678	Behrens 1	35	76	6/52	45.0	490	501.2	11.2
27-697	Singer 1	48	82	4/55	4.0	516	518.3	2.3
27-873	RWD TW	44	63	11/55	+.8	511	508.9	-2.1

[1] Water level measured at time of drilling

[2] Difference = simulated water level minus static water level



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

EXPLANATION

Outcrop of bedrock

—620— SIMULATED WATER-TABLE CONTOUR--Shows altitude of simulated water table. Contour interval is variable. Datum is sea level

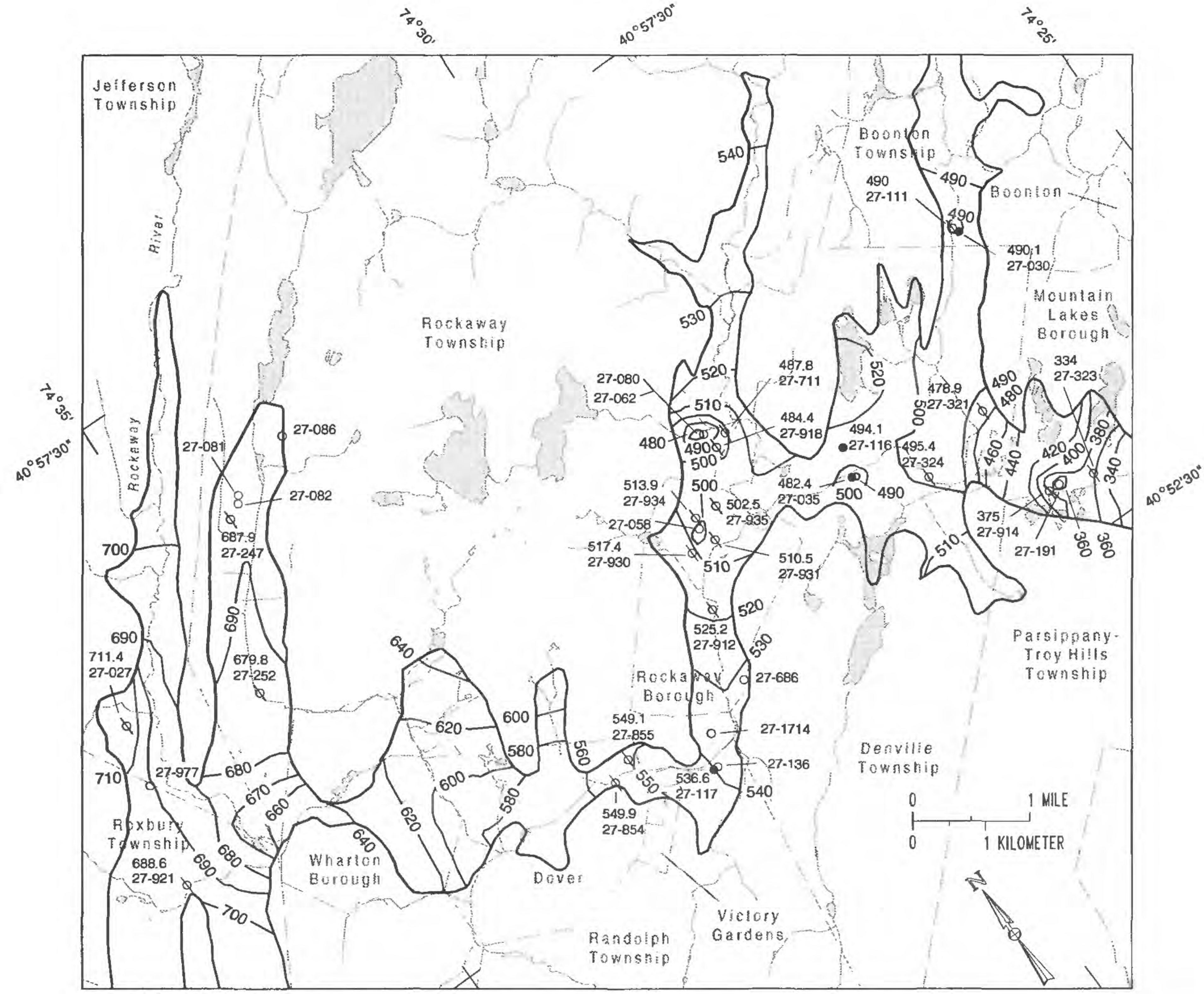
Approximate extent of the valley-fill deposits, modified from Canace and others, 1993, and Stanford, 1989a, 1989b

27-827 Location of production well and well number

646.5 27-826 Location of production well with water-level measurement. Upper number is altitude of simulated water table, in feet above sea level; lower number is well number

491.1 27-709 Location of observation well. Upper number is altitude of simulated water table, in feet above sea level; lower number is well number

Figure 20. Simulated water levels in the upper layer under stressed conditions.



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

EXPLANATION

— 620 — SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude of simulated potentiometric surface. Contour interval is variable. Datum is sea level

—— Approximate extent of the lower aquifer in the valley-fill deposits

● 482.4 / 27-035 — Location of production well with water-level measurement. Upper number is altitude of simulated potentiometric surface, in feet above sea level; lower number is well number

○ 27-058 — Location of production well and well number

ϕ 487.8 / 27-711 — Location of observation well. Upper number is altitude of simulated potentiometric surface, in feet above sea level; lower number is well number

Figure 21. Simulated water levels in the lower layer under stressed conditions.

Table 6. Measured and simulated water-level altitudes for stressed steady-state conditions, 1986

(Water-level altitudes in feet; --, no data)

New Jersey well number	Well name	Location in model: Row	Location in model: Column	Measured depth below land surface[1]	Measured water-level altitude (in feet above sea level): June 1986[2]	Measured water-level altitude (in feet above sea level): October 1986[3]	Simulated water-level altitude	Difference[4] (in feet)
				Upper aquifer				
27-032	BWD TW 1	17	80	10.9	490.7	490.2	490.1	-0.6
27-104	US Army-Picatinny MW 16	59	16	8.4	684.3	683.2	685.7	1.4
27-110	BWD 3	16	80	6.5	491.4	491.1	489.9	-1.5
27-189	MLWD 4	27	79	9.8	494.1	492.9	493.7	-.4
27-249	US Army-Picatinny 65-4	43	14	7.7	692.5	690.8	695.7	3.2
27-295	USGS S4	72	37	11.7	576.9	576.8	579.4	2.5
27-306	USGS D6	73	37	12.4	579.0	577.8	580.6	1.6
27-322	DOVWD TW 2	66	47	1.1	553.0	552.5	559.8	6.8
27-709	Keuffel 2	35	59	33.0	491.1	491.1	506.1	15.0
27-826	WWD 1	70	21	9.0	646.5	--	649.6	3.1
27-876	RWD TW 4	47	58	9.8	520.8	519.7	508.6	-12.2
27-910	Shell 10	37	58	48.2	495.6	493.9	505.3	9.7
27-915	WBWD TW 3	69	35	6.5	590.8	592.2	588.9	-1.9
27-917	NJDEP TP-2	36	61	16.2	503.0	500.8	512.3	9.4
27-920	BWD TW 6	15	80	4.0	491.5	491.0	490.2	-1.3
27-928	DEN OBS	65	59	4.8	539.6	--	537.6	-2.0
27-929	SAIC 1	48	56	14.4	531.3	530.0	517.9	-13.4
27-932	SAIC 4	43	59	9.2	501.8	501.0	500.6	-1.2
27-933	SAIC 5	40	57	25.5	504.4	501.3	508.2	3.8
				Lower aquifer				
27-027	NJDEP TW 9	62	5	11.2	714.4	713.0	709.5	-4.9
27-030	BWD 5	16	80	9.2	490.1	488.5	489.7	-.4
27-035	DTWD 5	39	71	26.8	482.4	475.4	487.9	5.5
27-111	BWD 4	16	79	9.1	490.0	488.4	490.4	.4
27-116	DTWD 4	36	70	17.5	494.1	492.7	504.6	10.5
27-117	DTWD 6	65	58	9.0	536.6	535.6	540.3	3.7
27-247	US Army-Picatinny 65-2	43	14	12.0	687.9	689.7	695.5	7.6
27-252	US Army-Picatinny LF 3	59	17	13.4	679.6	675.7	683.0	3.4
27-321	Geonics 2	33	82	35.6	478.9	475.1	487.0	8.1
27-323	Geonics 1	38	93	168.7	334.0	330.7	358.4	24.4
27-324	Geonics 4	39	78	5.0	495.4	493.4	497.6	2.2
27-711	Keuffel 4	35	59	36.4	487.8	488.6	492.7	4.9
27-854	DOVWD TW 3	67	50	3.8	549.9	550.0	552.4	2.5
27-855	DOVWD TW 4	65	51	4.7	549.1	548.8	550.5	1.4
27-912	RWD TW 3	51	58	5.9	525.2	523.3	518.4	-6.8
27-914	MLWD TW 5	40	89	130.0	375.0	374.5	378.0	3.0
27-918	RTWD TW 7	36	58	38.3	484.4	485.9	491.6	7.2
27-921	NJDEP TW 10	76	11	6.9	688.6	684.2	694.0	5.4
27-930	SAIC 2	46	56	37.8	517.4	515.7	515.1	-2.3
27-931	SAIC 3	44	58	4.7	510.5	508.2	505.6	-4.9
27-934	SAIC 6	43	56	18.2	513.9	511.3	508.1	-5.8
27-935	SAIC 7	41	58	21.9	502.5	500.7	506.3	3.8

[1] Measured depth below land surface in June 1986

[2] Model was calibrated to June 1986 water-level altitudes only

[3] October 1986 water-level altitudes are presented because they are commonly the lowest water-levels recorded for that year. They were not included in model calibration because only June 1986 streamflow measurements were available

[4] Difference = simulated water level minus June 1986 water level

Water-level measurements made in October 1986 are included in table 6 as an indication of the magnitude of seasonal fluctuations. Most of the water levels measured in October 1986 were the lowest measured that year. Fluctuations were generally less than 2 ft, but were as much as 7 ft in areas of pumpage. The low water levels in October may be the result of evapotranspiration.

The simulated water-level contours show that the gradients at the valley walls are steeper than those in the middle of the valley (figs. 20 and 21). The steeper gradients near the valley walls may indicate recharge from the upland areas, or the higher land-surface elevations at the valley walls than at the center of the valley. The discharge areas are the streams, the river in the center of the valley, and the wells. Cones of depression are apparent in the areas near production wells in Rockaway Township and Rockaway Borough.

Table 7 shows the difference between observed water levels measured at the time of drilling or well development and those measured recently, and the difference between simulated water levels under unstressed conditions and those under stressed conditions. Most of the wells listed in this table are production wells or are located near production wells. The static water levels were found on the well record. The method of measurement was not recorded and the accuracy of the measurements is unknown. The areas with the greatest declines are in Rockaway Township, Rockaway Borough, and Denville Township. The water levels have declined as a result of ground-water withdrawals.

