Sources of Water to Wells in Updip Areas of the Wenonah-Mount Laurel Aquifer, Gloucester and Camden Counties, New Jersey

By Martha K. Watt and Lois M. Voronin

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s)/m]
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

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

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

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

Sources of Water to Wells in Updip Areas of the Wenonah-Mount Laurel Aquifer, Gloucester and Camden Counties, New Jersey

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Abstract

Since 1996, when the New Jersey Department of Environmental Protection (NJDEP) restricted ground-water withdrawals from the Potomac-Raritan-Magothy aquifer system in the southern New Jersey Coastal Plain as a result of excessive drawdown, Coastal Plain communities have been interested in developing alternate sources of water supply for their residents. The use of ground water from areas near the updip parts of the overlying confined aquifers where withdrawals are not restricted is being considered to meet the demand for drinking water. Concerns have arisen, however, regarding the potential effects of increased withdrawals from these areas on ground-water flow to streams and wetlands as well as to the deeper, confined parts of the aquifers. Therefore, the U.S. Geological Survey, in cooperation with the NJDEP, conducted a study to investigate the sources of water to currently inactive wells in the updip part of the Wenonah-Mount Laurel aquifer in Gloucester and Camden Counties, New Jersey. Of particular interest is whether the primary source of the increased withdrawals is likely to be the aquifer outcrop or the downdip, confined part of the aquifer.

The outcrop of the Wenonah-Mount Laurel aquifer covers nearly 8 mi^2 (square miles), or about 46 percent of Deptford Township's 17.56-mi^2 area. The Deptford Township Municipal Utilities Authority owns six currently (2005) inactive wells in the Wenonah-Mount Laurel aquifer at the southeastern boundary of Deptford Township, 1.25 mi (miles) from the outcrop. For the purposes of this study, an existing ground-water-flow model of the New Jersey Coastal Plain aquifers was used to simulate ground-water-flow conditions in Gloucester and Camden Counties in 1998.

Two alternative withdrawal scenarios were superimposed on the results of the 1998 simulation. In the first (the "full-allocation" scenario), full-allocation withdrawal rates established by the NJDEP were applied to 45 existing wells in the Deptford Township area. In the second (the "additional-withdrawal" scenario), the full-allocation scenario was modified by adding an additional withdrawal of 1.62 million gallons per day from the six inactive Deptford Township withdrawal wells.

Simulated drawdown for the full-allocation scenario is zero to near zero in Deptford Township. Changes are greatest downdip from Deptford Township, where a broad area of 5- to 10-ft (feet) drawdowns is simulated; maximum drawdown at the center of the cone of depression is 20 ft. Water levels declined as much as 10 ft around individual wells whose current withdrawals are only a small percentage of their allotted allocation.

Simulated drawdown for the additional-withdrawal scenario exceeds 40 ft and is centered around the six inactive Deptford Township withdrawal wells. The area in which the simulated drawdown is 5 ft extends approximately 3.75 mi downdip from the wells and 2 mi updip, into the outcrop.

Water budgets based on the simulation results for the full-allocation and additional-withdrawal scenarios were calculated and compared, with particular focus on a 75-mi^2 area in and around Deptford Township that includes the outcrop of the Wenonah-Mount Laurel aquifer and part of the area downdip from the outcrop (budget zone 2). The comparison of the two water budgets for zone 2 shows that 46 percent of the withdrawals from the six inactive Deptford Township wells would result from reduced stream base flow in the outcrop of the Wenonah-Mount Laurel aquifer and 35 percent would result from increased downward flow from the overlying Vincentown aquifer. Four percent would result from increased flow from the downdip areas of the Wenonah-Mount Laurel aquifer, 5 percent would result from decreased flow to the downdip areas of the Wenonah-Mount Laurel aquifer, and 5 percent would result from decreased flow to the underlying Englishtown aquifer system. The remaining 4 percent was attributed to decreased upward flow to the overlying Vincentown aquifer.

Records from three streamflow-gaging stations and four low-flow partial-record stations around the Deptford Township area were analyzed to determine base flow for comparison to the water-budget values. Statistics from only one station, Still Run near Mickleton, N.J. (01476600), were used in the estimation of base-flow reduction because the Wenonah-Mount Laurel outcrop covers 75 percent of the drainage basin's area. The unit-area base flow of 1.05 cubic feet per second per square mile calculated for the Still Run station was assumed for all streams draining the outcrop. Using this

base-flow value, the outcrop area of 22.61 mi^2 within budget zone 2 would yield 23.7 ft^3/s (cubic feet per second) of base flow. Simulation results for this budget zone include a 1.15-ft^3/s decrease in ground-water flow to streams from the full-allocation scenario to the additional-withdrawal scenario. This decrease represents a 4.9-percent reduction in the average stream base flow of 23.7 ft^3/s estimated for streams draining the Wenonah-Mount Laurel aquifer outcrop within the area of budget zone 2. Therefore, on the basis of the simulations, the primary sources of the water withdrawn from the Wenonah-Mount Laurel aquifer when the six inactive withdrawal wells in Deptford Township are pumped would be the Wenonah-Mount Laurel aquifer outcrop and the Vincentown aquifer rather than downdip parts of the Wenonah-Mount Laurel aquifer. The relatively low transmissivity of the Wenonah-Mount Laurel aquifer (500-1,000 feet squared per day) and the proximity of the wells to the outcrop area are the primary factors that control the source of water to these wells.

Introduction

Since 1996, when the New Jersey Department of Environmental Protection (NJDEP) restricted ground-water withdrawals from the Potomac-Raritan-Magothy aquifer system in the southern New Jersey Coastal Plain as a result of excessive drawdown, Coastal Plain communities have been interested in developing alternate sources of water supply for their residents. The use of ground water from areas near the updip parts of the overlying confined aquifers where withdrawals are not restricted is being considered to meet the demand for drinking water.

Three aquifers that potentially could be used for water supply in the southern New Jersey Coastal Plain are the Vincentown aquifer, the Wenonah-Mount Laurel aquifer, and the Englishtown aquifer system. The Vincentown aquifer is 20 to 80 ft thick and extends in the subsurface from Monmouth to Salem Counties, but only in a narrow band 3 to 10 mi wide adjacent and parallel to the outcrop area. The moderately permeable sands in and near the outcrop grade rapidly into finer grained silts and clays downdip. The Englishtown aquifer system thins from northeast to southwest and commonly is less than 40 ft thick in the study area. Sands in this aquifer system become finer to the southwest, and local silt and clay beds are common. (See Zapecza, 1989.) In contrast, the Wenonah-Mount Laurel aquifer tends to thicken to the southwest (Barksdale and others, 1958); it consists primarily of sand in the study area and is 100 to 120 ft thick (Zapecza, 1989).

Currently (2005), all production wells that tap the Wenonah-Mount Laurel aquifer between northern Burlington County and Salem County are within 10 mi of the downdip (southeastern) extent of the Wenonah-Mount Laurel aquifer outcrop (Zapecza, 1989). In 1998, water withdrawn for public supply from the Wenonah-Mount Laurel aquifer—most from wells 3 to 10 mi from the downdip extent of the aquifer outcrop (fig. 1)—totaled 9.01 Mgal/d. Interest in developing new sources of water has raised questions however, concerning the sources of water to wells that would withdraw from the updip portions of the aquifer, 1 to 3 mi from the downdip extent of the aquifer outcrop. Therefore, the U.S. Geological Survey (USGS), in cooperation with the NJDEP, conducted a study to examine the effects of increased withdrawals from the updip portion of the Wenonah-Mount Laurel aquifer on ground-water flow to streams and wetlands, and (or) downdip to deeper, confined portions of the Wenonah-Mount Laurel aquifer. Of particular interest is whether the primary source of water withdrawn from updip wells is likely to be the downdip, confined part of the aquifer or the aquifer outcrop.

An existing model of the New Jersey Coastal Plain (Voronin, 2003) was used to simulate withdrawals from wells near the Wenonah-Mount Laurel aquifer outcrop. The simulation results, as well as ground-water flow budgets and base-flow analysis, were used to estimate the effects of the withdrawals from the Wenonah-Mount Laurel aquifer on the surface-water system in the outcrop area and on the ground-water system in the deeper, confined portion of the aquifer. The results of this study will be useful in aiding water managers to understand the effects of withdrawals near the outcrops of regional confined aquifers in other parts of the Northern Atlantic Coastal Plain.

Purpose and Scope

This report describes the results of a simulation of ground-water flow in the Wenonah-Mount Laurel aquifer using an existing ground-water-flow model (Voronin, 2003). Two alternative withdrawal scenarios are simulated to determine the sources of water to six currently inactive wells in the Deptford Township area. The report describes the hydrogeology of the study area, the model used to run the withdrawal scenarios, the model input, estimated withdrawals for 45 existing wells in the Deptford Township area, and the simulation results for each of the withdrawal scenarios. Simulation results include maps of simulated water levels, drawdowns, and ground-water budgets for the two alternative withdrawal scenarios. Results of base-flow analysis for three streamflow-gaging stations and four low-flow partial-record stations around Deptford Township are presented. Changes in simulated discharge to streams and simulated available drawdown resulting from potential increases in ground-water withdrawals are discussed.

Description of Study Area

The study area includes Gloucester and Camden Counties and adjacent portions of Salem and Burlington Counties in the Coastal Plain of New Jersey (fig. 2). Deptford Township is in the northeastern part of Gloucester County, bordering Camden County. The Wenonah-Mount Laurel aquifer outcrop covers nearly 8 mi^2, or about 46 percent of Deptford Township's

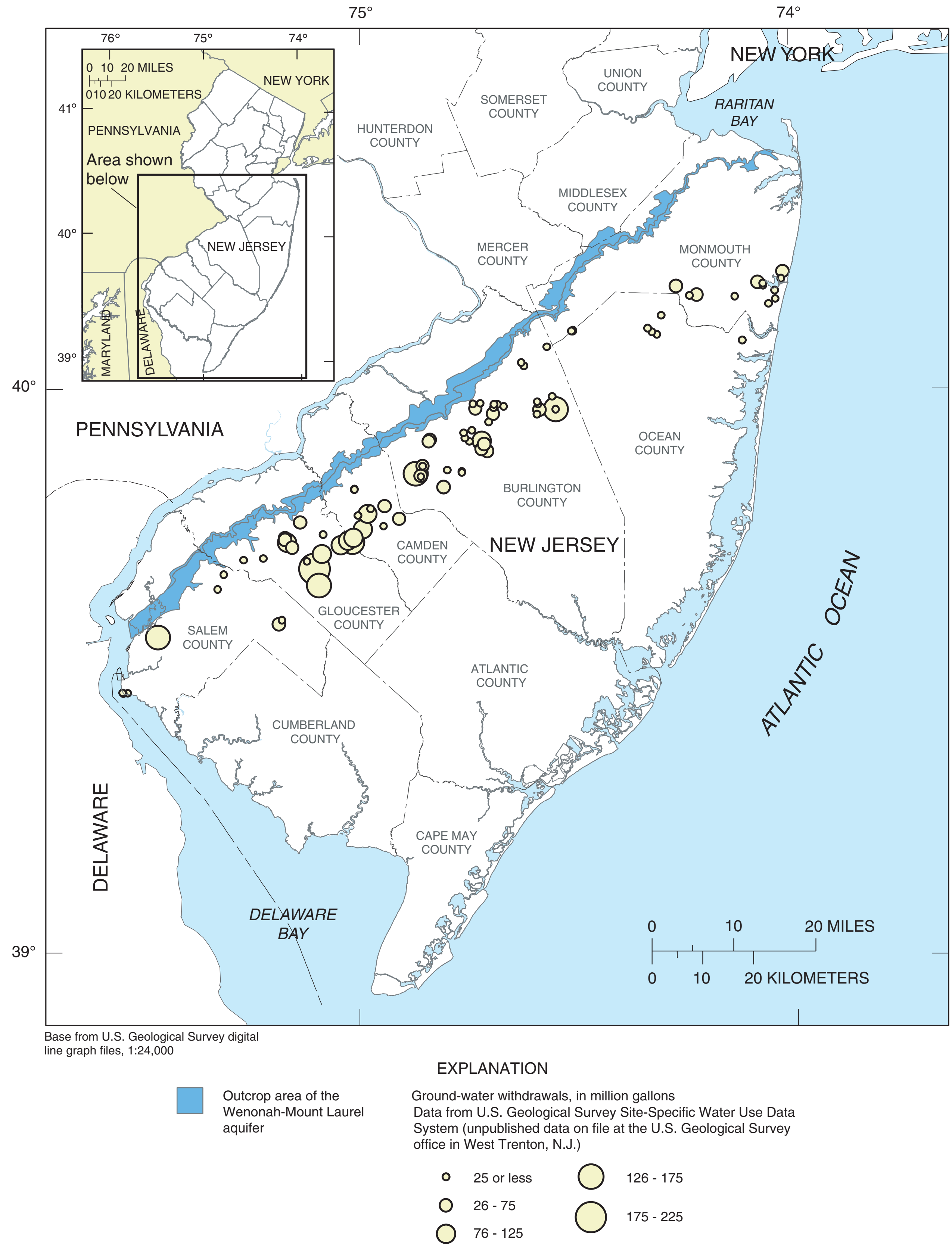
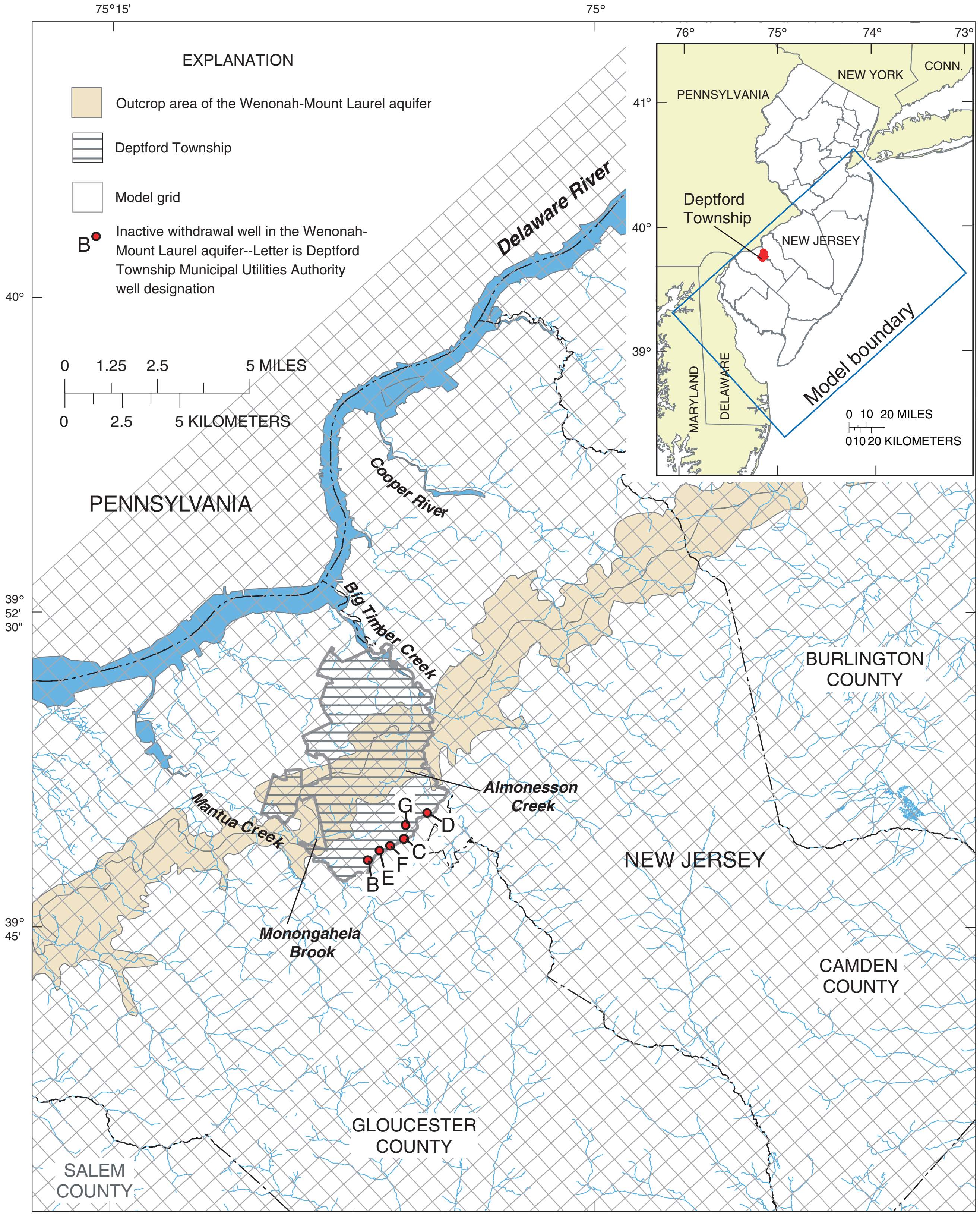


Figure 1. Location and amount of water withdrawn for public supply from the Wenonah-Mount Laurel aquifer New Jersey Coastal Plain, 1998.