Figure 22 shows the losing and gaining reaches of the Rockaway River as simulated by the model. The losing cells are located near pumping centers in Wharton Borough, the Town of Dover, and Denville, Rockaway, and Boonton Townships. Streambed conductance was adjusted during calibration so that ground water would discharge to the river under unstressed conditions. Additional losing cells are located in stream cells representing some upland tributaries in Berkshire Valley and the valley of Beaver Brook. These tributaries showed losing and gaining reaches during the three seepage runs, results of which are listed in table 3.

The amount of recharge distributed to each active cell in layer 1 is shown in figure 14. The total amount of recharge input to the model was about 46 Mgal/d. This value includes a small amount of ground-water flow from outside the Rockaway River Basin that is derived from the Lamington River Basin and Mountain Lakes Borough. Ground-water recharge was compared to low-flow discharge, which was assumed to be equal to base flow, from measurements made during 1984-86 (table 8) to validate the ground-water-recharge value applied to each subbasin draining to its respective reach between two discharge-measurement sites. The difference in discharge was calculated by subtracting the measured low-flow discharge at a measurement site from the low-flow discharge at the next successive upstream station (table 3). As shown in table 8, measured base flow at a surface-water station can differ from the estimated ground-water recharge assigned between the stations, in part because ground-water and surface-water divides do not always coincide, so that the area contributing to ground-water recharge may be different from the area contributing to the measured stream discharge. Also, this comparison was limited to available data from three seepage runs conducted over a 2-year period, whereas the rate of ground-water recharge was averaged over a period of 49 years during which precipitation varied and ground-water withdrawals increased.

The rate of recharge assigned to each active cell in the upper layer is shown in figure 14. An increase in recharge from upland areas at the valley perimeter caused water levels to rise more than 10 ft in Berkshire Valley and the valley of Beaver Brook. Simulated heads in these valleys were much higher than observed water levels or land-surface elevations. Removal of

Table 7. Measured and simulated depths to water under unstressed and stressed conditions at selected wells in the study area

(Depth to water in feet below land surface)

New Jersey well number	Well name	Location in model		Well depth, in feet below land surface	Measured unstressed conditions[1]		Simulated depth to water, unstressed conditions	Measured stressed conditions[2]		Simulated depth to water, stressed conditions	Difference[3]	
		Row	Column		Date	Depth to water		Date	Depth to water		Measured (in feet)	Simulated (in feet)
27-109	BWD 2	17	80	38.0	12/30	10.5	9.6	10/86	12.2	11.4	-1.7	-1.8
27-110	BWD 3	16	80	25.0	8/46	3.9	6.1	10/86	6.8	8.0	-2.9	-1.9
27-136	DTWD 3	65	59	132.0	10/46	2.0	2.4	11/88	6.5	8.2	-4.5	-5.8
27-035	DTWD 5	39	71	198.0	9/61	20.0	5.9	10/87	33.8	21.3	-13.8	-15.4
27-854	DOVWD TW 3	67	50	81.0	8/60	3.8	1.2	10/87	3.8	1.3	0	-.1
27-855	DOVWD TW 4	65	51	138.0	4/62	2.5	3.4	10/87	5.2	3.4	-2.7	0
27-290	DOVWD TW 5	72	38	64.0	8/71	13.0	9.9	11/88	14.2	18.9	-1.2	-9.0
27-137	RWD 1	44	58	48.7	9/22	4.0	8.8	12/88	13.3	13.8	-9.3	-5.0
27-057	RWD 3R	51	58	138.0	7/61	4.0	12.4	10/86	7.9	12.8	-3.9	-.4
27-697	Singer 1	48	82	75.0	4/55	4.0	1.7	2/88	10.5	1.5	-6.5	-.2
27-826	WWD 1	70	21	42.0	9/53	9.0	5.1	2/87	9.8	5.4	-.8	-.3
27-915	WWD TW 3	69	35	65.0	7/71	5.0	8.0	10/86	7.7	8.3	-2.7	-.3

[1] Measured unstressed depths to water from well record

[2] Measured stressed depths to water were measured with a steel tape

[3] Difference = unstressed condition minus stressed condition

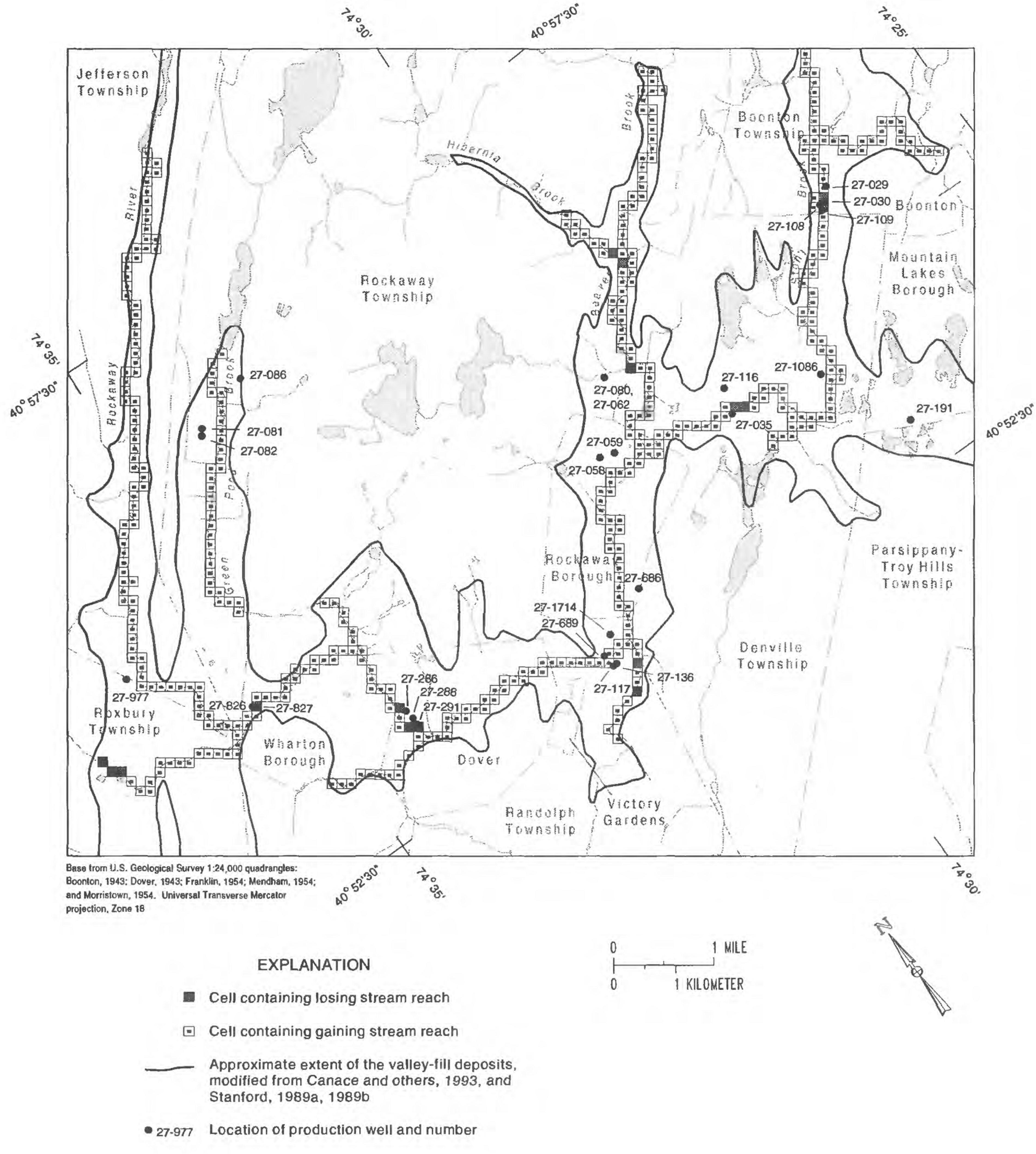


Figure 22. Simulated losing and gaining reaches of the Rockaway River and tributaries under stressed conditions.

Table 8. Measured streamflow gains or losses in the Rockaway River and simulated discharges

(ft^3/s, cubic feet per second; Mgal/d, million gallons per day; a negative value indicates a losing reach; a positive value indicates a gaining reach)

Surface-water stations at upstream and downstream ends of reach[1]	Difference in measured discharge between stations (ft^3/s)			Simulated discharge value	
	10/17/84	9/19/85	6/3/86	(ft^3/s)	(Mgal/d)
01379700-01379740	3.7	0.0	12.3	9.7	6.2
01379740-01379880	15.0	11.7	24.2	20.3	13.1
01379880-01380110	2.4	4.0	10.6	6.2	4.0
01380110-01380145	3.0	14.2	19.5	7.4	4.8
01380145-01380335	5.1	-5.0	-3.0	4.7	3.0
01379700-01380335	29.2	24.9	59.7	57.9	37.3

[1] See figure 8 for locations of stations and table 3 for discharge measurements

the additional ground-water recharge from the contributing upland areas caused the simulated heads to fall. Berkshire Valley is a narrow valley surrounded by steep ridges overlain by till. Runoff from surrounding upland areas may flow down the steep slopes directly to streams, allowing a small amount of upland runoff to infiltrate the valley-fill sediments. In parts of Beaver Brook valley the surficial deposits consist of fine lacustrine sediments of low hydraulic conductivity; therefore, the rate of infiltration of runoff was expected to be small. Ground-water recharge was reduced at the boundary of the Rockaway and Lamington River Basins, where simulated heads also were high. At the Lamington River Basin boundary in Roxbury Township, the number of streams and tributaries is small. This area is characterized by low relief and contains several ponds and excavation sites where water may be stored and, therefore, not directly available for recharge.

Flow Budgets Under Unstressed and Stressed Conditions

The ground-water flow budgets for unstressed and stressed conditions determined by using the calibrated steady-state model are presented in table 9. Total recharge used in the simulation (43.2 Mgal/d) is less than total recharge calculated from seepage run data of June 3, 1986 (46.3 Mgal/d). The difference likely results from the limits to distribution of recharge throughout the modeled area imposed by the discretization of the model, where each model cell is 500 ft on a side. In both cases, inflow to the valley-fill aquifers includes recharge to surficial deposits, leakage from streams and lakes, and lateral flow across the boundaries. Outflow from the valley-fill aquifers includes discharge to streams, lateral flow across boundaries, and, for the steady-state simulation under stressed conditions, discharge to pumped wells. The flow budgets indicate that ground-water withdrawals from the valley-fill aquifers have reduced ground-water discharge to the Rockaway River and increased leakage from the river to the upper aquifer along certain reaches. Under unstressed conditions inflow to the aquifer system was 43.2 Mgal/d from ground-water recharge, 1.0 Mgal/d from naturally losing streams, and about 0.8 Mgal/d from leakage from lakes. Ground-water discharge to the streams was 44.5 Mgal/d. Results of the steady-state simulation under stressed conditions indicate inflow consisting of 43.2 Mgal/d from ground-water recharge, 2.9 Mgal/d from stream leakage from losing reaches, and about 0.8 Mgal/d from lakes. Outflow consists primarily of ground-water discharge to streams (37.3 Mgal/d), discharge to wells (9.1 Mgal/d), and flow out of the modeled area (0.5 Mgal/d). These ground-water flow budgets indicate that the sources of water to pumped wells are intercepted ground-water discharge and increased infiltration of streamflow relative to unstressed conditions. Ground-water withdrawals (9.1 Mgal/d) from the glacial deposits have caused a reduction in ground-water discharge to streams of 7.2 Mgal/d and an increase in stream leakage of 1.9 Mgal/d. Simulation results also indicate that ground-water withdrawals from the lower aquifer cause an increase in vertical leakage from the upper aquifer of 1.5 Mgal/d, relative to that under unstressed steady-state conditions.