Base from U.S. Geological Survey
digital line graph files, 1:24,000

Figure 2. Location of Deptford Township, extent of ground-water-flow model, model grid, and inactive withdrawal wells, New Jersey Coastal Plain.

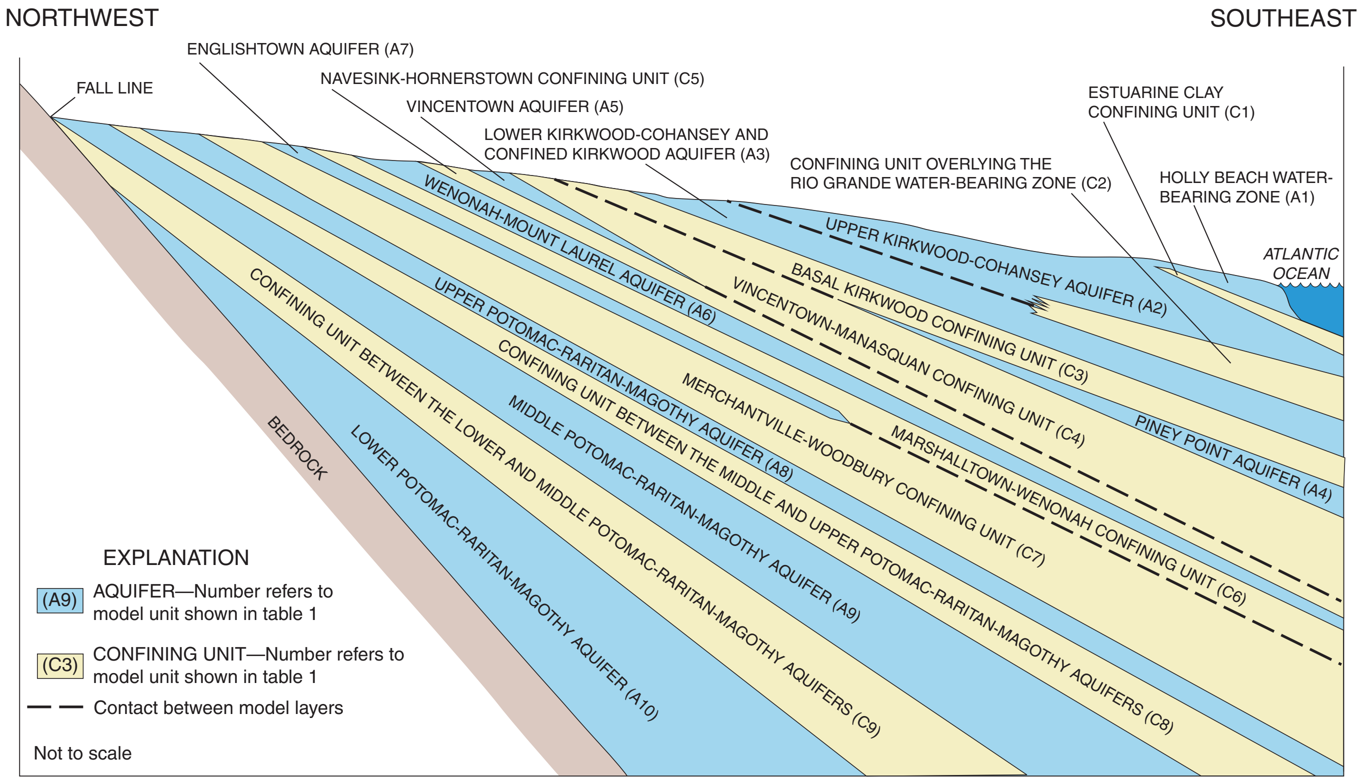


Figure 3. Generalized hydrogeologic section through the New Jersey Coastal Plain.

17.56-mi^2 area. Two streams flow across the Wenonah-Mount Laurel aquifer outcrop in Deptford Township: Monongahela Brook, a tributary to Mantua Creek; and Almonesson Creek, a tributary to Big Timber Creek. Six currently inactive withdrawal wells in the Wenonah-Mount Laurel aquifer (labeled B-G in fig. 2) at the southeastern boundary of Deptford Township, 1.25 mi from the Wenonah-Mount Laurel aquifer outcrop, are owned by the Deptford Township Municipal Utilities Authority (MUA). These wells were included in the model to examine the effects of simulated withdrawals from them on the ground-water and surface-water flow systems and to determine the sources of water to these wells.

To examine the effects of withdrawals from the Wenonah-Mount Laurel aquifer, which is hydraulically connected to aquifers and confining units above and below, the entire hydrologic system and associated stresses must be simulated. Therefore, the calibrated ground-water flow model used in this investigation simulates flow in the entire New Jersey Coastal Plain. The extent of the regional model is shown in figure 2.

Hydrogeologic Setting

The New Jersey Coastal Plain consists of a seaward-dipping wedge of unconsolidated sediments that range in age from Cretaceous to Holocene (fig. 3). These sediments consist mainly of clay, silt, sand, and gravel. Units that are mostly sand and gravel are permeable and are considered aquifers, and those that are mostly silt and clay are relatively impermeable and are considered confining units.

The Wenonah-Mount Laurel aquifer is directly overlain by a complex series of geologic units ranging in age from Late Cretaceous to Miocene. These units are predominantly silty and clayey glauconitic quartz sands and, as a group, are known as the “composite” confining unit (Zapecza, 1989, p. B14). This unit (called the Vincentown-Manasquan confining unit and Navesink-Hornerstown confining unit in figure 3), which has low to moderate permeability, separates the Wenonah-Mount Laurel aquifer from the younger Kirkwood-Cohansey aquifer system. Three minor aquifers can be found in the composite confining unit (table 1); only the Vincentown aquifer, which coincides with the Vincentown Formation, is important in the study area because it contains fairly permeable sand that can be used locally as a source of water.

The Wenonah-Mount Laurel aquifer consists of the coarse-grained part of the Wenonah Formation and the Mount Laurel Sand, both of Late Cretaceous age (table 1 and fig. 3; Zapecza, 1989). The aquifer extends beneath much of the Coastal Plain of New Jersey and crops out in a narrow band 1 to 3 mi wide that extends from Monmouth County southwest into Salem County (fig. 1). The aquifer reaches thicknesses of 100 to 120 ft near its outcrop in Burlington, Camden, Gloucester, and Salem Counties. Elsewhere, thicknesses of 60 to 80 ft are common. (See Zapecza, 1989.)

The Wenonah-Mount Laurel aquifer is directly underlain by the Marshalltown-Wenonah confining unit, which is made

Table 1. Geologic and hydrogeologic units of the New Jersey Coastal Plain and model units used in this study.

[Modified from Martin (1998, table 2); Zapecza (1989, table 2); and Seaber (1965, table 3); shading indicates adjacent geologic or hydrogeologic unit is not present in the updip or downdip areas]

SYSTEM	SERIES	GEOLOGIC UNIT	HYDROGEOLOGIC UNIT	MODEL UNITS[3]	
				Updip	Downdip
Quaternary	Holocene	Alluvial deposits	Undifferentiated	Upper Kirkwood-Cohansey aquifer (A2)	(shaded)
Quaternary	Holocene	Beach sand and gravel	Undifferentiated	Upper Kirkwood-Cohansey aquifer (A2)	Holly Beach water-bearing zone (A1)
Quaternary	Pleistocene	Cape May Formation	Kirkwood-Cohansey[1]	(shaded)	Estuarine Clay confining unit (C1)
Quaternary	Pleistocene	Cape May Formation	Kirkwood-Cohansey[1]	(shaded)	Upper Kirkwood-Cohansey aquifer (A2)
Tertiary	Miocene	Pennsauken Formation	Undifferentiated	Upper Kirkwood-Cohansey aquifer (A2)	(shaded)
Tertiary	Miocene	Bridgeton Formation	Kirkwood-Cohansey aquifer system	Upper Kirkwood-Cohansey aquifer (A2)	Upper Kirkwood-Cohansey aquifer (A2)
Tertiary	Miocene	Beacon Hill Gravel	Kirkwood-Cohansey aquifer system	Upper Kirkwood-Cohansey aquifer (A2)	Upper Kirkwood-Cohansey aquifer (A2)
Tertiary	Miocene	Cohansey Sand	Kirkwood-Cohansey aquifer system	Upper Kirkwood-Cohansey aquifer (A2)	Upper Kirkwood-Cohansey aquifer (A2)
Tertiary	Miocene	Kirkwood Formation	Kirkwood-Cohansey aquifer system	Lower Kirkwood-Cohansey aquifer (A3)	Upper Kirkwood-Cohansey aquifer (A2)
Tertiary	Miocene	Kirkwood Formation	Confining unit	(shaded)	Confining unit overlying the Rio Grande water-bearing zone (C2)
Tertiary	Miocene	Kirkwood Formation	Rio Grande[2]	(shaded)	Confined Kirkwood aquifer (A3)
Tertiary	Miocene	Kirkwood Formation	Confining unit	(shaded)	Confined Kirkwood aquifer (A3)
Tertiary	Miocene	Kirkwood Formation	Atlantic City 800-foot sand	(shaded)	Confined Kirkwood aquifer (A3)
Tertiary	Miocene	Kirkwood Formation	Composite confining unit	Basal Kirkwood confining unit (C3)	Basal Kirkwood confining unit (C3)
Tertiary		Piney Point Formation	Composite confining unit: Piney Point aquifer	Piney Point aquifer (A4)	Piney Point aquifer (A4)
Tertiary	Eocene	Shark River Formation	Composite confining unit	Vincentown-Manasquan confining unit (C4)	Vincentown-Manasquan confining unit (C4)
Tertiary	Eocene	Manasquan Formation	Composite confining unit	Vincentown-Manasquan confining unit (C4)	Vincentown-Manasquan confining unit (C4)
Tertiary	Paleocene	Vincentown Formation	Composite confining unit: Vincentown aquifer	Vincentown aquifer (A5)	Vincentown-Manasquan confining unit (C4)
Tertiary	Paleocene	Hornerstown Sand	Composite confining unit	Navesink-Hornerstown confining unit (C5)	Navesink-Hornerstown confining unit (C5)
Cretaceous	Upper Cretaceous	Tinton Sand	Composite confining unit	Navesink-Hornerstown confining unit (C5)	Navesink-Hornerstown confining unit (C5)
Cretaceous	Upper Cretaceous	Red Bank Sand	Composite confining unit: Red Bank sand	Navesink-Hornerstown confining unit (C5)	Navesink-Hornerstown confining unit (C5)
Cretaceous	Upper Cretaceous	Navesink Formation	Composite confining unit	Navesink-Hornerstown confining unit (C5)	Navesink-Hornerstown confining unit (C5)
Cretaceous	Upper Cretaceous	Mount Laurel Sand	Wenonah-Mount Laurel aquifer	Wenonah-Mount Laurel aquifer (A6)	Wenonah-Mount Laurel aquifer (A6)
Cretaceous	Upper Cretaceous	Wenonah Formation	Wenonah-Mount Laurel aquifer	Wenonah-Mount Laurel aquifer (A6)	Wenonah-Mount Laurel aquifer (A6)
Cretaceous	Upper Cretaceous	Marshalltown Formation	Marshalltown-Wenonah confining unit	Marshalltown-Wenonah confining unit (C6)	Marshalltown-Wenonah confining unit (C6)
Cretaceous	Upper Cretaceous	Englishtown Formation	Englishtown aquifer system	Englishtown aquifer (A7)	Merchantville-Woodbury confining unit (C7)
Cretaceous	Upper Cretaceous	Woodbury Clay	Merchantville-Woodbury confining unit	Merchantville-Woodbury confining unit (C7)	Merchantville-Woodbury confining unit (C7)
Cretaceous	Upper Cretaceous	Merchantville Formation	Merchantville-Woodbury confining unit	Merchantville-Woodbury confining unit (C7)	Merchantville-Woodbury confining unit (C7)
Cretaceous	Upper Cretaceous	Magothy Formation	Potomac-Raritan-Magothy aquifer system: Upper aquifer	Upper Potomac-Raritan-Magothy aquifer (A8)	Upper Potomac-Raritan-Magothy aquifer (A8)
Cretaceous	Upper Cretaceous	Raritan Formation	Potomac-Raritan-Magothy aquifer system: Confining unit	Confining unit between the Middle and Upper Potomac-Raritan-Magothy aquifers (C8)	Confining unit between the Middle and Upper Potomac-Raritan-Magothy aquifers (C8)
Cretaceous	Upper Cretaceous	Raritan Formation	Potomac-Raritan-Magothy aquifer system: Middle aquifer	Middle Potomac-Raritan-Magothy aquifer (A9)	Middle Potomac-Raritan-Magothy aquifer (A9)
Cretaceous	Upper Cretaceous	Potomac Group	Potomac-Raritan-Magothy aquifer system: Confining unit	Confining unit between the Lower and Middle Potomac-Raritan-Magothy aquifers (C9)	Confining unit between the Lower and Middle Potomac-Raritan-Magothy aquifers (C9)
Cretaceous	Lower Cretaceous	Potomac Group	Potomac-Raritan-Magothy aquifer system: Lower aquifer	Lower Potomac-Raritan-Magothy aquifer (A10)	Lower Potomac-Raritan-Magothy aquifer (A10)
Pre-Cretaceous		Bedrock	Bedrock confining unit		

[1] Kirkwood-Cohansey aquifer system
[2] Rio Grande water-bearing zone
[3] 'A' refers to modeled aquifer. 'C' refers to modeled confining unit. Number refers to model unit (Voronin, 2003).

up of the Marshalltown Formation and the fine-grained lower part of the Wenonah Formation; this unit is considered leaky (table 1 and fig. 3). The Marshalltown-Wenonah confining unit is underlain by the Englishtown aquifer system, which extends from Monmouth County to Salem County in a thin, irregular band. To the southwest in Gloucester and Salem Counties, it thins and undergoes a transition from sands to mostly silts and clays. The Englishtown aquifer system is not a major source of water between Burlington County and southern Salem County because of its reduced thickness and finer texture and the presence of other productive aquifers (Nichols, 1977, p. 20).