Because no predevelopment streamflow data were available for the upper Rockaway River Basin, the effects of increased ground-water withdrawals on ground-water discharge to the river could not be quantified; however, it is assumed that as ground-water withdrawals from the valley-fill deposits increase, ground-water discharge to the river will decrease by an equal amount, after equilibrium has been reestablished.

Table 9. Ground-water flow budgets for the steady-state simulations under unstressed and stressed conditions

(Mgal/d, million gallons per day)

	Inflow (Mgal/d)			Outflow (Mgal/d)	
	Unstressed	Stressed		Unstressed	Stressed
Recharge	43.2	43.2	Discharge to streams	44.5	37.3
Leakage from lakes	.8	.8	Leakage to lakes	0	0
Boundary fluxes	0	0	Boundary fluxes	.5	.5
Stream leakage	1.0	2.9	Withdrawals	0	9.1
Total	45.0	46.9	Total	45.0	46.9

Model Sensitivity

An evaluation of model sensitivity to adjustments in values of aquifer characteristics was conducted as part of the calibration procedure. The modified characteristics were horizontal hydraulic conductivity, transmissivity, and vertical hydraulic conductivity. Each characteristic was varied separately for each simulation. The effects of these adjustments on water levels and the flow budget were analyzed after each model run.

In some areas, primarily in cells along the valley sides adjacent to the uplands, the model was sensitive to the altitude of the bottom of the upper layer. In the ground-water flow model, when the simulated hydraulic head for a cell under unconfined conditions falls below the altitude of the bottom of the layer, saturated thickness is zero and the cell becomes inactive. To mitigate this, the bottom altitudes of these cells were lowered a few feet.

Water levels changed significantly in response to adjustments in some hydraulic characteristics near some pumping centers. A 20-percent increase or decrease in the horizontal hydraulic conductivity of the upper layer had little effect in most of the modeled area, except near the pumping center in Rockaway Township, where lacustrine deposits of low horizontal hydraulic conductivity are present. A decrease in horizontal conductivity in this area resulted in a decline in water levels of more than 20 ft in both aquifers. A 20-percent increase or decrease in the horizontal hydraulic conductivity of the lower layer resulted in a change of more than 10 ft in simulated heads for both aquifers in the area of Rockaway Township and Rockaway Borough. A 20-percent increase or decrease in the vertical hydraulic conductivity of the confining layer resulted in changes in water levels of more than 15 ft at the Mountain Lakes Borough and Denville Township pumping centers.

Simulated Effects of Increased Withdrawals

Two scenarios of increased ground-water withdrawals predicted for 2000 and 2040 were simulated to predict water levels and streamflow depletion by using the calibrated steady-state stressed-condition model heads as the initial condition. The results of these simulations show the response of the valley-fill aquifers to increased ground-water withdrawals from existing wells and pumping at sites of potential sources of future water supply and the effects of increased ground-water withdrawals on the ground-water contribution to the Rockaway River (base flow).

Increased withdrawals have resulted in concern about the potential effects of increased demand for water on water levels and ground-water discharge to the Boonton Reservoir. Increases in pumpage could reduce the ground-water contribution to the river and potentially affect the court-ordered passing flow of 7 Mgal/d (Summers and others, 1978, p. 55) that Jersey City must release downstream to the lower Rockaway River Basin to protect the quality of water available to users downstream from the Boonton Reservoir. In order to maintain a steady flow of 7 Mgal/d below the Boonton Reservoir, a steady flow must be maintained above the reservoir that accounts for evaporation losses from the reservoir. The sum of the minimum downstream flow requirement of 7 Mgal/d and the estimated annual evaporation losses for the Boonton Reservoir of 32 in/yr (1.6 Mgal/d) (Summers and others, 1978) totals 8.6 Mgal/d.

Estimated ground-water demand at existing pumping centers in 2000 was calculated by increasing the 1986 withdrawals (table 4) from municipal supply wells in proportion to the population estimates for 1985 and 2000 (D.H. Woodbridge, Morris County Planning Board, written commun., 1986). The estimated withdrawals were assigned to wells operating in the study area in 1986 and 1987. Because population estimates for 2040 were not available for each township and borough in the study area, the 1986 ground-water withdrawals were increased by 25 percent to estimate the withdrawals for the study area for 2040; for Rockaway Borough, however, withdrawals were increased by 25 percent of the estimate for 2000. Areas in Rockaway and Denville Townships and Mountain Lakes Borough that are considered to be a potential source of future water supply also were incorporated into the predictive simulations. Projected pumpage rates for potential areas of future water-supply development (figs. 23-27) are listed in table 10. Withdrawals from existing industrial wells were not increased for the predictive scenarios, except at St. Clare's Hospital (fig. 23) at a location near the existing well (well 27-1086).

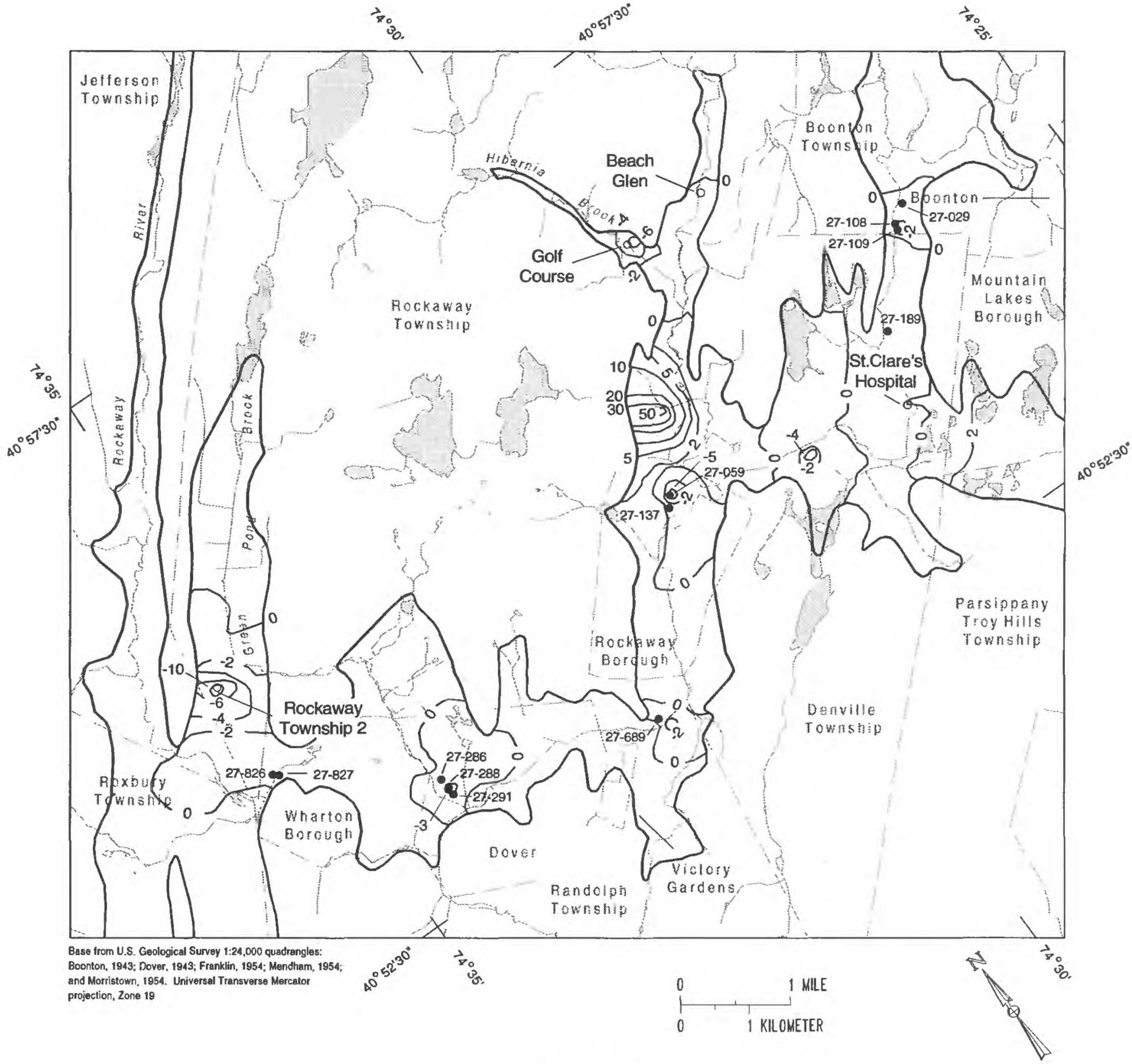
Two-thirds of the water supplied to the Town of Boonton, which is located outside the study area, is withdrawn from wells located along the Rockaway River in Boonton Township. The Boonton Township water supply is obtained almost entirely from private domestic wells, although some residents receive water from the Boonton Water Department. Estimated withdrawals from the Boonton well field for 2000 and 2040 were calculated from projected population estimates for Boonton Township. The increase for Victory Gardens Borough, which obtains its water supply from the Town of Dover, was included in the withdrawals for the Town of Dover.

Effects of Predicted Withdrawals, 2000

The change in hydraulic head in the upper and lower layers resulting from the predicted increase in withdrawals by 2000 relative to stressed steady-state conditions in 1986 is shown in figures 23 and 24, respectively. Water levels declined in areas where withdrawals increased at the public supply wells for Rockaway Borough, the Town of Dover, and Mountain Lakes Borough (figs. 20 and 21). The declines in water level were not sufficient to cause the water level to drop below the pump or to cause significant well interference. Simulated ground-water flow patterns at the pumping centers of Wharton Borough and Boonton Township were similar to 1986 flow patterns.

In the upper aquifer, simulated water levels near pumped wells decreased about 5 ft in Rockaway Borough and as much as about 4 ft in the Town of Dover in response to an increase in ground-water withdrawals at these sites. Water levels at the water-supply development site for Rockaway Township (Rockaway Township 2) located south of Green Pond Brook (fig. 23) declined a maximum of 10 ft with increased pumpage in that area. Simulated drawdowns in the lower aquifer near the pumping centers in Mountain Lakes Borough declined a maximum of 6 ft, and declined a maximum of 4 ft near production well number 5 (27-035) in Denville Township relative to 1986 water levels. Heads in Rockaway Township near production wells 27-080 and 27-062 (fig. 21) recovered over 50 ft in the upper and lower aquifers because pumping in this area was not simulated. Water levels in the area of the water-supply development site for Rockaway Township (well 27-704, fig. 24) declined a maximum of 23 ft.

Ground-water discharge to Hibernia Brook (fig. 23) at times may be insufficient to supply water to the golf-course development site at the proposed pumpage rate; under conditions of low flow, water may be drawn from Beaver Brook to supply this well. The lowest discharge at streamflow-gaging station 01380075, less than 0.5 mi downstream from the water-supply development site, during the 1985 seepage run (table 3) was 0.83 ft^3/s (0.5 Mgal/d), which is less than the anticipated pumpage rate of 1.2 ft^3/sec (0.75 Mgal/d). Because no other discharge measurements were made on this tributary, actual streamflow above the streamflow-gaging station under extreme low-flow conditions is unknown.



EXPLANATION

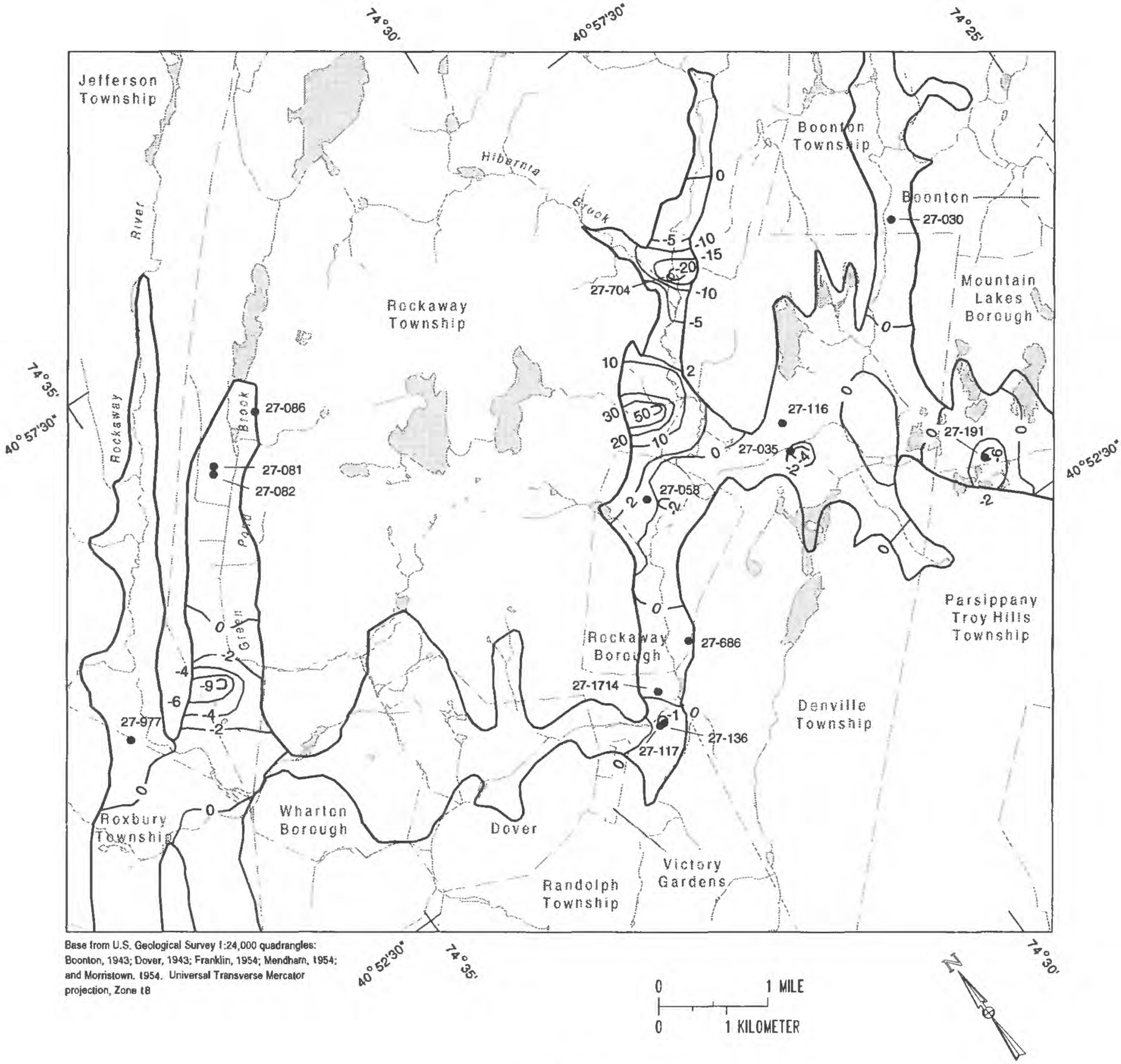
— 0 — LINE OF EQUAL DIFFERENCE BETWEEN SIMULATED WATER LEVELS UNDER CONDITIONS OF ANTICIPATED GROUND-WATER WITHDRAWALS BY 2000 AND SIMULATED WATER LEVELS UNDER 1986 STEADY-STATE CONDITIONS--Contour interval is variable

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

● 27-826 Location of production well and number

○ Beach Glen Area of proposed withdrawals

Figure 23. Simulated change in water levels in the upper aquifer based on 1986 steady-state conditions and anticipated ground-water withdrawals by 2000.



EXPLANATION

— 0 — LINE OF EQUAL DIFFERENCE BETWEEN SIMULATED WATER LEVELS UNDER CONDITIONS OF ANTICIPATED GROUND-WATER WITHDRAWALS BY 2000 AND SIMULATED WATER LEVELS UNDER 1986 STEADY-STATE CONDITIONS--Contour interval is variable

—— Approximate extent of the lower aquifer in the valley-fill deposits,

● 27-117 Location of production well and number

○ 27-704 Area of proposed withdrawals

Figure 24. Simulated change in water levels in the lower aquifer based on 1986 steady-state conditions and anticipated ground-water withdrawals by 2000.

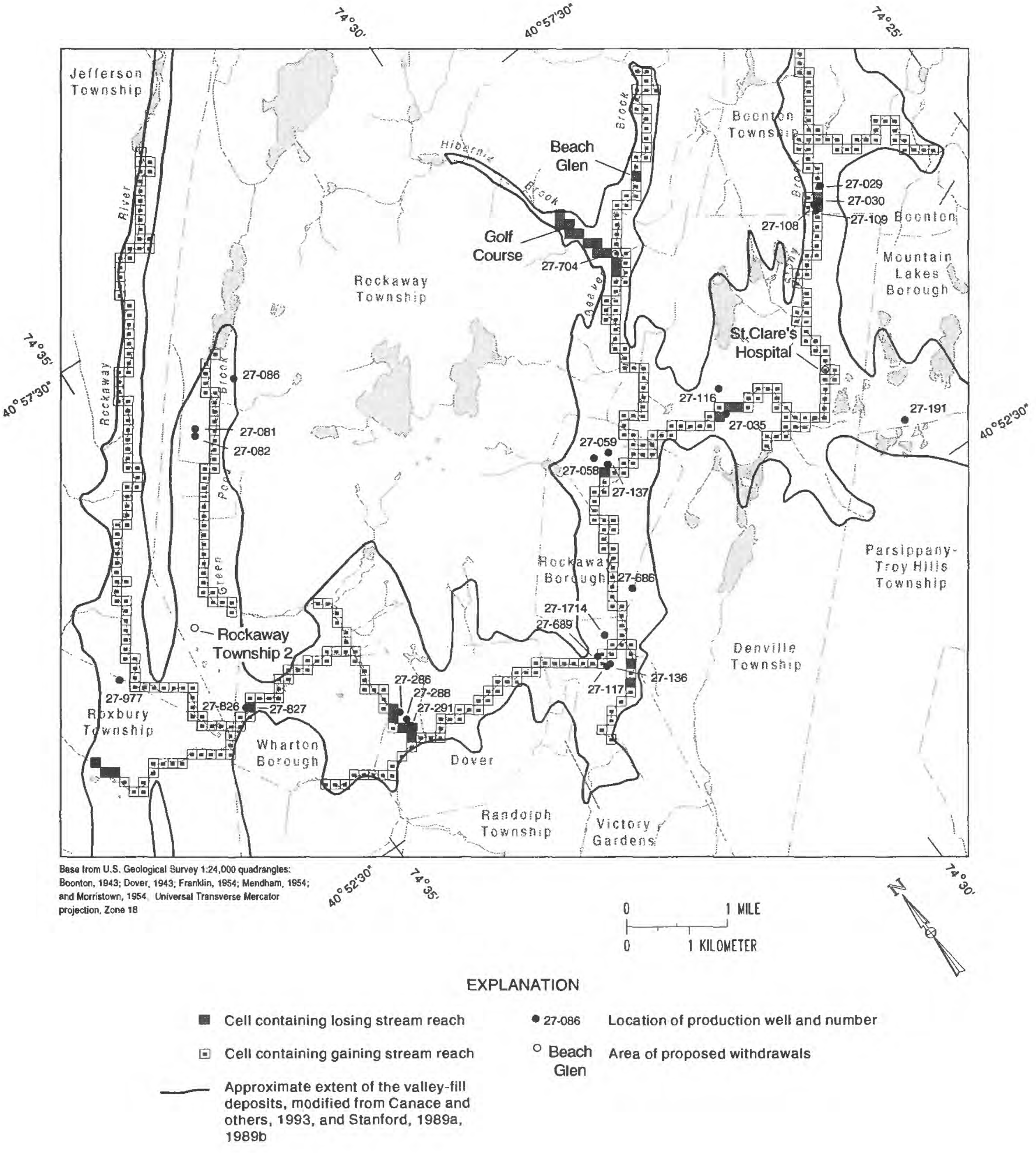
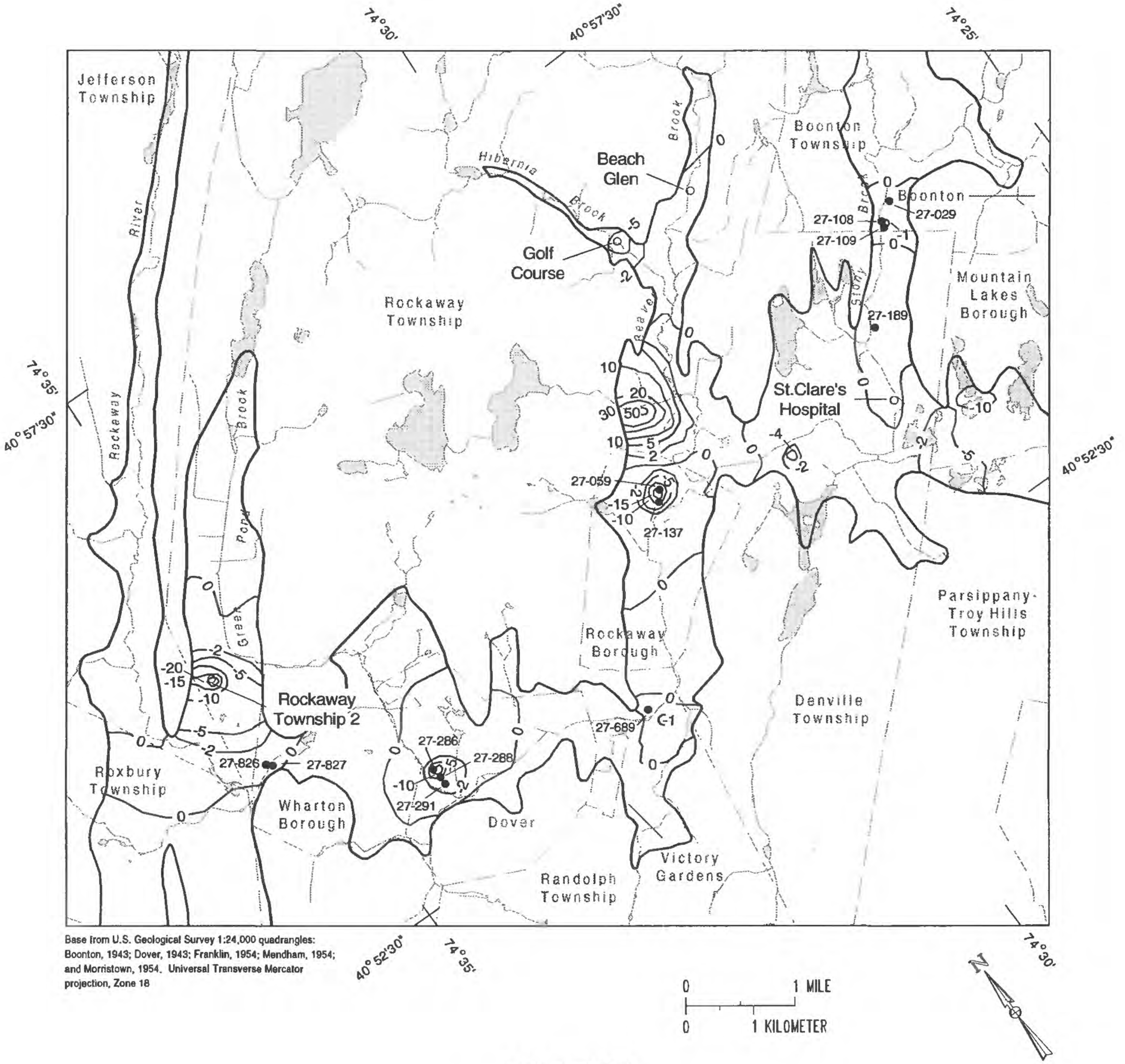