The Englishtown aquifer system is underlain by the Merchantville-Woodbury confining unit, which is the most extensive confining unit in the Coastal Plain (table 1 and fig. 3). The Merchantville-Woodbury confining unit is underlain by the Potomac-Raritan-Magothy aquifer system, which is the most productive aquifer system in the Coastal Plain. The Potomac-Raritan-Magothy aquifer system is underlain by the pre-Cretaceous bedrock. Additional discussion of the hydrogeology of the New Jersey Coastal Plain, including these units, can be found in Zapecza (1989).

The potentiometric surface of the Wenonah-Mount Laurel aquifer in and around Deptford Township ranges in altitude from 81 ft below NGVD 29 within the cone of depression that extends across the Camden-Gloucester County border downdip from Deptford Township, to more than 87 ft above NGVD 29 in the northern part of Camden County (Lacombe and Rosman, 2001) (fig. 4). The aquifer is recharged by precipitation, mainly at low points in the outcrop area, and by leakage through overlying hydrogeologic units (Barksdale and others, 1958; Hardt and Hilton, 1969). Most of the recharge moves locally through the aquifer and is discharged to streams that cross the outcrop area (Barksdale and others, 1958).

Simulation of Ground-Water Flow

An existing ground-water-flow model (Voronin, 2003) was used to simulate flow in and around Deptford Township under two alternative withdrawal conditions to examine the effects of ground-water withdrawals on ground- and surface-water flow. Results of the simulations were used to estimate the amount of ground water flowing into and out of specified budget zones, or groups of model cells, and to determine the sources of water to wells. In addition, “available drawdown,” defined as the distance between the top of the aquifer layer and the water level in the aquifer under withdrawal conditions, was determined.

Model Design

As part of the USGS Regional Aquifer System Analysis (RASA) program, a model was developed and calibrated for the New Jersey Coastal Plain (Martin, 1998). This model simulates flow in the sediments that make up the 10 aquifers and 9 intervening confining units of the New Jersey Coastal Plain (table 1, fig. 3). The cell size ranged from 6.25 mi^2 in the southeastern part of the Coastal Plain to 47.5 mi^2 in offshore areas. The model was designed with a coarse grid because the model area was large—9,000 mi^2—and computer capabilities were limited.

For this study, a revised version of the original RASA model was used to evaluate the effects of ground-water withdrawals on flow and water levels in the Wenonah-Mount Laurel aquifer in Gloucester and Camden Counties. The revised RASA model (Voronin, 2003) includes (1) a rediscretization of the model parameters with a finer cell size, (2) a spatially variable recharge rate that is based on rates determined as part of recent studies of the surficial aquifers in the Coastal Plain, and (3) ground-water withdrawal data from 1981-98.

The input data for the revised RASA model (Voronin, 2003) were formatted for use with MODFLOW-96, a version of the modular finite-difference ground-water-flow model by Harbaugh and McDonald (1996). The grid in the revised model consists of 135 rows and 245 columns; the cell size is 0.25 mi^2 in the northern and southwestern New Jersey Coastal Plain, including the area in and around Deptford Township; elsewhere, the cell size is 0.31 mi^2 in the southeastern Coastal Plain, and as large as 3.16 mi^2 in offshore areas. The ratio of the number of cells in the revised RASA model (Voronin, 2003) to the number of cells in the original RASA model (Martin, 1998) is 25 to 1 in onshore areas.

The assignment of the Coastal Plain sediments into aquifers and confining units in the original RASA model was not changed in the revised model (table 1, fig. 3). Most of the dipping Coastal Plain units have outcrop areas that receive recharge from precipitation and are in direct contact with streams. All of the layers are modeled as confined with a constant saturated thickness. Aquifer and confining-unit outcrop areas are modeled with an areally variable recharge rate, overlying constant-head stream cells, and an unconfined storage coefficient.

Martin (1998) modeled the 10 major aquifers and the streams using an 11-layer model in which the streams were represented as a layer of overlying constant-head nodes. In the revised model (Voronin, 2003), the streams were modeled using the River and Drain packages of MODFLOW-96 and required no layer designation. The finer grid-cell size in the revised model allows for more accurate representation of the streams. Each of the larger cells in the original RASA model (Martin, 1998) represented at least one reach of a stream, and, in many cells, many stream reaches were represented. Consequently, the stream stage for each original cell represented an average stage of all stream reaches in a cell. In contrast, the maximum stream length represented in each model cell in the revised model is approximately 80 percent smaller than the maximum stream length represented in the original RASA model, and not all cells representing unconfined or outcropping aquifers contain a stream (see Voronin, 2003). Model rediscretization also allows simulated withdrawals to be

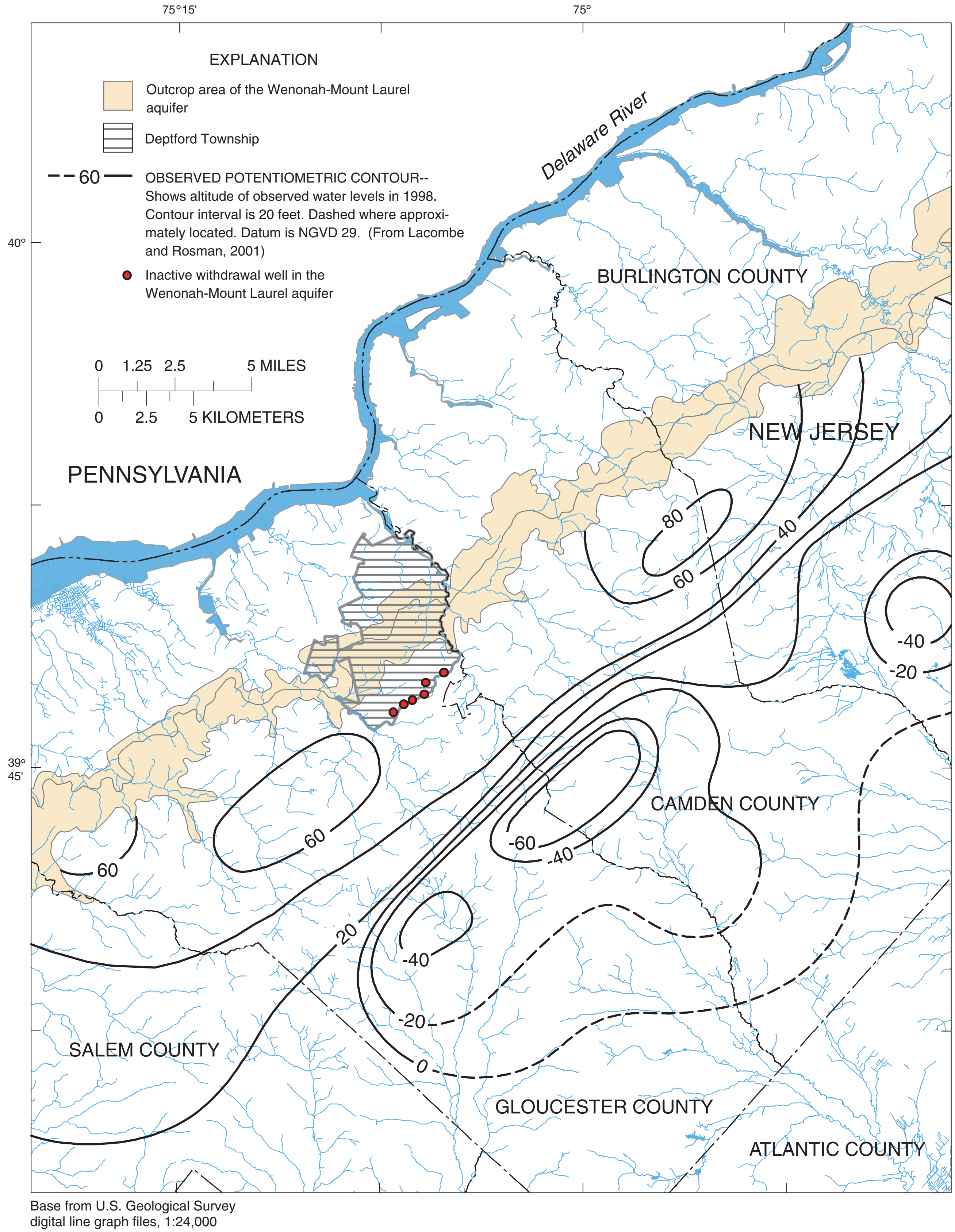


Figure 4. Observed potentiometric surface of the Wenonah-Mount Laurel aquifer in and around Deptford Township, N.J., 1998.

located more accurately. Withdrawals are located at the center of the model cell nearest to each well's location.

The model boundaries in the revised model (Voronin, 2003) are the same as those used in Martin's (1998) original 11-layer RASA model and are shown in cross-section view in figure 5. The northwestern (updip) limit of Coastal Plain sediments is the Fall Line and is modeled as a no-flow boundary. The lower boundary of the model is crystalline bedrock and is modeled as a no-flow boundary. Flows at the lateral boundaries in the northeast and southwest are from Martin's original RASA model for stress periods 1 to 3. The lateral-boundary flows for stress periods 4 to 21 were calculated by using the New Jersey Coastal Plain model constructed by Pope and Gordon (1999), except those in the Potomac-Raritan-Magothy aquifer system at the boundary between Delaware and New Jersey. Outward lateral fluxes at the Delaware-New Jersey boundary were increased to reflect the large increase in ground-water withdrawals in Delaware since 1988.

The southeastern (downdip) model boundary in the Potomac-Raritan-Magothy aquifer system is a stationary no-flow boundary that represents the downdip limit of freshwater in the aquifer. The Englishtown aquifer system and the Wenonah-Mount Laurel, Vincentown, and Piney Point aquifers are not continuous throughout the New Jersey Coastal Plain. The limit of these aquifers in the southeast also is modeled as a no-flow boundary. The southeastern model boundary in the lower, confined part of the Kirkwood-Cohansey aquifer system and the upper, unconfined part of the Kirkwood-Cohansey aquifer system is a specified-flux boundary. The upper boundary of the model is a head-dependent-flux boundary in cells that rep-

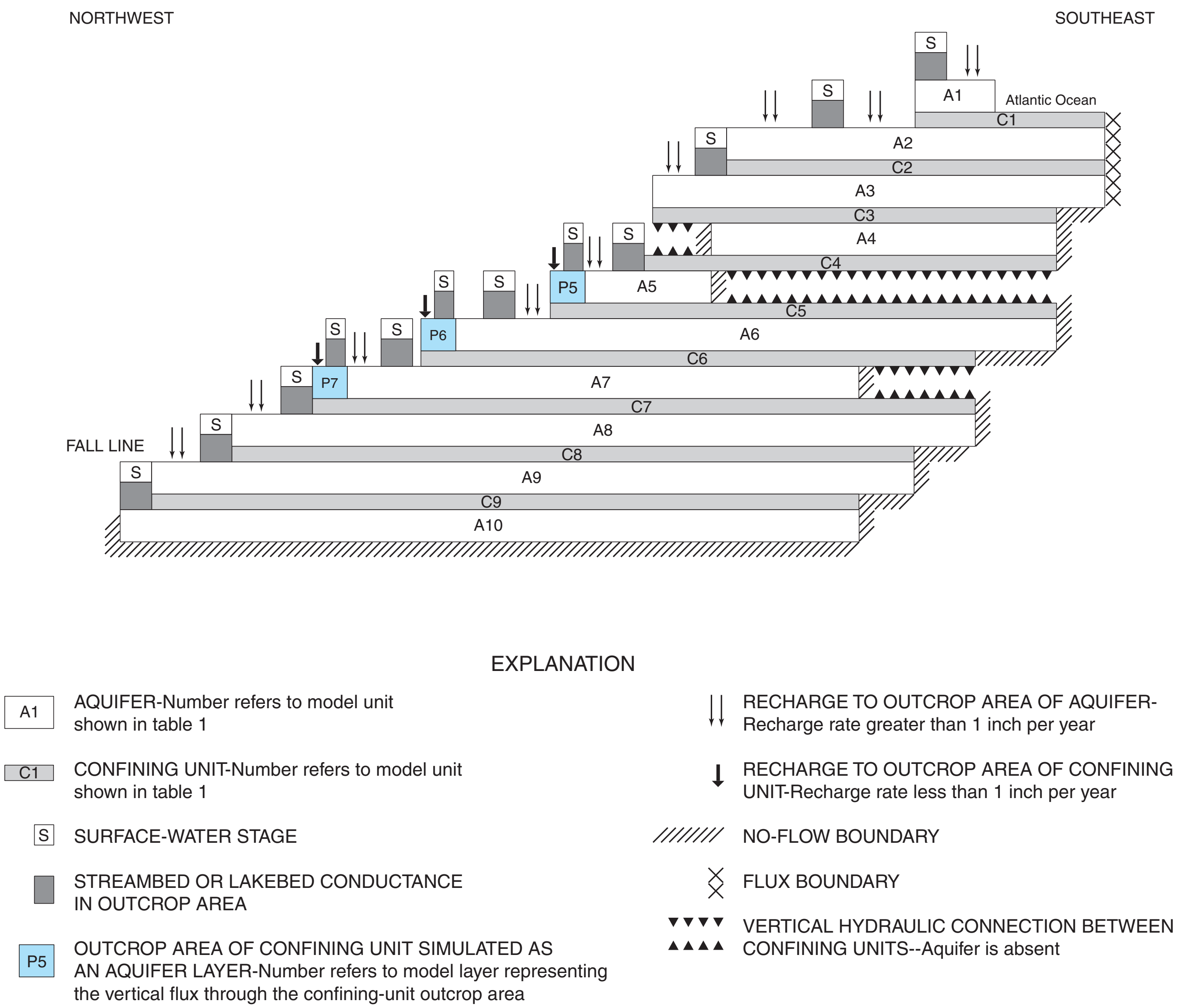


Figure 5. Schematic representation of aquifers, confining units, and boundary conditions used in the revised ground-water-flow model of the New Jersey Coastal Plain. (Modified from Martin, 1998, fig.4)

resent the stream reaches in the model area. In other onshore areas, the upper boundary is a recharge boundary where all applied ground-water recharge flows downward through confining units and aquifers or laterally into aquifers. In offshore areas, the upper boundary is a constant freshwater equivalent water level (see Voronin, 2003).

At the upper boundary of the revised model, a spatially variable recharge rate is applied to cells that represent the outcrop areas of aquifers and confining units without wetlands (fig. 5). The recharge rate applied to the outcrop areas is equal to long-term precipitation minus long-term evapotranspiration and surface-water runoff. The amount of precipitation that becomes surface-water runoff is controlled by the topography and lithology of the outcrop area. The precipitation that recharges the outcrop areas eventually flows to surface-water bodies, such as streams or the ocean, as ground-water discharge. Ground-water discharge can be local flow to nearby streams within the shallow aquifer system, intermediate flow to nearby streams, or regional flow to larger rivers or the ocean (see Voronin, 2003).