Figure 25. Predicted losing and gaining reaches of the Rockaway River and tributaries simulated under anticipated increases in ground-water withdrawals by 2000.



EXPLANATION

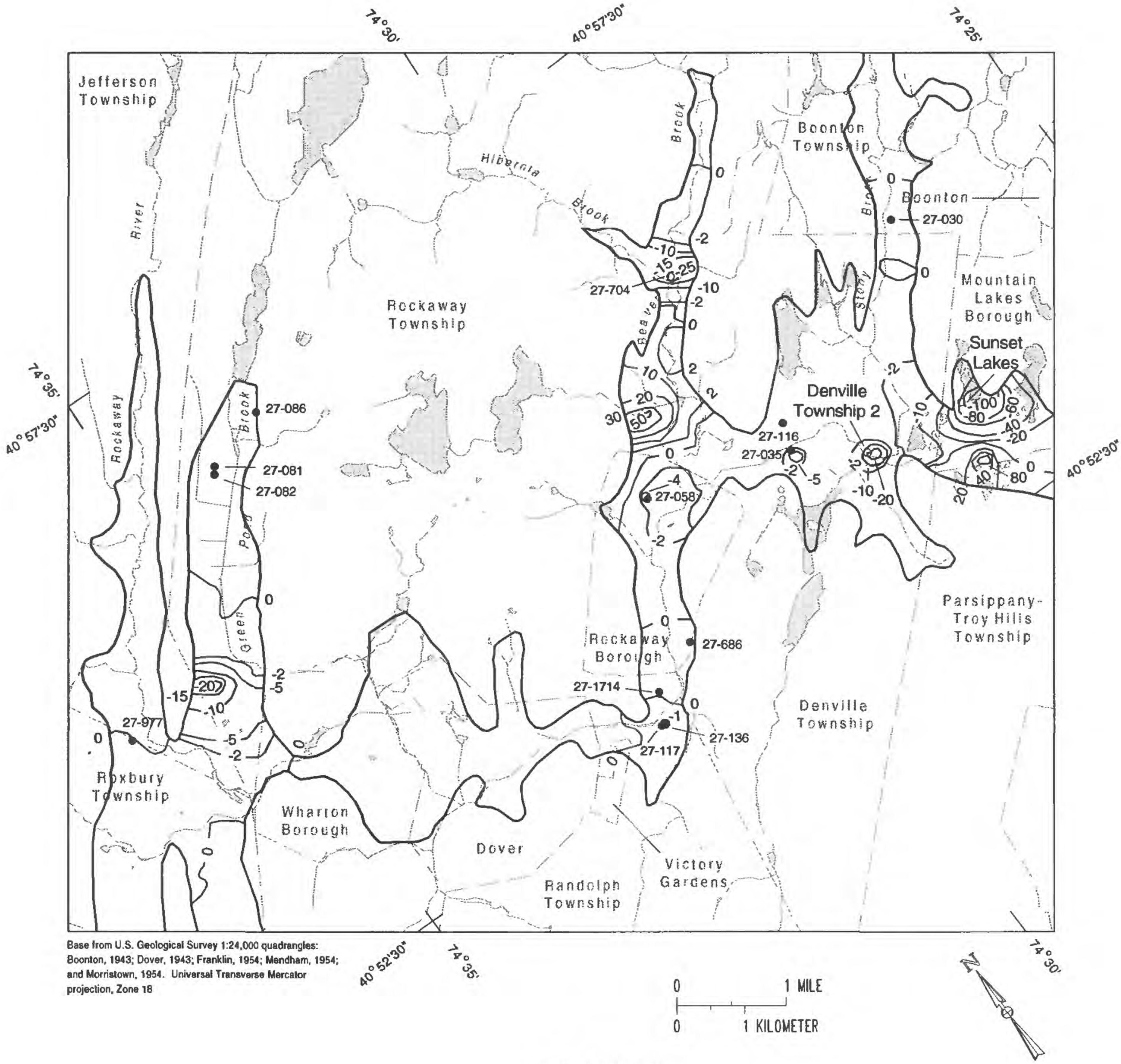
— 0 — LINE OF EQUAL DIFFERENCE BETWEEN SIMULATED WATER LEVELS UNDER CONDITIONS OF ANTICIPATED GROUND-WATER WITHDRAWALS BY 2040 AND SIMULATED WATER LEVELS UNDER 1986 STEADY-STATE CONDITIONS--Contour interval is variable

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

● 27-826 Location of production well and number

○ Beach Glen Area of proposed withdrawals

Figure 26. Simulated change in water levels in the upper aquifer based on 1986 steady-state conditions and anticipated ground-water withdrawals by 2040.



EXPLANATION

— 0 — LINE OF EQUAL DIFFERENCE BETWEEN SIMULATED WATER LEVELS UNDER CONDITIONS OF ANTICIPATED GROUND-WATER WITHDRAWALS BY 2040 AND SIMULATED WATER LEVELS UNDER 1986 STEADY-STATE CONDITIONS--Contour interval is variable

Approximate extent of the lower aquifer in the valley-fill deposits,

• 27-117 Location of production well and number

○ 27-704 Area of proposed withdrawals

Figure 27. Simulated change in water levels in the lower aquifer based on 1986 steady-state conditions and anticipated ground-water withdrawals by 2040.

Table 10. Sites of water-supply development simulated in the predictive simulations

(Mgal/d, million gallons per day; --, site not used)

Water-supply development sites	Use of site	Location in model			Projected withdrawals for 2000 (Mgal/d)	Projected withdrawals for 2040 (Mgal/d)
		Layer	Row	Column		
		DENVILLE TOWNSHIP				
Denville Township 1	Test well	2	39	78	--	1
St. Clare's Hospital	Water supply	1	34	81	.1	.12
		MOUNTAIN LAKES BOROUGH				
Sunset Lake	Municipal supply backup	2	34	88	--	.84
		ROCKAWAY TOWNSHIP				
Rockaway Township 1[1]	Municipal supply	2	22	59	.7	.87
Rockaway Township 2	Municipal supply	1	62	15	.5	1
Golf-course development	Commercial/irrigation	1	19	54	.75	.75
Beach Glen	Water-supply backup	1	14	61	.25	.5
				TOTAL	2.3	5.08

[1] New Jersey well number 27-704

The flow budget for the valley-fill aquifers in 2000 is shown in table 11. Total ground-water withdrawals in this simulation were 11.5 Mgal/d. Leakage from losing reaches of the river contributed 4.1 Mgal/d. This leakage was 1.2 Mgal/d greater than the stream leakage during recent (1986) conditions. Ground-water discharge to streams throughout the modeled area was 36.1 Mgal/d, which was 1.4 Mgal/d less than ground-water discharge simulated in 1986. If the number of water suppliers in the Rockaway River Basin downstream from the reservoir remains unchanged, under conditions of average ground-water recharge an increase in ground-water withdrawals of 2.4 Mgal/d from the valley-fill deposits relative to 1986 pumpage yields an average simulated ground-water discharge to the Rockaway River in 2000 of 36.1 Mgal/d (table 11), which is greater than the minimum downstream passing flow.

Losing reaches along the Rockaway River simulated by the model are shown in figure 25. Areas of streamflow loss include areas near the pumping centers of the Town of Dover, Boonton Township, and Rockaway and Wharton Boroughs, where water flows from the river to the upper aquifer. Water flows from the river to the lower aquifer by leakage through the confining unit in Denville Township. A comparison of simulated stream leakage in 1986 with that simulated for 2000 (table 12) shows additional streamflow loss in reaches between areas of increased withdrawals. A streamflow loss from the river of about 1 Mgal/d was simulated between the pumping centers of the Town of Dover, Rockaway Borough, and Rockaway and Denville Townships. The increase in ground-water withdrawals from those in 1986 at those pumping centers was about 1.8 Mgal/d.

Effects of Predicted Withdrawals, 2040

The change in hydraulic head resulting from the increase in withdrawals from the upper and lower layers anticipated by 2040 relative to stressed steady-state conditions in 1986 are shown in figures 26 and 27, respectively. In comparison to conditions in June 1986 (figs. 20 and 21), the cones of depression at the pumped wells in Rockaway and Mountain Lakes Boroughs, in Denville Township, and at the golf-course development well and the water-supply development site for Rockaway Township (27-704, fig. 27) were steeper. Flow patterns near the pumping centers in Wharton Borough and Boonton Township were similar to those in 1986. Water-level declines were not significant, except possibly at the Rockaway Borough well field. Current (1986) water levels in the area of the well field are about 15 ft below land surface. Increases in pumpage of about 0.8 Mgal/d by 2040 yielded simulated water-level declines of more than 15 ft in this area, and significantly increased the extent of the cone of depression around this well field. The Rockaway Borough production well in the lower aquifer also showed a decline of 4 ft. Because Rockaway Borough production well number 1 (27-137) is shallow (less than 49 ft deep), water-level declines of this magnitude potentially could affect the yield of the well.

The cone of depression in the upper aquifer around the Rockaway Township water-supply development site (Rockaway Township 2) south of Green Pond Brook covered a larger area than it did in the 2000 simulation, and water levels declined a maximum of 22 ft. Simulated water levels around the site of water-supply development for Rockaway Township (well 27-704) in Beaver Brook valley declined a maximum of 29 ft. Simulated water levels at the site of proposed withdrawals in Denville Township (Denville Township 1) declined a maximum of 20 ft. A cone of depression was present in Mountain Lakes Borough as a result of pumpage from the water-supply development site at Sunset Lakes in both the upper and lower aquifers. Simulated water levels at this site declined more than 100 ft in the lower aquifer. Because the heads simulated for stressed steady-state conditions were more than 20 ft higher than the measured water levels, the water-level declines that will be observed as a result of the relocation of the Mountain Lakes Borough water-supply well to the Sunset Lakes area may be

Table 11. Ground-water flow budgets for the predictive simulations

(Mgal/d, million gallons per day)

	Inflow (Mgal/d)			Outflow (Mgal/d)	
	Scenario 1 (2000)	Scenario 2 (2040)		Scenario 1 (2000)	Scenario 2 (2040)
Recharge	43.2	43.2	Discharge to streams	36.1	34.2
Recharge from lakes	.8	.8	Leakage to lakes	0	0
Boundary fluxes	0	0	Boundary fluxes	.5	.5
Stream leakage	4.1	5.3	Withdrawals	11.5	14.6
Total	48.1	49.3	Total	48.1	49.3

Table 12. Simulated stream leakage from the Rockaway River between streamflow-gaging stations, 1986, 2000, and 2040

(Mgal/d, million gallons per day)

Surface-water stations at upstream and downstream ends of reach[1]	Pumping Center[2]	Simulated stream leakage between stations (Mgal/d)			Increase in withdrawals between stations (Mgal/d)	
		1986	2000	2040	1986-2000	1986-2040
01379700-01379740	1	6.2	6.0	5.6	0.5	1.0
01379740-01379880	2	13.1	12.7	12.2	.4	.8
01379880-01380110	3	4.0	3.8	3.4	1.1	1.9
01380110-01380145	4	4.8	4.6	3.9	.3	1.3
01380145-01380335	5	3.0	3.0	2.9	.1	.1

[1] See figure 8 for locations of stations and table 3 for 1986 discharge measurements

[2] Major water users near indicated reach: 1, Wharton Borough; 2, Town of Dover and Denville Township; 3, Rockaway Borough and Rockaway Township; 4, Denville Township; 5, Boonton Township

greater than those simulated. Withdrawals at the Parsippany-Troy Hills pumping center are located outside the modeled area and were not increased during predictive simulations. However, water levels in Mountain Lakes Borough could decline further if withdrawals at Parsippany-Troy Hills also increase.

The ground-water flow budget for the valley-fill aquifers in 2040 is presented in table 11. Total ground-water withdrawals are 14.6 Mgal/d. Leakage from losing reaches of the Rockaway River is 5.3 Mgal/d, a 2.4 Mgal/d increase from 1986. The total amount of ground-water discharge to streams is about 34.2 Mgal/d, a decrease of 3.1 Mgal/d from the 1986 average discharge, which was 37.3 Mgal/d. Under conditions of average ground-water recharge, an increase in ground-water withdrawals of 5.5 Mgal/d relative to 1986 pumpage yields an average simulated ground-water discharge to the Rockaway River in 2040 of 34.2 Mgal/d (table 11), which is greater than the minimum downstream passing flow.

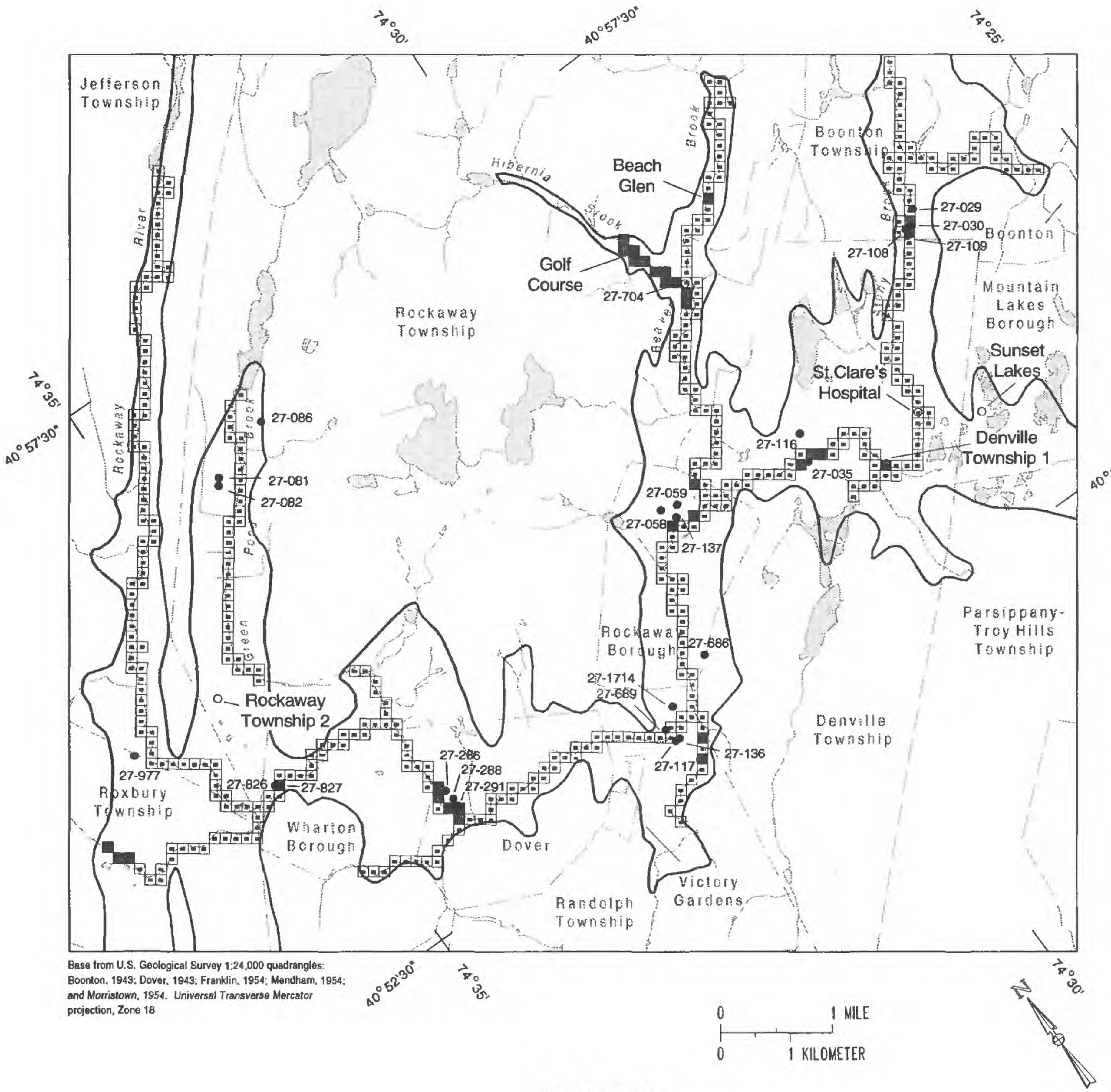
Losing reaches of the Rockaway River simulated by the model are shown in figure 28. Areas of streamflow loss include areas near the pumping centers of the Town of Dover and Wharton Borough, where water flows from the river to the upper aquifer. In Denville and Boonton Townships, water flows from the river to the lower aquifer by means of leakage through the confining unit. A comparison of simulated stream leakage in 1986 with that simulated for 2040 (table 12) shows losses in streamflow between areas of increased withdrawals. A streamflow loss of about 2.4 Mgal/d was simulated between the pumping centers of Rockaway Borough, the Town of Dover, and Rockaway and Denville Townships. The increase in ground-water withdrawals from the 1986 value totaled about 4 Mgal/d at these pumping centers.

Effects of Increased Withdrawals under Low-Flow Conditions

The modeling analysis was used to evaluate the effects of increases in withdrawals on streamflow under average steady-state conditions. Simulation results show that the average flow at the streamflow-gaging station above the Boonton Reservoir (01380500) exceeds the flow needed to meet the minimum passing flow below the reservoir under conditions of increased withdrawals anticipated during 1986-2000 and during 1986-2040. During periods of extreme low flow, however, the flow at the streamflow-gaging station above the Boonton Reservoir may not be sufficient to meet the minimum passing flow below the reservoir. Statistics of flow duration of the Rockaway River at this station can be used to determine the frequency of occurrence of flows that are less than that needed to meet the minimum passing flow.

Flow-duration-curve analysis is useful for analyzing the availability and variability of streamflow. The flow-duration curve indicates the percentage of time specified discharges were equaled or exceeded in a particular stream during a given period. It can be used to estimate the probable future behavior of the stream if the basin is not significantly altered by human activity (Gillespie and Schopp, 1981).

The flow needed above the Boonton Reservoir if ground-water withdrawals increase from 9.1 Mgal/d to 11.5 Mgal/d by 2000 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 (2.4 Mgal/d), or 11.0 Mgal/d. Whenever flow in the Rockaway River above the Boonton Reservoir is less than 11.0 Mgal/d, the flow at streamflow-gaging station 01380500, located about 1 mile upstream from the Boonton Reservoir, will be less than the flow required to meet the minimum passing flow below the reservoir. Analysis of flow-duration statistics shows that flow at station 01380500 was less than the flow needed by 2000 (11.0 Mgal/d) during 0.7 percent of the period of record (October 1937-September 1986).



EXPLANATION

- ■ Cell containing losing stream reach
- ▣ Cell containing gaining stream reach
- —— Approximate extent of the valley-fill deposits, modified from Canace and others, 1993, and Stanford, 1989a, 1989b
- ● 27-086 Location of production well and number
- ○ Beach Glen Area of proposed withdrawals

Figure 28. Predicted losing and gaining reaches of the Rockaway River and tributaries simulated under anticipated increases in ground-water withdrawals by 2040.

The flow needed upstream from the Boonton Reservoir if ground-water withdrawals increase from 9.1 Mgal/d to 14.6 Mgal/d during 1986-2040 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 (5.5 Mgal/d), or 14.1 Mgal/d. Analysis of flow-duration statistics shows that flow at station 01380500 was less than the flow needed by 2040 (14.1 Mgal/d) during 1.8 percent of the period of record (October 1937-September 1986). These periods of insufficient average flow are considered to be of little significance in comparison to the periods of sufficient flow.

Changes in precipitation affect ground-water recharge and ground-water discharge to streams. During extended periods of extreme low-flow conditions, the minimum passing flow requirement above the reservoir may not be met part of the time. An analysis of transient ground-water flow conditions would be needed to determine the likely response of the ground-water system to drought conditions because the response of the ground-water system to the drought and to the establishment of new equilibrium conditions is subject to a time lag. However, flow-duration statistics for the drought of 1962-66 can be used to provide an indication of the probable magnitude of flows during future drought periods. During 0.7 percent of the period from October 1962 through September 1966, the flow above the Boonton Reservoir was less than the flow of 8.6 Mgal/d needed above the Boonton Reservoir. During 5.3 percent of this period, the flow above the reservoir was less than the sum of the mandated minimum passing flow (7.0 Mgal/d), the anticipated loss to evaporation (1.6 Mgal/d), and the increased ground-water withdrawal rate anticipated by 2000 (2.4 Mgal/d). During 11.6 percent of this period, the flow was less than the sum of the minimum passing flow, anticipated loss to evaporation, and the increased ground-water withdrawal rate anticipated by 2040 (5.5 Mgal/d).