The revised model was calibrated by trial-and-error adjustment of the vertical-leakance values, storage-coefficient values, streambed-conductance values, lateral-boundary fluxes, and recharge rates. During model calibration, it was found that changes to only the five model parameters listed above improved the calibration in any particular area; therefore, these parameters were changed from Martin's (1998) original RASA model-input data. These five parameters were adjusted during model calibration to minimize the difference between simulated and measured values of one or more of the following: (1) estimated base flow for five river basins, (2) water levels in 28 selected observation wells for which long-term hydrographs were available, and (3) potentiometric surfaces for 1978, 1983, 1988, 1993, and 1998 conditions (see Voronin, 2003).

In general, the water levels simulated with the revised model (Voronin, 2003) and measured water levels match closely; in most areas they are within 20 ft. Long-term hydrographs of simulated and measured water levels for 28 wells show that simulated water levels, in general, are within 25 ft of measured water levels and, in most cases, are within 5 ft. The simulated and calculated base flows at continuous streamflow-gaging stations in five river basins in the Coastal Plain compare well: all differences are less than 31 percent. The two largest basins with the longest periods of record match within 11 percent; the differences for the three smaller basins range from 14 to 31 percent (see Voronin, 2003). For a detailed discussion of the design, calibration, and boundaries of the original and revised RASA models, refer to Martin (1998) and Voronin (2003), respectively.

In this study, minor changes were made to the revised RASA model. The vertical conductance (hydraulic conductivity divided by thickness) of the Vincentown-Manasquan confining unit, including the area in and around Deptford Township, was modified to improve the representation of the geohydrologic framework. Properties in fewer than 50 cells of the revised RASA model were changed. Withdrawal data for wells in and around Deptford Township for the two alternative scenarios were collected and added to the model; however, no additional calibration or sensitivity analysis was done. Use of the RASA model for this analysis is appropriate because the model was designed and shown to be an effective tool to simulate ground-water flow in the confined aquifer system and to provide reasonable estimates of the sources of water to wells (Martin, 1998). The Deptford Township wells are in the confined part of the aquifer, near its updip limit. Increased withdrawals from the Deptford Township area are expected to affect flow to streams in the nearby outcrop area and regional confined flow. Simulation results are used to estimate flow budgets to determine whether the source of water for the proposed Deptford Township withdrawals is likely to be the confined portion of the aquifer or the aquifer outcrop. Changes in flow to individual streams are not evaluated because of the regional scale of the model.

Description of Scenarios

The revised RASA model (Voronin, 2003) was used to simulate steady-state ground-water flow in and around Deptford Township under two alternative withdrawal conditions. The confined aquifers throughout the Coastal Plain of New Jersey typically respond quickly to changes in stress. Simulated hydrographs from Martin (1998) generally show that simulated water levels approach steady-state quickly (by the end of the pumping period). The steady-state water-supply scenarios simulate maximum changes in the ground-water flow system that are likely to occur after several years of constant withdrawals.

Initially, steady-state water levels were simulated using 1998 withdrawals. The results of this simulation provide a baseline with which to compare the results of the other simulations and the synoptic water levels measured in the Coastal Plain in 1998 (Lacombe and Rosman, 2001) (fig. 4). The first of two alternative withdrawal scenarios (full allocation) is a simulation of water levels that could occur if 1998 conditions were modified so that ground-water withdrawals from 45 existing wells in and around the Deptford Township area were equal to the maximum allocated withdrawals. The second withdrawal scenario (additional withdrawals) is a simulation of water levels resulting from 1998 withdrawals and full-allocation withdrawals from the 45 wells plus an additional 1.62 Mgal/d pumped from the six currently inactive Deptford Township MUA withdrawal wells screened in the Wenonah-Mount Laurel aquifer near its updip limit in Deptford Township. Results of this simulation provide information on the sources of water to these wells and on the effects of withdrawals from these wells on the ground-water flow system in the surrounding area.

Estimation of Withdrawals

Different withdrawal-data sets were used for the two alternative withdrawal scenarios. First, the model was used to delineate the area of influence (Modica, 1998), or cone of depression, attributed to withdrawals from the six currently inactive withdrawal wells in the Wenonah-Mount Laurel aquifer in Deptford Township. The area of influence was defined as the area in which the drawdown exceeded about 0.5 ft when withdrawals of 1.62 Mgal/d were added to the 1998 withdrawals. Water users within the area of influence may affect or be affected by increased withdrawals in Deptford Township. Nineteen water purveyors with 45 wells that withdraw water from the Wenonah-Mount Laurel aquifer within the area of influence were identified for inclusion in the full-allocation and additional-withdrawal scenarios (fig. 6).

Monthly or annual full-allocation withdrawal values for the Wenonah-Mount Laurel aquifer within the area of influence were obtained from Bureau of Water Allocation (BWA) permit files at the NJDEP office in Trenton, N.J. In most cases, the BWA allocation permits do not specify withdrawal limits on a well-by-well basis; rather, limits typically are specified for the entire BWA permit or for groups of wells in the same aquifer. The full-allocation withdrawal rates of individual wells were estimated by comparing the relative withdrawals among wells included in a BWA permit on the basis of water-use data obtained from NJDEP. Average yearly withdrawals for 1994-98 for each well included in a BWA permit were totaled and the percentage of the total for the permit was calculated for each well. This percentage was applied to the Wenonah-Mount Laurel aquifer full-allocation value for each permit to calculate the full-allocation value for each well. Estimates of the full-allocation conditions for BWA permits with specific allocations for the Wenonah-Mount Laurel aquifer are shown in table 2.

For BWA permits in which the full allocation was not specified by aquifer, the historical distribution of withdrawals among aquifers was used to estimate each aquifer's full-allocation withdrawals. The percentage of the total average 1994-98 withdrawal for each aquifer was calculated. This percentage was then applied to the full-allocation value for the permit to estimate the Wenonah-Mount Laurel aquifer withdrawal at full allocation. The Wenonah-Mount Laurel aquifer full-allocation value was then subdivided based on the percentage of the total average 1994-98 withdrawals from the Wenonah-Mount Laurel aquifer for each well. Estimates of full-allocation withdrawals for BWA permits with combined allocations are shown in table 3. The increase from average 1994-98 ground-water withdrawals to full allocation for the 45 wells in the Wenonah-Mount Laurel aquifer within the area of influence was 1,693.8 Mgal/yr.

Water Levels and Drawdown

A simulated potentiometric-surface or drawdown map was constructed for each scenario—a simulated potentiometric-surface map for 1998 withdrawal conditions and a simulated drawdown map showing the change in water levels produced by increased withdrawals for the full-allocation and additional-withdrawal scenarios. For the full-allocation scenario, the drawdown is the change from the 1998 simulated water levels. For the additional-withdrawal scenario, drawdown is the difference in water levels from the full-allocation to the additional-withdrawal scenario.

1998 Simulation

Simulated steady-state water levels in Deptford Township in 1998 are 30 to 40 ft above NGVD 29 (fig. 7). Water-level altitudes in small cones of depression downdip from Deptford Township range from 20 to 40 ft below NGVD 29. Simulated water levels northeast and southwest of Deptford Township are relatively high (40 to 80 ft above NGVD 29), possibly as a result of the hydraulic connection with the overlying unconfined aquifer.

Full-Allocation Scenario

Simulated drawdown for the full-allocation scenario (fig. 8) is zero to near zero in Deptford Township under full-allocation conditions. Changes are greatest downdip from Deptford Township, where a broad area of 5- to 10-ft drawdowns is simulated; maximum drawdown at the center of the cone of depression is 20 ft. Water levels declined as much as 10 ft around individual wells whose current withdrawals are only a small percentage of their allotted allocation.

Additional-Withdrawal Scenario

Simulated drawdown for the additional-withdrawal scenario (fig. 9) is greater than 40 ft and is centered around the six inactive withdrawal wells in Deptford Township. Drawdown decreases to 5 ft approximately 3.75 miles downdip from the wells and 2 miles updip, into the outcrop.

Available Drawdown

Model simulations of the full-allocation scenario and the additional-withdrawal scenario were used to determine "available drawdown." Available drawdown is defined as the distance between the water level in the aquifer and the top of the aquifer. The drawdowns for the full-allocation scenario and

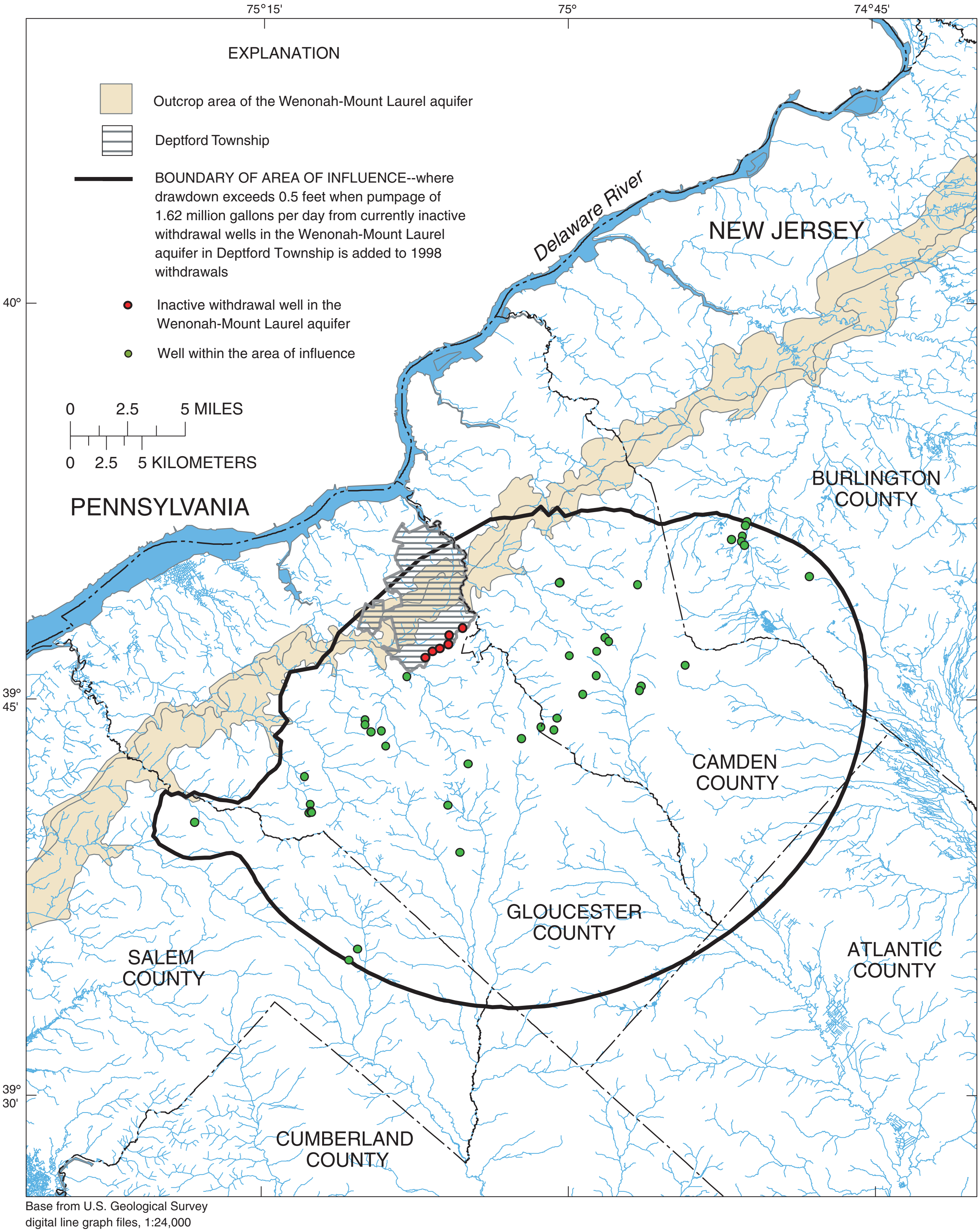


Figure 6. Wells within the area of influence of the inactive withdrawal wells in the Wenonah-Mount Laurel aquifer in Deptford Township in the full-allocation and additional-withdrawal scenarios, New Jersey Coastal Plain.

Table 2. Simulated ground-water withdrawals during 1994-98 and estimated full-allocation withdrawals from wells in the Wenonah-Mount Laurel aquifer near Deptford Township, N.J.

[All withdrawals are in million gallons per year; small differences in totals may be caused by independent rounding; USGS, U.S. Geological Survey; NJDEP, New Jersey Department of Environmental Protection; BWA, Bureau of Water Allocation; --, no value]

USGS well number	NJDEP well permit number	Ground-water withdrawals 1994	1995	1996	1997	1998	A Average yearly withdrawals 1994-98	B Percentage of total average yearly withdrawals 1994-98	Permitted full allocation	C Full allocation by well based on percent (B)	Difference between full allocation and average yearly withdrawals (C-A)
BWA permit number 5039											
5-1413	31-49987	0.000	0.000	0.000	73.969	66.34	28.062	20.016	--	82.868	--
5-1189	31-31317	5.446	30.972	26.887	0	48.47	22.355	15.946	--	66.016	--
5-1406	31-40672	5.083	20.404	0.000	95.137	48.47	33.819	24.123	--	99.869	--
5-1415	31-50015	0.000	0.000	0.000	73.075	46.95	24.005	17.123	--	70.888	--
5-245	31-00163	29.778	20.874	0.000	0.000	0.000	10.130	7.226	--	29.916	--
5-1414	31-49988	0.000	0.000	0.000	66.813	42.3	21.823	15.566	--	64.443	--
5-247	31-00110	0.000	0.000	0.000	0.000	0.000	0.000	0.000	--	0.000	--
5-715	51-00016	0.000	0.000	0.000	0.000	0.000	0.000	0.000	--	0.000	--
5-1167	31-03845	0.000	0.000	0.000	0.000	0.000	0.000	0.000	--	0.000	--
Total		40.307	72.250	26.887	308.994	252.530	140.194	100	414	414	273.806
BWA permit number 5095											
7-449	31-04749	0.000	0.000	0.000	0.000	0.000	0.000	0.000	--	0.000	--
7-448	31-04426	119.800	71.596	80.025	33.341	35.940	68.140	100	--	140	--
Total		119.800	71.596	80.025	33.341	35.940	68.140	100	140	140	71.860
BWA permit number 10108W											
7-228	31-05139	19.320	21.440	15.062	12.418	0.000	13.648	100	36.5	36.5	--
Total		19.320	21.440	15.062	12.418	0.000	13.648	100	36.5	36.5	22.852
BWA permit number 10408W											
15-1457	50-10706	0.000	0.000	0.000	0.000	4.220	0.844	33.333	--	12.167	--
15-1456	50-10707	0.000	0.000	0.000	0.000	4.220	0.844	33.333	--	12.167	--
15-1455	50-10705	0.000	0.000	0.000	0.000	4.220	0.844	33.333	--	12.167	--
15-1454	50-10708	0.000	0.000	0.000	0.000	0.000	0.000	0.000	--	0.000	--
Total		0.000	0.000	0.000	0.000	12.660	2.532	100	36.5	36.5	33.968
BWA permit number 2039P											
7-513	31-07766	0.191	2.970	0.000	5.236	20.890	5.857	47.070	--	31.537	--
7-993	31-16443	14.475	13.223	0.000	5.236	0.000	6.587	52.932	--	35.464	--
Total		14.666	16.193	0.000	10.472	20.890	12.444	100	67.0	67.0	54.556
BWA permit number 2147P											
7-401	31-02371	3.804	4.06	6.735	8.814	8.520	6.387	76.734	--	27.624	--
7-969	31-00629	4.837	4.392	0.453	0.000	0.000	1.936	23.266	--	8.376	--
Total		8.641	8.452	7.188	8.814	8.520	8.323	100	36.0	36.0	27.677
BWA permit number 2391P											
15-1387	51-00215	0.000	0.000	0.000	24.041	26.820	10.172	100	--	83.101	--
Total		0.000	0.000	0.000	24.041	26.820	10.172		83.101	83.101	72.929

Table 2. Simulated ground-water withdrawals during 1994-98 and estimated full-allocation withdrawals from wells in the Wenonah-Mount Laurel aquifer near Deptford Township, N.J.—Continued.