SUMMARY AND CONCLUSIONS

Most public water supply in the upper Rockaway River valley consists of ground water from the valley-fill aquifers. Ground-water withdrawals have increased from about 3 Mgal/d in 1950 to more than 9 Mgal/d in 1986. Ground water is withdrawn from valley-fill deposits which comprise an upper and a lower aquifer. Generally, the upper aquifer is unconfined and the lower aquifer is locally confined. 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 for public supply below the Boonton Reservoir. A ground-water flow model was used to simulate and evaluate the effects of current and predicted withdrawals on the valley-fill flow system.

The valley-fill deposits in the study area are of glacial, lacustrine, and fluvial origin, and consist of gravel, sand, silt, and clay deposited in glacial lakes and outwash sheets, and till deposited in the terminal moraine. These deposits average 150 ft in thickness in the centers of valleys but exceed 200 ft in thickness in some areas. The valley fill is surrounded and underlain by bedrock, which is less permeable than the glacial sediments. The valley-fill aquifers include (1) an upper, unconfined aquifer of sand and gravel that was deposited over a discontinuous and leaky confining unit consisting of glaciolacustrine silt, clay, fine sand, and till, or, in some areas, over bedrock; and (2) a lower aquifer consisting of deposits of sand and gravel, which is locally confined. Recharge enters the unconfined aquifer by infiltration of precipitation from land surface to the water table and by runoff from adjacent uplands. Recharge enters the lower aquifer by infiltration through overlying units. The average total ground-water recharge to the valley-fill aquifers as infiltration of precipitation and recharge from upland areas and induced leakage from streams is estimated to be about 46 Mgal/d. The upper aquifer discharges to wells and streams, and the lower aquifer discharges to wells and to streams through overlying units. The average ground-water discharge to the Rockaway River in the study area is about 37.2 Mgal/d.

A ground-water flow model was used to simulate predevelopment and current (1986) average steady-state conditions in the valley-fill aquifers in an area of about 20 mi^2 in the upper Rockaway River valley. Unstressed conditions were simulated to determine the effects of pumping on the ground-water contribution to streamflow and on the ground-water flow in the valley-fill aquifers. Two predictive simulations were used to evaluate the effects of predicted increases in ground-water withdrawals by 2000 and 2040. Water levels measured in June 1986 were used to represent current average water levels, pumpage during 1986 was averaged to represent current pumpage, and low-flow discharges measured in June 1986 were used to represent the current average ground-water discharge to the Rockaway River.

Results of simulations indicate that ground water withdrawn from wells in the study area is derived from a decrease in ground-water discharge to streams and by an increase in vertical leakage to the lower aquifer from the overlying upper aquifer. Vertical leakage between the upper and lower aquifers increased by 1.5 Mgal/d relative to leakage simulated for unstressed conditions as a result of pumping from the lower aquifer. Results of the simulation of stressed conditions show that some reaches of the Rockaway River near pumping centers lose water to the aquifer, and that streamflow decreases with increased ground-water withdrawals. Low-flow measurements made during 1984-86 show losses in streamflow near production wells screened in the upper aquifer in Wharton and Rockaway Boroughs, Dover, and Boonton Township. Simulation results also show streamflow losses in these areas and the presence of a losing reach near the Rockaway Township pumping center.

The predictive simulations were used to show the effects of additional stresses on ground-water flow patterns in the valley-fill aquifer and the effect of increased ground-water withdrawals on streamflow in the Rockaway River. Locations for sites of potential water-supply development within the study area were tested by including additional wells or relocating current production wells and examining the effects on water levels, ground-water flow patterns, and streamflow. Under pumping conditions predicted by 2000 and 2040, streamflow depletion observed during 1986 continued near the well fields in the Town of Dover, Boonton Township, and Wharton Borough. River reaches lost water to the lower aquifer near the Denville Township well field through increased leakage from the river to the lower aquifer. Relocation of the Rockaway Township pumping center resulted in streamflow loss along the Beaver Brook tributary in Rockaway Township. Streamflow loss from the Rockaway River caused by an increase in withdrawals in Rockaway and Denville Townships, Rockaway Borough, and the Town of Dover increased by about 1 Mgal/d from 1986 to 2000, and by more than 2 Mgal/d from 1986 to 2040.

The amount of water needed above the Boonton Reservoir to sustain the mandated downstream flow is estimated to be 8.6 Mgal/d. This amount was determined from 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. Current (1986) average stream base flow above the Boonton Reservoir (37.2 Mgal/d) is greater than the sum of the minimum passing flow requirement downstream from the Boonton Reservoir and anticipated evaporation losses under conditions of average ground-water withdrawals (9.1 Mgal/d). It is assumed that as ground-water withdrawals from the valley-fill aquifers increase, ground-water discharge to the river will decrease by an equal amount, after equilibrium has been reestablished. The average ground-water-discharge rate above the Boonton Reservoir will likely continue to exceed the sum of the flow rates downstream as a result of reservoir evaporation losses and anticipated increased ground-water withdrawals, if ground-water withdrawals, from the valley-fill aquifers increase to 11.5 Mgal/d, predicted by the year 2000, and if ground-water withdrawals increase to 14.6 Mgal/d, predicted by the year 2040.

As withdrawals increase, average annual stream base flow above the Boonton Reservoir is sufficient to provide the minimum outflow needed below the reservoir; however, the minimum passing flow may not be met during periods of extreme low flow, such as the drought of 1962-66, because a decrease in precipitation will decrease ground-water discharge to streams. Results of analysis of flow duration for the Rockaway River above the Boonton Reservoir during periods of extreme low flow (during the drought of 1961-66), show that, during 5.3 percent of the drought of 1962-66, the flow above the reservoir was less than 11.0 Mgal/d, which is the sum of minimum passing flow, lake evaporation losses, and the increased ground-water withdrawals anticipated by the year 2000. During 11.6 percent of the drought of 1962-66, the flow above the Boonton Reservoir was less than 14.1 Mgal/d, which is the sum of the minimum passing flow, lake evaporation losses, and the increased withdrawals anticipated by the year 2040.

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Table 2. Records of wells in the study area

(gal/min, gallons per minute; –, data not available; *, open interval)

New Jersey well number	New Jersey permit number	Local well identifier	Owner	Well-completion date
		Boonton Township		
27-029	25-12046	BWD 6	Boonton Water Dept.	08-01-64
27-030	25-07495	BWD 5	Boonton Water Dept.	05-30-58
27-032	25-17311	BWD FIELD	Boonton Water Dept.	02-18-74
27-108	–	BWD 1	Boonton Water Dept.	10-20-30
27-109	–	BWD 2	Boonton Water Dept.	12-10-30
27-110	–	BWD 3	Boonton Water Dept.	08-28-46
27-111	–	BWD 4	Boonton Water Dept.	01-22-57
27-920	–	BWD TW 6	Boonton Water Dept.	10-01-64
		Denville Township		
27-035	25-09515	DTWD 5	Denville Township Water Dept.	09-28-61
27-115	45-00324	DTWD 1	Denville Township Water Dept.	05-16-28
27-116	–	DTWD 4	Denville Township Water Dept.	01-13-58
27-189	–	MLWD 4	Mountain Lakes Water Dept.	08-25-47
27-321	–	GEONICS 2	Rockaway River Country Club	09-21-79
27-324	25-21172	GEONICS 4	St. Clare's Hospital	09-27-79
27-663	25-01531	BERNSTORF 1	Bernstorf, B.	06-12-52
27-678	25-01670	BEHRENS 1	Behrens, Henry	06-07-52
27-697	25-03993	SINGER 1	N.J. Power and Light	04-15-55
27-917	25-24852	NJDEP TP 2	N.J. Dept. of Environmental Protection	00-00-84
27-1086	–	ST. CLARE'S	St. Clare's Hospital	–
		Dover Town		
27-286	25-13542	DOVWD 1	Dover Water Dept.	03-28-66
27-288	–	DOVWD 3	Dover Water Dept.	09-06-40
27-290	–	DOVWD TW 5	Dover Water Dept.	08-11-71
27-291	25-16024	DOVWD 5	Dover Water Dept.	09-10-71
27-295	25-24887	USGS S4	U.S. Geological Survey	05-10-84
27-306	25-25322	USGS D6	U.S. Geological Survey	08-14-84
27-322	25-09435	DOVWD TW 2	Dover Water Dept.	08-09-60
27-357	25-10565	DOVWD 4-HOOEY	Dover Water Dept.	07-19-62
27-401	25-01454	BROWN 1	Brown, Harry A.	12-11-51
27-854	25-09494	DOVWD TW 3	Dover Water Dept.	08-30-60
27-855	25-10461	DOVWD TW 4	Dover Water Dept.	04-05-62
27-1320	–	DOVWD 1-ABANDONED	Dover Water Dept.	09-16-25
		Jefferson Township		
27-027	–	NJDEP TW 9	N.J. Dept. of Environmental Protection	05-04-81
		Mountain Lakes Borough		
27-191	25-14698	MLWD 5	Mountain Lakes Water Dept.	01-08-69
27-323	25-21173	GEONICS 1	Mountain Lakes Water Dept.	09-11-79
27-402	25-01463	ONORATI 1	Onorati, Sebastiano	02-17-52
27-914	25-13697	MLWD TW 5	Mountain Lakes Water Dept.	10-28-66
		Randolph Township		
27-117	25-19071	DTWD 6	Denville Township Water Dept.	09-06-77
27-135	–	DTWD 2	Denville Township Water Dept.	10-10-31
27-136	–	DTWD 3	Denville Township Water Dept.	10-28-46
27-928	–	DTWD OBS	Denville Township Water Dept.	00-00-86