USGS well number	NJDEP well permit number	Ground-water withdrawals 1994	1995	1996	1997	1998	A Average yearly withdrawals 1994-98	B Percentage of total average yearly withdrawals 1994-98	Permitted full allocation	C Full allocation by well based on percent (B)	Difference between full allocation and average yearly withdrawals (C-A)
BWA permit number 2424E											
15-1452	31-36292	0.000	0.000	13.039	0.000	34.580	9.524	100	--	30	--
Total		0.000	0.000	13.039	0.000	34.580	9.524		30	30	20.476
BWA permit number 5004											
5-1405	31-44924	0.000	0.000	0.000	126.747	138.930	53.135	100	--	160	--
Total		0.000	0.000	0.000	126.747	138.930	53.135		160	160	106.865
BWA permit number 5194											
15-1367	31-45997	62.304	100.399	88.504	97.146	108.190	91.309	51.957	--	179.772	--
15-1384	31-45999	72.631	95.808	61.386	90.624	101.700	84.430	48.043	--	166.229	--
Total		134.935	196.207	149.890	187.770	209.890	175.738	100	346	346	170.262
BWA permit number 5215											
33-22	31-04612	30.076	31.223	25.222	27.506	24.810	27.767	41.430	--	33.144	--
33-456	31-19206	38.579	40.169	35.760	39.702	42.070	39.256	58.571	--	46.857	--
Total		68.655	71.392	60.982	67.208	66.880	67.023	100	80	80.0	12.977
BWA permit number 5244											
15-1108	31-39216	123.945	82.075	92.246	148.484	148.880	119.126	100	--	184	--
Total		123.945	82.075	92.246	148.484	148.880	119.126	100	184	184	64.874
BWA permit number 5314											
15-1117	31-44254	0.710	1.964	39.059	49.448	35.7	25.376	23.517	--	55.499	--
15-1118	31-44253	2.121	2.389	74.491	67.672	64.52	42.239	39.143	--	92.378	--
15-1119	31-44252	1.395	2.493	33.729	73.479	90.37	40.293	37.340	--	88.123	--
Total		4.226	6.846	147.279	190.599	190.590	107.908	100	236	236	128.092
BWA permit number 5335											
7-738	31-37611	105.837	90.262	99.729	106.197	99.360	100.277	100	--	105	--
Total		105.837	90.262	99.729	106.197	99.360	100.277	100	105	105	4.723
BWA permit number GL0088											
15-1459	0-01105	0.000	0.000	0.864	12.800	4.870	3.707	100	--	204	--
Total		0.000	0.000	0.864	12.800	4.870	3.707	100	204	204	200.293
BWA permit number SA0049											
33-178	30-01107	0.000	0.000	0.000	0.000	6.00	1.2	100	--	192	--
Total		0.000	0.000	0.000	0.000	6.00	1.2	100	192	192	190.80

Table 3. Simulated ground-water withdrawals during 1994-98 and estimated full-allocation withdrawals for permits with combined allocations from the Wenonah-Mount Laurel aquifer near Deptford Township, N.J.

[All withdrawals are in million gallons per year; small differences in totals may be caused by independent rounding; USGS, U.S. Geological Survey; NJDEP, New Jersey Department of Environmental Protection; BWA, Bureau of Water Allocation; MLRW, Wenonah-Mount Laurel aquifer; EGLS, Englishtown aquifer system; COH, Cohansey Sand; PRM, Potomac-Raritan-Magothy aquifer system; --, no value]

USGS well number	Aquifer	NJDEP well permit number	Ground-water withdrawals 1994	1995	1996	1997	1998	A Average yearly withdrawals 1994-98	B Percentage of total from all aquifers (A)	C Permitted full allocation	D Estimated aquifer withdrawal at full allocation (B*C)/100	E Percentage of total from MLRW (A)	F Estimated MLRW full allocation by well based on percent (E*D)/100	Difference between estimated MLRW full allocation and total MLRW withdrawal (F-A)
BWA permit number 5204														
7-307	MLRW	51-00013	0.000	0.000	0.000	0.000	0.000	0.000	--	--	--	0.000	0.000	--
7-308	MLRW	51-00014	0.140	0.383	20.564	0.000	10.185	6.254	--	--	--	9.740	17.289	--
7-306	MLRW	51-00012	0.091	18.175	31.822	12.887	4.582	13.511	--	--	--	21.042	37.349	--
7-305	MLRW	51-00011	0.137	0.406	32.699	16.598	4.390	10.846	--	--	--	16.891	29.981	--
7-414	MLRW	51-00010	71.277	64.324	32.400	0.000	0.000	33.600	--	--	--	52.327	92.879	--
Total withdrawals from MLRW			71.645	83.288	117.485	29.485	19.157	64.212	13.770	--	177.497	100	177.498	113.285
7-730	EGLS	31-29317	64.743	43.264	64.020	275.391	188.280	127.140	--	--	--	--	--	--
7-731	EGLS	31-29319	0.000	37.924	42.575	127.946	115.550	64.799	--	--	--	--	--	--
7-729	EGLS	31-29318	61.236	99.906	66.237	261.714	171.820	132.183	--	--	--	--	--	--
7-732	EGLS	31-29320	90.188	26.970	54.900	115.015	102.830	77.981	--	--	--	--	--	--
Total withdrawals from EGLS			216.167	208.064	227.732	780.066	578.480	402.102	86.230	--	1,111.503	--	--	--
Total withdrawals from all aquifers			**287.812**	**291.352**	**345.217**	**809.551**	**597.637**	**466.314**		**1,289**				

Table 3. Simulated ground-water withdrawals during 1994-98 and estimated full-allocation withdrawals for permits with combined allocations from the Wenonah-Mount Laurel aquifer near Deptford Township, N.J.—Continued.

			Ground-water withdrawals											
								A	B	C	D	E	F	
USGS well number	Aquifer	NJDEP well permit number	1994	1995	1996	1997	1998	Average yearly withdrawals 1994-98	Percentage of total from all aquifers (A)	Permitted full allocation	Estimated aquifer withdrawal at full allocation (B*C)/100	Percentage of total from MLRW (A)	Estimated MLRW full allocation by well based on percent (E*D)/100	Difference between estimated MLRW full allocation and total MLRW withdrawal (F-A)
BWA permit number 5007														
7-685	MLRW	31-22273	98.398	95.981	107.567	121.002	110.120	106.614	--	--	--	29.459	123.370	--
7-719	MLRW	31-24643	133.338	113.520	133.784	64.389	88.920	106.790	--	--	--	29.507	123.574	--
7-903	MLRW	31-46607	0.000	0.000	112.422	104.843	101.480	63.749	--	--	--	17.615	73.768	--
7-846	MLRW	31-46606	0.000	0.000	99.304	128.865	135.290	72.692	--	--	--	20.086	84.117	--
7-599	MLRW	31-20169	20.505	2.304	13.919	0.000	23.600	12.066	--	--	--	3.334	13.962	--
Total withdrawals from MLRW			252.241	211.805	466.996	419.099	459.410	361.910	26.046		418.792	100	418.792	56.882
7-890	COH	31-32432	0.000	7.991	0.000	0.000	0.000	1.598	--	--	--	--	--	--
7-603	COH	31-16697	141.447	117.724	114.277	174.071	185.600	146.624	--	--	--	--	--	--
7-691	COH	31-24727	23.256	3.063	0.003	26.172	60.170	22.533	--	--	--	--	--	--
7-866	COH	31-32431	0.000	0.000	0.000	0.000	210.980	42.196	--	--	--	--	--	--
7-898	COH	31-46605	0.000	0.000	116.007	177.580	0.000	58.717	--	--	--	--	--	--
7-905	COH	31-46604	0.000	0.000	76.360	9.286	0.000	17.129	--	--	--	--	--	--
7-889	COH	31-32433	0.000	0.000	0.000	0.000	36.710	7.342	--	--	--	--	--	--
Total withdrawals from COH			164.703	128.778	306.647	387.109	493.460	296.139	21.313					
7-250	PRM	31-08176	301.390	272.212	137.458	153.099	108.590	194.550	--	--	--	--	--	--
7-252	PRM	31-05581	470.000	504.724	300.016	300.328	248.910	364.796	--	--	--	--	--	--
7-249	PRM	31-02703	157.408	105.617	117.978	155.077	184.560	144.128	--	--	--	--	--	--
7-600	PRM	31-08539	0.000	0.000	0.000	60.200	79.650	27.970	--	--	--	--	--	--
Total withdrawals from PRM			928.798	882.553	555.452	668.704	621.710	731.443	52.641					
Total withdrawals from all aquifers			**1,345.742**	**1,223.136**	**1,329.095**	**1,474.912**	**1,574.580**	**1,389.493**		**1,607.880**				

Table 3. Simulated ground-water withdrawals during 1994-98 and estimated full-allocation withdrawals for permits with combined allocations from the Wenonah-Mount Laurel aquifer near Deptford Township, N.J.—Continued.

USGS well number	Aquifer	NJDEP well permit number	Ground-water withdrawals 1994	1995	1996	1997	1998	A Average yearly withdrawals 1994-98	B Percentage of total from all aquifers (A)	C Permitted full allocation	D Estimated aquifer withdrawal at full allocation (B*C)/100	E Percentage of total from MLRW (A)	F Estimated MLRW full allocation by well based on percent (E*D)/100	Difference between estimated MLRW full allocation and total MLRW withdrawal (F-A)
BWA permit number 5135														
15-1060	MLRW	31-30571	154.796	161.550	184.820	141.863	217.400	172.086	--	--	238.763	100.000	238.763	
Total withdrawals from MLRW			154.796	161.550	184.820	141.863	217.400	172.086	23.687	1,008.000	238.763	100.00	238.763	66.677
15-63	PRM	31-04176	82.308	222.029	108.387	149.763	135.120	139.521	--	--	--	--	--	--
15-62	PRM	51-00042	102.215	85.664	39.414	171.295	150.050	109.728	--	--	--	--	--	--
15-60	PRM	31-02358	254.300	180.282	199.300	128.199	156.860	183.788	--	--	--	--	--	--
15-361	PRM	31-07709	99.804	80.786	154.331	177.702	94.290	121.383	--	--	--	--	--	--
Total withdrawals from PRM			538.627	568.761	501.432	626.959	536.320	554.420	76.313					
15-1392	COH	31-47568	0.000	0.000	0.000	0.000	0.000	0.000	--	--	--	--	--	--
15-1386	COH	31-47567	0.000	0.000	0.000	0.000	0.000	0.000	--	--	--	--	--	--
15-1385	COH	31-47569	0.000	0.000	0.000	0.000	0.000	0.000	--	---	--	--	--	--
Total withdrawals from COH			0.000	0.000	0.000	0.000	0.000	0.000	0.000					
Total withdrawals from all aquifers			**693.423**	**730.311**	**686.252**	**768.822**	**753.720**	**726.506**		**1,607.880**				

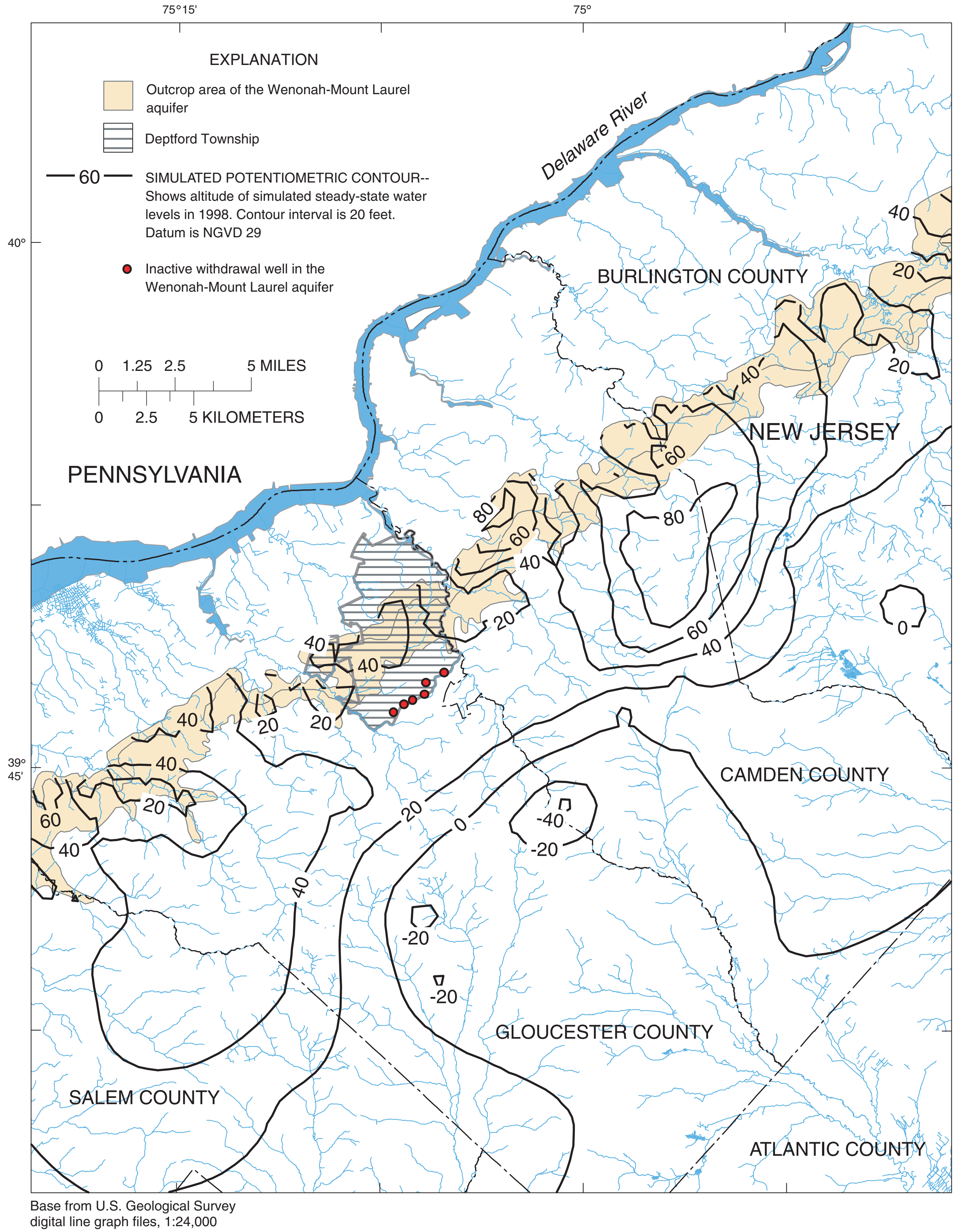


Figure 7. Simulated steady-state potentiometric surface of the Wenonah-Mount Laurel aquifer in and around Deptford Township, N.J., 1998.