Table 2. Records of wells in the study area--Continued

New Jersey well number	Primary use of site[1]	Primary use of water[2]	Altitude of land surface[3] (feet)	Depth of well[4] (feet)	Depth of screened or open interval (feet)	Diameter of screened or open interval (inches)	Aquifer code[5]	Reported well yield (gal/min)
				Boonton Township				
27-029	W	P	495.5	55.0	--	--	112SFDF1	600
27-030	W	P	499.3	106	74.7-106	10	112SFDF2	300
27-032	O	U	501.6	40.0	36 - 40	4	112SFDF1	--
27-108	W	P	504.9	43.0	20 - 40	26	112SFDF1	382
27-109	W	P	502.9	38.0	20 - 38	26	112SFDF1	400
27-110	W	U	497.9	25.0	20 - 25	26	112SFDF1	250
27-111	W	U	499.1	102.3	75.9-102.3	10	112SFDF2	340
27-920	T	U	495.5	59	57 - 59	1.6	112SFDF1	--
				Denville Township				
27-035	W	P	509.2	201	178 -198	16	112SFDF2	1,018
27-115	W	U	520	147	106 -146	12	112SFDF2	--
27-116	W	P	511.6	117	96 -116	16	112SFDF2	542
27-189	C	P	503.9	64.0	32 - 64	17	112SFDF1	560
27-321	O	U	514.4	167	167 -175*	6	112SFDF2	--
27-324	O	U	500.5	200	185 -200*	6	112SFDF2	--
27-663	W	H	535	92	--	6	112SFDF2	12
27-678	W	N	535	126	121 -126	--	112SFDF2	--
27-697	W	N	520	75.0	55 - 75	8	112SFDF2	225
27-917	O	U	519.2	47	37 - 47	2	112SFDF1	--
27-1086	W	T	530	78.5	65.5- 78.5	10	112SFDF1	136
				Dover Town				
27-286	W	P	591.6	65.0	45 - 65	18	112SFDF1	1,711
27-288	W	P	590.1	74.0	52 - 74	15	112SFDF1	1,625
27-290	T	U	589.6	68.0	48 - 68	8	112SFDF1	525
27-291	W	P	590.1	64.0	44 - 64	18	112SFDF1	1,529
27-295	O	U	588.6	28.6	18.6- 28.6	2	112SFDF1	--
27-306	O	U	591.4	60.5	50.5- 59.5	4	112SFDF1	--
27-322	O	U	555	62.0	47 - 62	8	112SFDF1	1,455
27-357	W	U	555	138	118 - 138	18	112SFDF2	566
27-401	W	H	630	87.0	45 - 65	--	112SFDF2	--
27-854	O	U	553.7	81.0	65 - 81	8	112SFDF2	100
27-855	O	U	553.9	150	126 -150	8	112SFDF2	--
27-1320	Z	U	590	68.0	35.5- 64.5	18	112SFDF1	1,000
				Jefferson Township				
27-027	O	U	725.6	98.0	78 - 98	6	112SFDF2	--
				Mountain Lakes Borough				
27-191	W	P	505.0	332	235 -332	8,12	112SFDF2	1,212
27-323	O	U	502.8	250	237 -250*	6	112SFDF2	--
27-402	W	H	520	31.0	--	--	112SFDF1	--
27-914	T	U	505.0	345	295 -345	8	112SFDF2	--
				Randolph Township				
27-117	U	C	545.6	139.6	125-139.6	16	112SFDF2	406
27-135	W	U	550	136	126 -136	16	112SFDF2	760
27-136	W	P	550	135	117 -132	16	112SFDF2	737
27-928	O	U	544.3	13.4	--	--	112SFDF1	--

Table 2. Records of wells in the study area--Continued

New Jersey well number	New Jersey permit number	Local well identifier	Owner	Well-completion date
		Rockaway Borough		
27-057	25-09669	RWD 3R	Rockaway Water Dept.	07-26-61
27-058	25-10403	RWD 5	Rockaway Water Dept.	11-30-62
27-059	25-18231	RWD 6	Rockaway Water Dept.	03-01-76
27-137	--	RWD 1	Rockaway Water Dept.	09-05-22
27-138	--	RWD 3	Rockaway Water Dept.	02-20-43
27-686	25-14015	MCWILLIAMS 339	McWilliams Forge Inc.	10-04-66
27-873	25-04935	RWD TW-FLAGGE ST.	Rockaway Water Dept.	11-03-55
27-876	25-05419	RWD TW 4	Rockaway Water Dept.	04-30-56
27-912	--	RWD TW 3R	Rockaway Water Dept.	--
27-929	25-27147	SAIC 1	N.J. Dept. of Environmental Protection	12-09-85
27-930	25-27148	SAIC 2	N.J. Dept. of Environmental Protection	01-20-86
27-931	25-27149	SAIC 3	N.J. Dept. of Environmental Protection	01-06-86
27-932	25-27150	SAIC 4	N.J. Dept. of Environmental Protection	01-16-86
27-933	25-27151	SAIC 5	N.J. Dept. of Environmental Protection	02-18-86
27-934	25-27152	SAIC 6	N.J. Dept. of Environmental Protection	02-10-86
27-935	25-27153	SAIC 7	N.J. Dept. of Environmental Protection	02-03-86
		Rockaway Township		
27-062	25-14324	RTWD 6	Rockaway Township Water Dept.	07-21-67
27-080	25-15364	RTWD 7	Rockaway Township Water Dept.	12-23-69
27-081	--	US ARMY-PICATINNY 129	US ARMY-Picatinny Arsenal	02-27-48
27-082	--	US ARMY-PICATINNY 130	US ARMY-Picatinny Arsenal	02-27-48
27-084	--	US ARMY-PICATINNY 430A	US ARMY-Picatinny Arsenal	08-05-43
27-086	--	US ARMY-PICATINNY 410	US ARMY-Picatinny Arsenal	10-19-42
27-087	--	US ARMY-PICATINNY 305A	US ARMY-Picatinny Arsenal	00-00-38
27-104	--	US ARMY-PICATINNY MW 16	US ARMY-Picatinny Arsenal	01-15-81
27-247	25-23214	US ARMY-PICATINNY 65-2	US ARMY-Picatinny Arsenal	12-09-82
27-249	25-23216	US ARMY-PICATINNY 65-4	US ARMY-Picatinny Arsenal	12-15-82
27-252	25-23210	US ARMY-PICATINNY LF 3	US ARMY-Picatinny Arsenal	12-14-82
27-261	--	US ARMY-PICATINNY DH 8	US ARMY-Picatinny Arsenal	03-01-47
27-502	25-01563	JAYNE 1	Jayne, Robert	03-14-52
27-689	25-03494	AUSTENAL 1	Austenal Laboratory Incorporated	06-15-54
27-704	25-09626	HEWLETT-PACKARD	Rockaway Township Water Dept.	11-22-60
27-709	25-21465	KEUFFEL 2	Keuffel and Esser Company	07-14-80
27-711	25-21467	KEUFFEL 4	Keuffel and Esser Company	08-19-80
27-910	--	SHELL 10	N.J. Dept. of Environmental Protection	03-24-81
27-918	--	RTWD TW 7	Rockaway Township Water Dept.	12-23-69
27-1714	25-14562	AUSTENAL 2	Austenal Laboratory Incorporated	03-03-67
		Roxbury Township		
27-921	--	NJDEP TW 10	N.J. Dept. of Environmental Protection	05-05-81
27-977	25-21483	EVERGREEN ACRES 1	Roxbury Township Water Dept.	08-02-80

Table 2. Records of wells in the study area--Continued

New Jersey well number	Primary use of site[1]	Primary use of water[2]	Altitude of land surface[3] (feet)	Depth of well[4] (feet)	Depth of screened or open interval (feet)	Diameter of screened or open interval (inches)	Aquifer code[5]	Reported well yield (gal/min)
				Rockaway Borough				
27-057	Z	U	531.2	139	10 -138	12	112SFDF2	--
27-058	W	P	520	80.3	65.3-80.3	16	112SFDF2	50
27-059	W	P	520	83.0	58 - 83	12	112SFDF1	210
27-137	W	P	520	48.7	39 - 48.7	24	112SFDF1	540
27-138	Z	U	530	142.5	100 -140	12	112SFDF2	800
27-686	W	N	560	148	147 -148	8	112SFDF2	--
27-873	O	U	510	81.0	70 - 81	6	112SFDF2	--
27-876	O	U	530.7	72.0	61 - 72	--	112SFDF1	50
27-912	T	U	531.2	128	104 -125	2.1	112SFDF2	--
27-929	O	U	546.2	30.1	10.1-30.1	4	112SFDF1	--
27-930	O	U	555.6	92.0	72 - 92	4	112SFDF2	--
27-931	O	U	515.2	88.3	68.3-88.3	4	112SFDF2	--
27-932	O	U	511.0	37.0	17 - 37	4	112SFDF1	--
27-933	O	U	530.8	73.2	53.2-73.2	4	112SFDF1	--
27-934	O	U	532.1	61.0	41 - 61	4	112SFDF2	--
27-935	O	U	524.7	68.3	48.3-68.3	4	112SFDF2	--
				Rockaway Township				
27-062	W	P	520	163	100 -163	12	112SFDF2	538
27-080	W	P	520	150	106 -146	12	112SFDF2	708
27-081	W	N	704	113	98 -113	10	112SFDF2	656
27-082	W	N	702	117	102 -117	10	112SFDF2	626
27-084	W	N	701	82.0	62 - 82	10	112SFDF2	405
27-086	W	N	711	85.0	75 - 85	10	112SFDF2	503
27-087	W	U	696	90.8	70.8-90.8	10	112SFDF2	--
27-104	O	U	692.6	20.4	10 - 20.4	4	112SFDF1	--
27-247	O	U	699.9	206	201 -206	4	112SFDF2	9
27-249	O	U	699.9	35.0	30 - 35	4	112SFDF1	--
27-252	O	U	693.1	157	152 -157	4	112SFDF2	--
27-261	T	U	700	210	-210	--	112SFDF2	--
27-502	W	H	540	40.0	38 - 40	--	112SFDF1	--
27-689	W	N	560	50.0	39 - 50	--	112SFDF1	403
27-704	W	N	510	125	94 -125	--	112SFDF2	548
27-709	O	U	524.1	50.0	- 50	6	112SFDF1	--
27-711	O	U	525.7	121	101 -121	--	112SFDF2	--
27-910	O	U	543.8	68	28 - 68	4	112SFDF1	--
27-918	O	U	522.7	149	97 -149	4,6	112SFDF2	--
27-1714	W	N	560	134	124 -134	6	112SFDF2	--
				Roxbury Township				
27-921	O	U	695.5	87.9	67.9-87.9	6	112SFDF2	--
27-977	W	P	710	208	-208	--	112SFDF2	--

Table 2. Records of wells in the study area--Continued

New Jersey well number	New Jersey permit number	Local well identifier	Owner	Well-completion date
		Wharton Borough		
27-353	25-15799	WWD 3	Wharton Water Dept.	04-16-71
27-826	25-02172	WWD 1	Wharton Water Dept.	09-08-53
27-827	25-08675	WWD 2	Wharton Water Dept.	12-21-60
27-915	25-15572	WWD TW 3	Wharton Water Dept.	06-29-70

New Jersey well number	Primary use of site[1]	Primary use of water[2]	Altitude of land surface[3] (feet)	Depth of well[4] (feet)	Depth of screened or open interval (feet)	Diameter of screened or open interval (inches)	Aquifer code[5]	Reported well yield (gal/min)
				Wharton Borough				
27-353	W	P	597.3	65	40 - 65	18	112SFDF1	1,500
27-826	W	P	655	42.0	32 - 42	16	112SFDF1	530
27-827	W	P	650	32.0	27 - 32	16	112SFDF1	700
27-915	T	U	597.3	65	40 - 65	8	112SFDF1	495

[1] Use of site

O	observation	W	withdrawal
T	test	Z	destroyed
U	unused		

[2] Use of water

- H domestic
- N industrial
- P public supply
- T institutional
- U unused

[3] Datum is sea level

[4] Datum is land surface

[5] Aquifer units

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