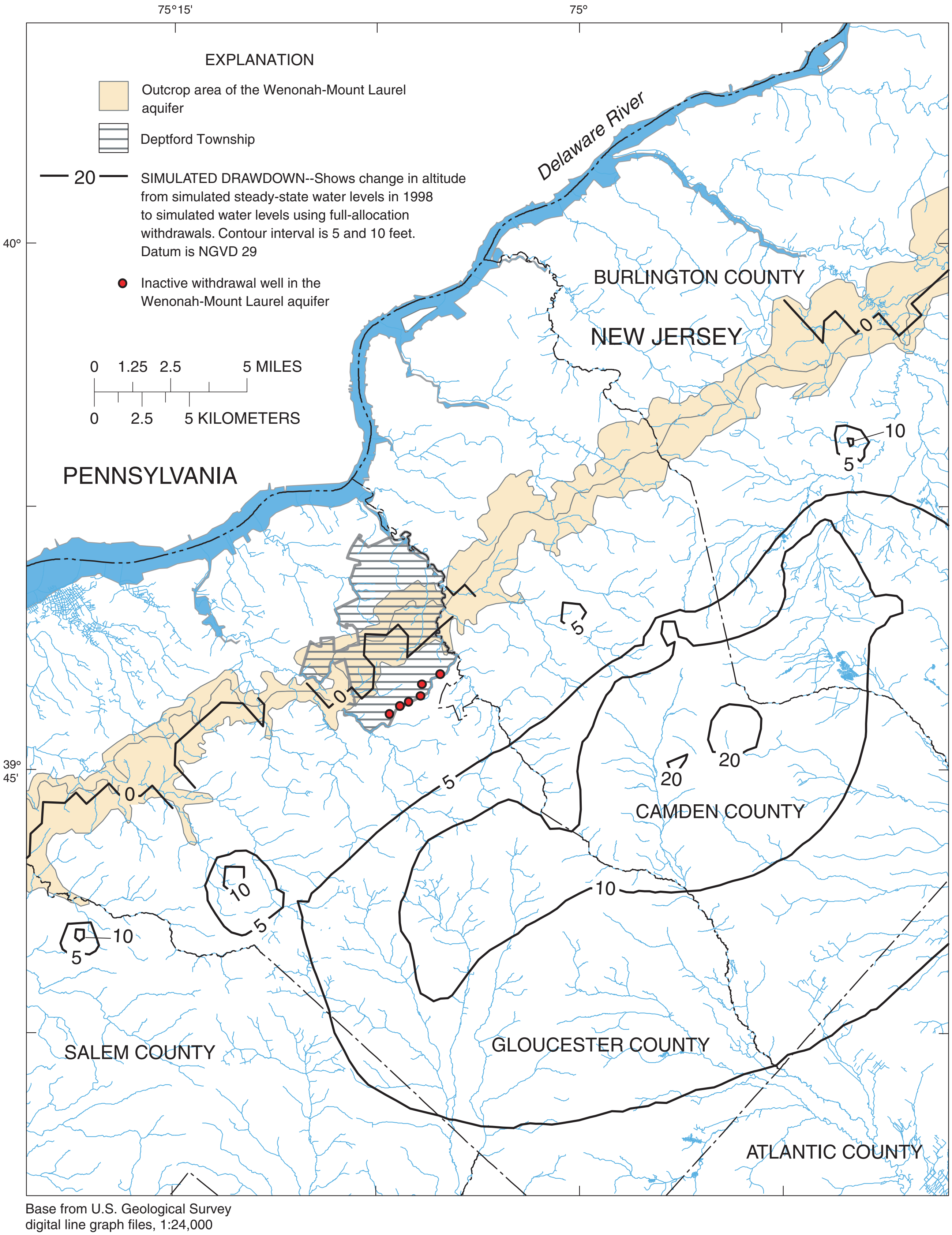
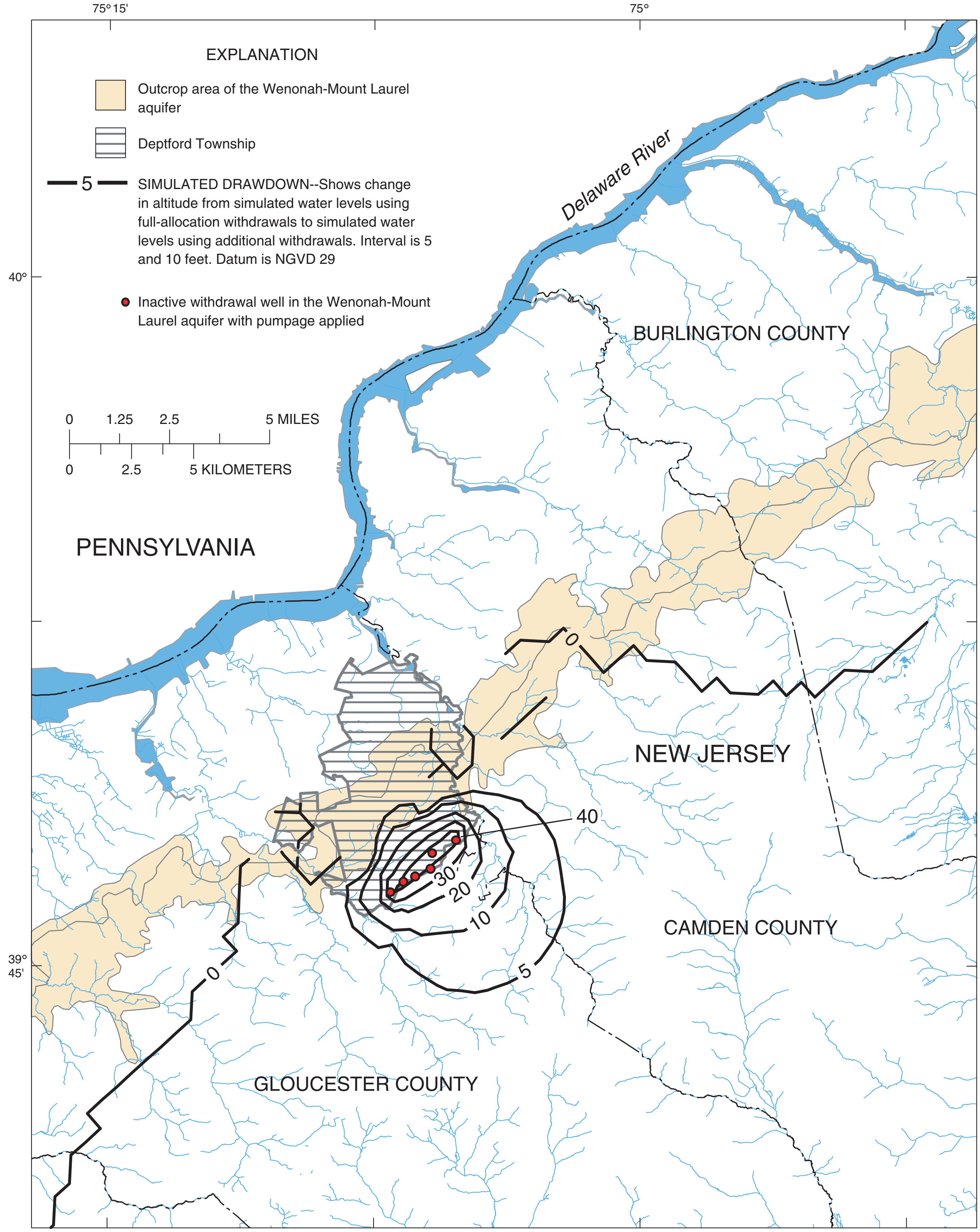


Figure 8. Simulated drawdown in the Wenonah-Mount Laurel aquifer in and around Deptford Township, N.J., showing change from simulated steady-state water levels in 1998 to simulated water levels in the full-allocation scenario.



Base from U.S. Geological Survey digital line graph files, 1:24,000

Figure 9. Simulated drawdown in the Wenonah-Mount Laurel aquifer in and around Deptford Township, N.J., showing change from simulated water levels in the full-allocation scenario to simulated water levels in the additional-withdrawal scenario.

the additional-withdrawal scenario were subtracted from the measured 1998 synoptic water levels (table 4) to estimate new water levels for these scenarios. The altitude of the top of the aquifer was then subtracted from the water level to estimate available drawdown.

In the full-allocation scenario, water levels range from about 10.4 to about 36.6 ft above the top of the aquifer. In the additional-withdrawal scenario, water levels in the six inactive Deptford Township withdrawal wells are below the top of the aquifer, indicating no available drawdown. Where the actual water levels are below the top of the aquifer, the resulting saturated thickness is less than the thickness of the aquifer; however, estimates of model transmissivity were based on the assumption that aquifer thickness is a reasonable estimate of aquifer saturated thickness. Therefore, the model transmissivity in the six withdrawal nodes is too high, causing simulated drawdowns to be smaller than drawdowns that would be simulated if model transmissivity were based on actual saturated thickness. Simulated drawdowns are expected to be underestimated only in close proximity to the withdrawal wells.

Sources of Water to Wells

Simulated ground-water-flow budgets for both the full-allocation and additional-withdrawal scenarios were analyzed to determine the effects of increased withdrawals on the ground-water-flow system in and around Deptford Township. Base-flow-separation and low-flow-correlation programs were used to calculate flow statistics for streamflow-gaging and low-flow partial-record stations, respectively, on streams that drain the outcrop of the Wenonah-Mount Laurel aquifer. The flow statistics were used as a baseline from which to estimate the potential effects of the two alternative withdrawal scenarios on streamflow. Calculated base flows were then compared with simulated base-flow values from the ground-water budgets to determine the effects of the withdrawals on surface-water flow.

Ground-Water Budgets

Water budgets were calculated from simulation results for the full-allocation and additional-withdrawal scenarios by using the computer program Zonebudget (Harbaugh, 1990). Eight zones, three of which are in the Wenonah-Mount Laurel aquifer, were designated in and downdip from the Wenonah-Mount Laurel aquifer outcrop and southeast of Deptford Township (fig. 10) to determine the effects of increased withdrawals on ground-water flow in selected areas. Results of the Zonebudget program for zones 1 to 5 for the full-allocation and additional-withdrawal scenarios are shown in table 5. Zone 1 (fig. 10) is in the Vincentown aquifer (where present) and overlies zones 2 to 4. Zones 2 to 4 are in the Wenonah-Mount Laurel aquifer (fig. 11). Zone 2 includes the aquifer outcrop area and the area surrounding the inactive Deptford Township withdrawal wells. Zone 3 is a narrow transition zone between the outcrop area (zone 2) and the downdip, confined part of the Wenonah-Mount Laurel aquifer (zone 4) where the 1998 synoptic water levels exhibited a steep gradient (fig. 4). Zone 5 is in the Englishtown aquifer system and underlies zones 2 to 4. Flows from zone 0 are horizontal flows into and out of the aquifer from outside the budget area. Flows from zones 6 and 7 are horizontal flow into the Vincentown aquifer (zone 1) and flow from the Englishtown aquifer system (zone 5), respectively. Zonebudget was used to calculate simulated ground-water flow into and out of each zone as well as to streams and wells.

The budgets calculated from the simulated flows for the two alternative withdrawal scenarios were compared, with a particular focus on zone 2 (table 5). Zone 2, which includes the Wenonah-Mount Laurel aquifer outcrop and the inactive withdrawal wells in Deptford Township pumped at 1.62 Mgal/d, is where the water budget changed the most. The budgets show that 46 percent of the Deptford Township withdrawals in the additional-withdrawal scenario (1.15 ft^3/s, or 0.74 Mgal/d) would originate from reduced stream base flow in the Wenonah-Mount Laurel outcrop and 35 percent (0.88 ft^3/s, or 0.57 Mgal/d) would result from increased downward flow from the overlying Vincentown aquifer. Five percent (0.13 ft^3/s, or 0.08 Mgal/d) would originate from a decrease in flow to the downdip areas of the Wenonah-Mount Laurel aquifer, and 5 percent (0.12 ft^3/s, or 0.08 Mgal/d) would be derived from a decrease in flow to the underlying Englishtown aquifer system. Additionally, 4 percent (0.11 ft^3/s, or 0.07 Mgal/d) would result from an increase in flow from the downdip areas of the Wenonah-Mount Laurel aquifer to the pumped wells and 4 percent (0.10 ft^3/s, or 0.06 Mgal/d) would result from decreased upward flow to the Vincentown aquifer (fig. 12).

Therefore, on the basis of the simulations, most of the water withdrawn from the Wenonah-Mount Laurel aquifer when the inactive withdrawal wells in Deptford Township are pumping would originate from the Wenonah-Mount Laurel aquifer outcrop and the Vincentown aquifer rather than from downdip parts of the Wenonah-Mount Laurel aquifer. The relatively low transmissivity of the Wenonah-Mount Laurel aquifer (500-1,000 ft^2/d) and the proximity of the wells to the outcrop area are the primary factors controlling the source of water to the pumped wells.

Base Flow

Estimated base flow at streamflow-gaging and low-flow partial-record stations on streams that drain the Wenonah-Mount Laurel aquifer outcrop was compared to the simulated "streams" budget term (table 5) to evaluate the potential reduction in stream base flow caused by the 1.62-Mgal/d withdrawals in the additional-withdrawal scenario. Because the wells are only about 1.25 mi from the Wenonah-Mount Laurel outcrop, streams that drain the outcrop area are the most likely

Table 4. Simulated available drawdown[1] in the inactive Wenonah-Mount Laurel aquifer withdrawal wells in Deptford Township, N.J., for full-allocation and additional-withdrawal scenarios.

[All measurements are in feet; well locations shown in figure 2; negative value indicates estimated water level is below the top of the Wenonah-Mount Laurel aquifer (G) or no available drawdown (H)]

Deptford Township well name	Model location		A	B	C	D	E	F	G	H
	Row	Column	Altitude of the top of Wenonah-Mount Laurel aquifer	Altitude of 1998 measured water level[2]	Drawdown between the simulated 1998 and full-allocation water levels	Estimated altitude of water level for the full-allocation withdrawal scenario [B – C]	Available drawdown for the full-allocation withdrawal scenario [D – A]	Drawdown between the simulated 1998 and additional-withdrawal water levels	Estimated altitude of water level for the additional-withdrawal scenario [B – F]	Available drawdown for the additional-withdrawal scenario [G – A]
B and E	24	89	10.71	48.04	0.70	47.34	36.63	44.01	4.03	-6.68
F	24	90	10.93	43.69	.82	42.87	31.94	45.67	-1.98	-12.91
C	24	91	14.26	39.34	.93	38.41	24.15	46.40	-7.06	-21.32
G	24	92	15.51	36.16	.94	35.22	19.71	47.17	-11.01	-26.52
D	24	93	13.26	24.54	.86	23.68	10.42	47.08	-22.54	-35.80

[1] Available drawdown is defined as the distance between the water level in the aquifer and the top of the aquifer.

[2] U.S. Geological Survey synoptic water-level data (Lacombe and Rosman, 2001)

Table 5. Simulated ground-water flows to and from budget zones in and around Deptford Township, N.J.

[ft^3/s, cubic feet per second; Mgal/d, million gallons per day; VNCN, Vincentown aquifer; MLRW, Wenonah-Mount Laurel aquifer; EGLS, Englishtown aquifer system; zone 0 designates horizontal flow into and out of the aquifer; --, not applicable; budget zones shown in figures 10 and 11; flow from zone 6 is vertical flow into the Vincentown aquifer; flow from zone 7 is vertical flow into the Englishtown aquifer system]

Simulated budget term	Flow				Ratio of flow in additional-withdrawal scenario to flow in full-allocation scenario (percent)	Percentage of the 1.62 Mgal/d withdrawn from the six inactive MLRW withdrawal wells in Deptford Township	Comments regarding the difference between the full-allocation and the additional-withdrawals scenarios
	Full-allocation scenario (ft^3/s)	Additional-withdrawal scenario (ft^3/s)	Difference in flows between the additional-withdrawal scenario and full-allocation scenario (ft^3/s)	Difference in flows between the additional-withdrawal scenario and full-allocation scenario (Mgal/d)			
Flow budget for zone 1 (Vincentown aquifer)							
IN:							
Recharge	0.65	0.65	0	0	100.00	0	
Zone 0 to 1	.15	.15	0	0	100.00	0	
Zone 2 to 1	.71	.61	-.10	-.06	85.92	4	Decrease in flow from the MLRW outcrop area
Zone 3 to 1	0	.01	.01	.01	--	0	
Zone 4 to 1	0	0	0	0	--	0	
Zone 6 to 1	16.02	16.84	.82	.53	105.12	33	Increase in flow from overlying aquifer
OUT:							
Streams	1.93	1.66	-0.27	-.17	86.01	11	Decrease in ground-water flow to streams overlying the VNCN outcrop
Zone 1 to 0	1.07	1.06	-.01	-.01	99.07	0	
Zone 1 to 2	6.98	7.86	.88	.57	112.61	35	Increase in flow to MLRW outcrop area
Zone 1 to 3	3.65	3.78	.13	.08	103.56	5	Increase in flow to MLRW transition zone
Zone 1 to 4	3.48	3.51	.03	.02	100.86	1	Increase in flow to MLRW confined zone
Zone 1 to 6	.42	.38	-.04	-.03	90.48	2	Decreased flow to overlying aquifers
Flow budget for zone 2 (Wenonah-Mount Laurel aquifer outcrop and vicinity with Deptford Township wells)							
IN:							
Recharge	9.72	9.72	0.00	0.00	--	0	
Zone 0 to 2	.37	.37	0	0	--	0	
Zone 1 to 2	6.98	7.86	.88	.57	112.61	35	Increase in flow from VNCN
Zone 3 to 2	.27	.38	.11	.07	140.74	4	Increase in flow from downdip MLRW
Zone 5 to 2	1.06	1.07	.01	.01	100.94	0	
OUT:							
Withdrawals	1.45	3.95	2.50	1.62	272.41	100	Six inactive Deptford Township wells
Streams	8.89	7.74	-1.15	-.74	87.06	46	Decrease in ground-water flow to streams overlying the MLRW outcrop
Zone 2 to 0	.49	.49	0	0	--	0	
Zone 2 to 1	.71	.61	-.10	-.06	85.92	4	Decrease in flow to the VNCN
Zone 2 to 3	.93	.80	-.13	-.08	86.02	5	Decrease in flow to downdip MLRW
Zone 2 to 5	5.93	5.81	-.12	-.08	97.98	5	Decrease in flow to EGLS

Table 5. Simulated ground-water flows to and from budget zones in and around Deptford Township, N.J.—Continued.

[ft^3/s, cubic feet per second; Mgal/d, million gallons per day; VNCN, Vincentown aquifer; MLRW, Wenonah-Mount Laurel aquifer; EGLS, Englishtown aquifer system; zone 0 designates horizontal flow into and out of the aquifer; --, not applicable; budget zones shown in figures 10 and 11; flow from zone 6 is vertical flow into the Vincentown aquifer; flow from zone 7 is vertical flow into the Englishtown aquifer system]

Simulated budget term	Flow: Full-allocation scenario (ft^3/s)	Flow: Additional-withdrawal scenario (ft^3/s)	Flow: Difference in flows between the additional-withdrawal scenario and full-allocation scenario (ft^3/s)	Flow: Difference in flows between the additional-withdrawal scenario and full-allocation scenario (Mgal/d)	Ratio of flow in additional-withdrawal scenario to flow in full-allocation scenario (percent)	Percentage of the 1.62 Mgal/d withdrawn from the six inactive MLRW withdrawal wells in Deptford Township	Comments regarding the difference between the full-allocation and the additional-withdrawals scenarios
Flow budget for zone 3 (Confined Wenonah-Mount Laurel aquifer)							
IN:							
Zone 0 to 3	0.15	0.16	0.01	0.01	106.67	0	
Zone 1 to 3	3.65	3.78	.13	.08	103.56	5	Increase in flow from VNCN
Zone 2 to 3	.93	.80	-.13	-.08	86.02	5	Decrease in flow from the MLRW outcrop area
Zone 4 to 3	.02	.02	0	0	--	0	
Zone 5 to 3	0	0	0	0	--	0	
OUT:							
Withdrawals	.14	.14	0	0	--	0	Existing MLRW wells
Zone 3 to 0	0	0	0	0	--	0	
Zone 3 to 1	0	.01	.01	.01	--	0	
Zone 3 to 2	.27	.38	.11	.07	140.74	4	Increase in flow to the MLRW outcrop area
Zone 3 to 4	2.15	2.06	-.09	-.06	95.81	4	Decrease in flow to the confined MLRW
Zone 3 to 5	2.19	2.19	0	0	--	0	
Flow budget for zone 4 (Confined Wenonah-Mount Laurel aquifer with existing withdrawals)							
IN:							
Zone 0 to 4	1.83	1.88	.05	.03	102.73	2	Increase in horizontal flow from outside the budget area
Zone 1 to 4	3.48	3.51	.03	.02	100.86	1	Increase in flow from the VNCN
Zone 3 to 4	2.15	2.06	-.09	-.06	95.81	4	Decrease in flow from MLRW transition zone
Zone 5 to 4	.87	.88	.01	.01	101.15	0	
OUT:							
Withdrawals	7.37	7.37	0	0	--	0	Existing MLRW wells
Zone 4 to 0	.01	.01	0	0	--	0	
Zone 4 to 1	0	0	0	0	--	0	
Zone 4 to 3	.02	.02	0	0	--	0	
Zone 4 to 5	.93	.93	0	0	--	0	

Table 5. Simulated ground-water flows to and from budget zones in and around Deptford Township, N.J.—Continued.

[ft^3/s, cubic feet per second; Mgal/d, million gallons per day; VNCN, Vincentown aquifer; MLRW, Wenonah-Mount Laurel aquifer; EGLS, Englishtown aquifer system; zone 0 designates horizontal flow into and out of the aquifer; --, not applicable; budget zones shown in figures 10 and 11; flow from zone 6 is vertical flow into the Vincentown aquifer; flow from zone 7 is vertical flow into the Englishtown aquifer system]

Simulated budget term	Flow: Full-allocation scenario (ft^3/s)	Flow: Additional-withdrawal scenario (ft^3/s)	Difference in flows between the additional-withdrawal scenario and full-allocation scenario (ft^3/s)	Difference in flows between the additional-withdrawal scenario and full-allocation scenario (Mgal/d)	Ratio of flow in additional-withdrawal scenario to flow in full-allocation scenario (percent)	Percentage of the 1.62 Mgal/d withdrawn from the six inactive MLRW withdrawal wells in Deptford Township	Comments regarding the difference between the full-allocation and the additional-withdrawals scenarios
Flow budget for zone 5 (Englishtown aquifer system)							
IN:							
Recharge	.99	.99	0	0	--	0	
Zone 0 to 5	.77	.79	.02	.01	102.60	1	Increase in horizontal flow from outside the budget area
Zone 2 to 5	5.93	5.81	-.12	-.08	97.98	5	Decrease in flow from MLRW outcrop area
Zone 3 to 5	2.19	2.19	0	0	--	0	
Zone 4 to 5	.93	.93	0	0	--	0	
OUT:							
Withdrawals	2.90	2.90	0	0	--	0	
Streams	1.20	1.20	0	0	--	0	
Zone 5 to 0	.53	.52	-.01	-.01	98.11	0	
Zone 5 to 2	1.06	1.07	.01	.01	100.94	0	
Zone 5 to 3	0	0	0	0	--	0	
Zone 5 to 4	.87	.88	.01	.01	101.15	0	
Zone 5 to 7	4.26	4.15	-.11	-.07	97.42	4	Decrease in flow to the underlying aquifer

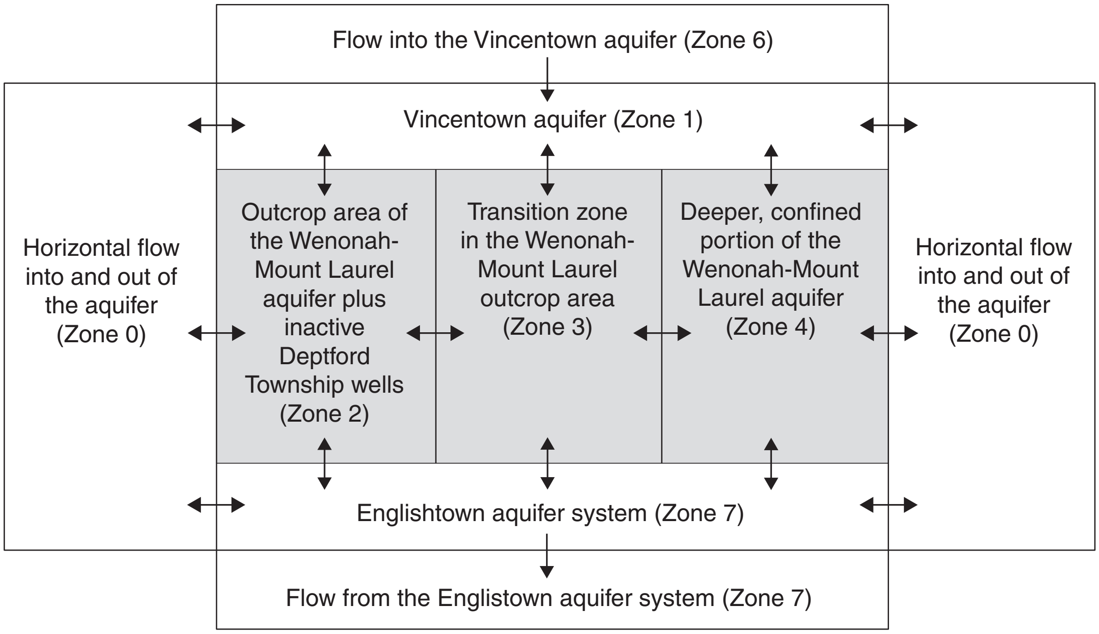


Figure 10. Generalized schematic diagram showing the zones in and around Deptford Township, N.J., used in the water-budget analysis of the New Jersey Coastal Plain. (Shaded area represents Wenonah-Mount Laurel aquifer.)

to be affected by the withdrawals and may be an important source of water to the pumped wells.

Estimation of Base Flow

No streamflow-gaging or low-flow partial-record stations are located within the Wenonah-Mount Laurel outcrop area within the area of influence of the inactive Deptford Township withdrawal wells (fig. 6). Therefore, records from the three streamflow-gaging stations and four low-flow partial-record stations that are closest to the area of influence were analyzed to determine mean annual base flow (fig. 13 and table 6). Base flow for the streamflow-gaging stations was calculated by using the RORA program (Rutledge, 1993). This program partitions the streamflow into overland flow, or direct runoff, and base flow, the ground-water component of streamflow. Mean annual discharge and base flow were calculated for the period of record (table 6).

Because only a finite number of discrete measurements is available for the low-flow partial-record stations, the mean annual discharge for those stations was calculated by using a low-flow-correlation program (MOVE.1—Maintenance of Variance Extension, Type 1) (Hirsch and others, 1982) that correlates the instantaneous low-flow discharge at a low-flow partial-record station with the concurrent mean daily discharge at a nearby streamflow-gaging station, or index station. An equation is produced of the “best-fit” line through the data points that represent the mean daily discharge at the index station and the measured discharge at the low-flow partial-record station. The equation of the best-fit line is then used to estimate, or predict, specific discharge statistics at the low-flow partial-record station on the basis of the values of the same discharge statistics measured at the index streamflow-gaging station. Estimates of base flow were calculated for each of the four low-flow partial-record stations by using base-flow statistics from an appropriate index station. Flow statistics for the streamflow-gaging stations are more reliable than those for the low-flow partial-record stations because more measurements are available.

For each station the percentage of the drainage basin that coincides with the Wenonah-Mount Laurel outcrop and the percentages that consist of aquifer and confining unit were determined (table 6). The statistics from one station, Still Run near Mickleton, N.J. (01476600), were selected for use in the estimation of base-flow reduction because nearly 76 percent of the drainage basin consists of the Wenonah-Mount Laurel outcrop (table 6, fig. 13). In addition, mean annual base flow at this site is 1.05 $(ft^3/s)/mi^2$, which is nearly identical to the average base flow for all seven sites (1.09 $(ft^3/s)/mi^2$). The period of record for this station is shorter than those for the other two streamflow-gaging stations, but the record is considered good (R.D. Schopp, U.S. Geological Survey, oral commun., 2003). Because the period of record is short and includes the 1960’s drought, base flow at this station was compared with that at another streamflow-gaging station with a long period of record that was operating at the same time. The base-flow program was run for the Salem River at Woodstown, N.J., streamflow-gaging station (01482500) for its entire period of record, 1942-84, to obtain mean streamflow and mean base-flow statistics. The base-flow program was run again for the Salem River at Woodstown station for the period of record corresponding to that of Still Run near Mickleton (1958-65) for comparison.

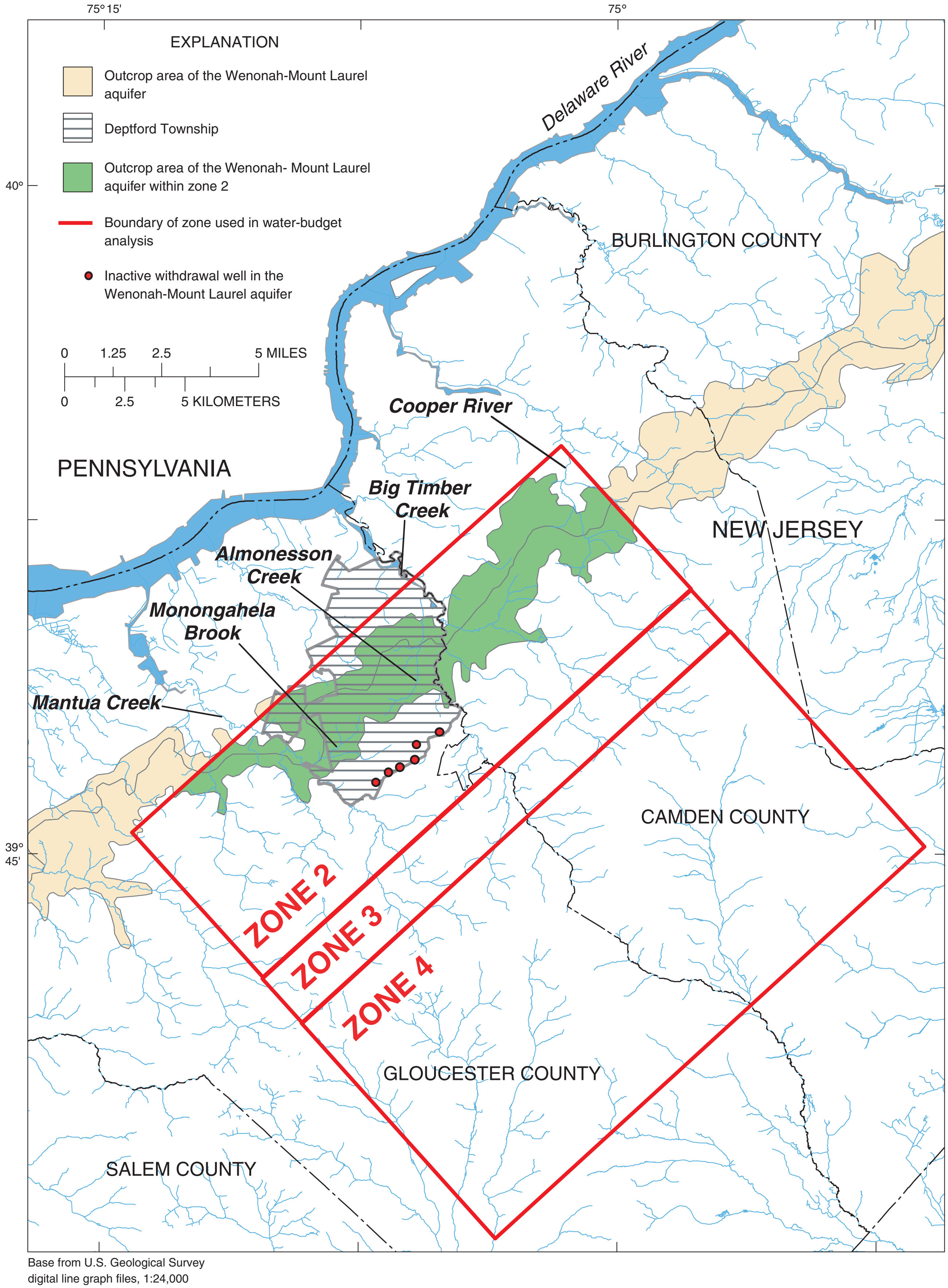


Figure 11. Map view of horizontal section through zones 2, 3, and 4 in and around Deptford Township, N.J., used in the water-budget analysis of the New Jersey Coastal Plain.

Table 6. Summary of discharge statistics for selected U.S. Geological Survey streamflow-gaging stations and results of low-flow correlations for low-flow partial-record stations that drain a portion of the Wenonah-Mount Laurel aquifer, near Deptford Township, N.J.

[mi^2, square mile; ft^3/s, cubic feet per second; in/yr, inches per year; station locations shown in figure 13]

Station name	Station number	Drainage area (mi^2)	Period of record	Mean annual discharge (ft^3/s)	Mean annual discharge ($(ft^3/s)/mi^2$)	Mean annual discharge (in/yr)	Mean annual base flow (ft^3/s)	Mean annual base flow ($(ft^3/s)/mi^2$)	Mean annual base flow (in/yr)	Percent base flow	Percentage of drainage area: Wenonah-Mount Laurel aquifer	Percentage of drainage area: Aquifer	Percentage of drainage area: Confining unit	Comments
Streamflow-gaging station														
South Branch Pennsauken Creek at Cherry Hill, N.J.	01467081	8.98	1968-75, 1978-2000	18.52	2.06	28.02	9.02	1.00	13.64	48.7	38	64.1	35.8	
Cooper River at Haddonfield, N.J.	01467150	17.0	1988-2000	28.63	1.68	22.88	14.80	.87	11.82	51.7	19.6	83.2	16.8	
Still Run near Mickleton, N.J.	01476600	3.98	1958-65	5.35	1.34	18.26	4.16	1.05	14.21	77.8	75.9	90.1	9.8	
Low-flow partial-record station														
North Branch Cooper River near Marlton, N.J.	01467160	5.34	1965-69, 1971, 1988-2000	7.25	1.36	18.44	5.93	1.11	15.08	81.8	3.8	61.0	39.0	Index station used in correlation is Mantua Creek at Pitman, N.J. (01475000)
North Branch Cooper River at Ellisburg, N.J.	01467180	10.5	1964-69, 1971-72, 1977, 1988-2000	10.95	1.04	14.17	9.89	.94	12.79	90.3	27.2	67.7	32.3	Index station used in correlation is Maurice River at Norma, N.J. (01411500)
Cooper River at Lawnside, N.J.	01467140	12.7	1964-72, 1988-2000	18.84	1.48	20.15	16.22	1.28	17.35	86.1	10.3	84.0	16.0	Index station used in correlation is Mantua Creek at Pitman, N.J. (01475000)
Basgalore Creek at Russell Mills Road near Swedesboro, N.J.	01477130	3.30	1957, 1966, 1994-97	6.08	1.84	25.03	4.63	1.40	19.06	76.2	23.7	72.3	27.7	Index station used in correlation is Raccoon Creek near Swedesboro, N.J. (01477120)

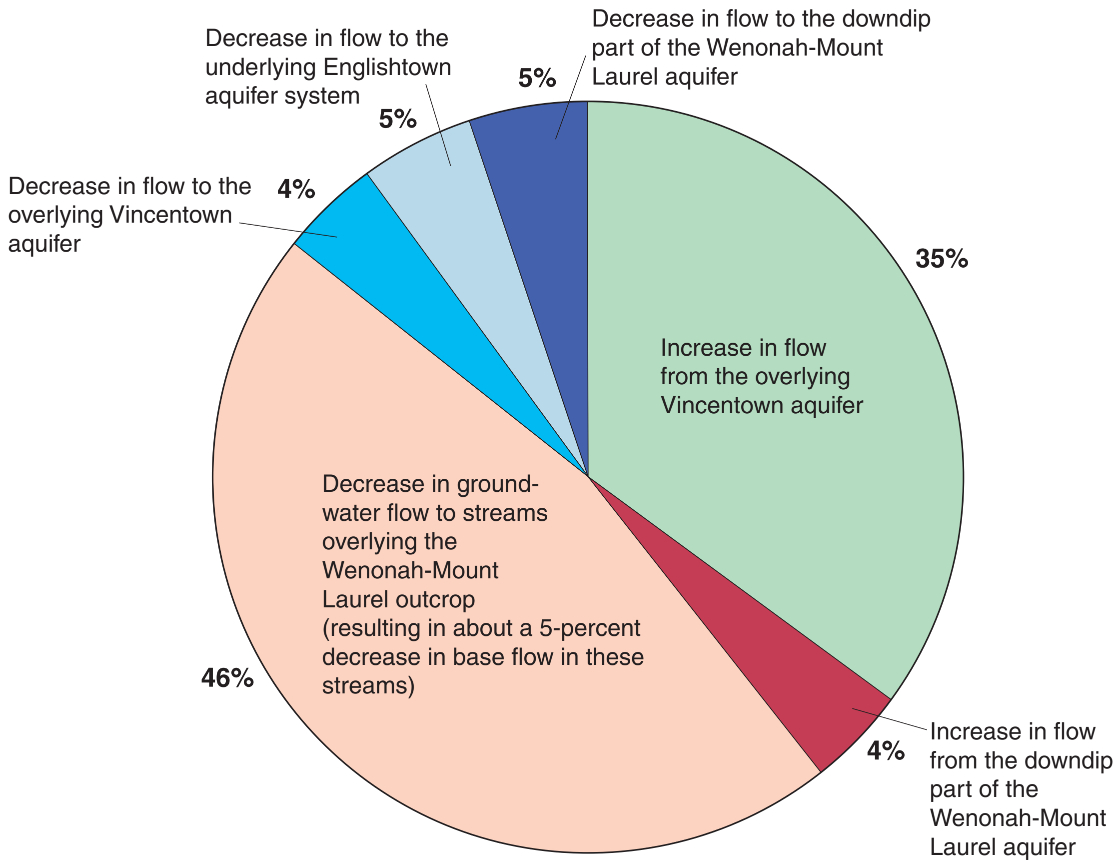


Figure 12. Simulated sources of water to the inactive Deptford Township withdrawal wells in the additional-withdrawal scenario. (Sources of water totals 99 percent as a result of independent rounding to the nearest percent.)

Mean base-flow values for Salem River at Woodstown for both periods (1942-84 and 1958-65) were nearly identical (11.41 and 11.38 ft^3/s, respectively), but mean streamflow was higher for the entire period of record (19.17 ft^3/s) than for 1958-65 (17.68 ft^3/s), indicating that the ground-water contribution to streamflow is relatively constant and that overland flow accounts for nearly all the variability in mean streamflow and percent base flow. Therefore, although the mean annual streamflow and percent base flow for the Still Run station probably are lower than they would have been had the period of record not included the drought, the value for mean annual base flow is a good estimate for that station. The mean annual base flow at Still Run (1.05 $(ft^3/s)/mi^2$) was assumed for all streams draining the Wenonah-Mount Laurel aquifer outcrop. Using this base-flow value, the outcrop area within budget zone 2 (22.61 mi^2) would yield 23.7 ft^3/s of base flow.

Estimated Base-Flow Reduction

Simulation results for zone 2 show base flow to streams in 1998 is 9.00 ft^3/s. Simulated base flow in the full-allocation and additional-withdrawal scenarios is 8.89 ft^3/s and 7.74 ft^3/s, respectively (table 5). The change in base flow from 1998 conditions to the full-allocation scenario (0.11 ft^3/s) is small; the change in base flow between the full-allocation and the additional-withdrawal scenarios, however, is 1.15 ft^3/s. This 1.15-ft^3/s decrease is a 4.9-percent reduction in ground-water flow to streams from the full-allocation scenario to the additional-withdrawal scenario (table 5).

The total simulated discharge to streams in the full-allocation scenario (8.89 ft^3/s (table 5)) is considerably less than the estimated base flow from the outcrop area (23.7 ft^3/s). The model simulated from 18 to 69 percent of the actual estimated base flow at the streamflow-gaging stations and low-flow partial-record stations. The value of simulated discharge to streams is closer to the value of estimated base flow at stations in basins that consist largely of the Kirkwood-Cohansey aquifer system outcrop. For stations in basins that consist largely of confining-unit outcrops, however, simulated discharge to streams is only a small percentage of estimated stream base flow. Simulated discharge to streams in these latter basins more closely resembles recharge to the deeper, confined parts of the aquifers than recharge to the outcrops. Despite this discrepancy, the simulated regional change in flow to streams is a reasonable estimate of the amount of water diverted from streams in the Deptford Township area in the additional-withdrawal scenario. Changes in flow to individual streams, however, cannot be verified without additional data.

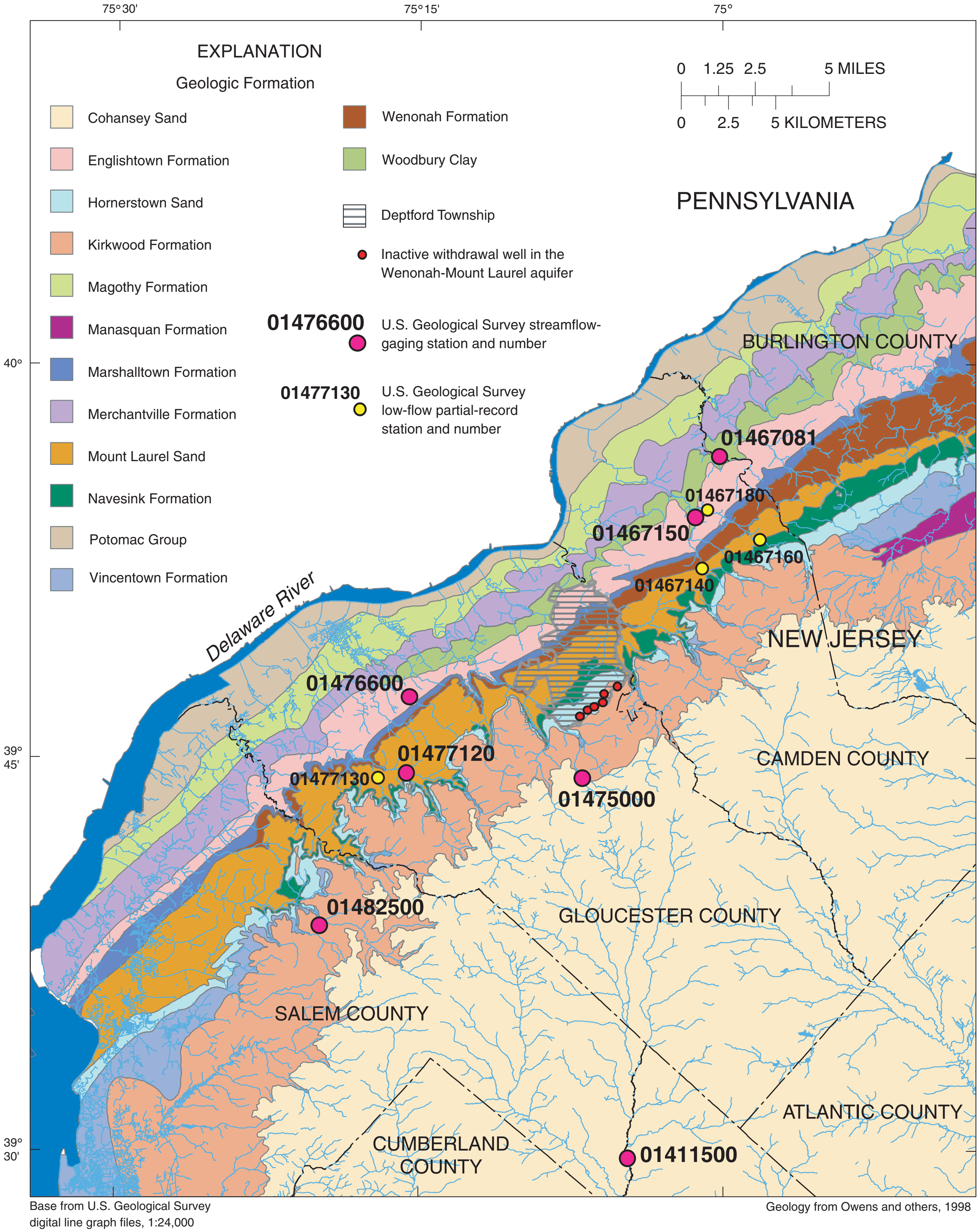


Figure 13. Geology in and around Deptford Township, N.J., and location of the U.S. Geological Survey streamflow-gaging stations and low-flow partial-record stations used in the base-flow analysis.

Limitations of the Model

All models are an approximation of the actual ground-water-flow system and are based on simplified representations of complex heterogeneous systems. Assumptions such as isotropy and vertical homogeneity within each layer are examples of simplified representations that can be sources of simulation errors. The presence of local-scale hydrologic features not represented in the model; the use of estimated values for model parameters such as stream base flow, stream leakance, and the transmissivity of the unconfined aquifer for areas where data are limited; and the use of averaged values as input data also may lead to errors.

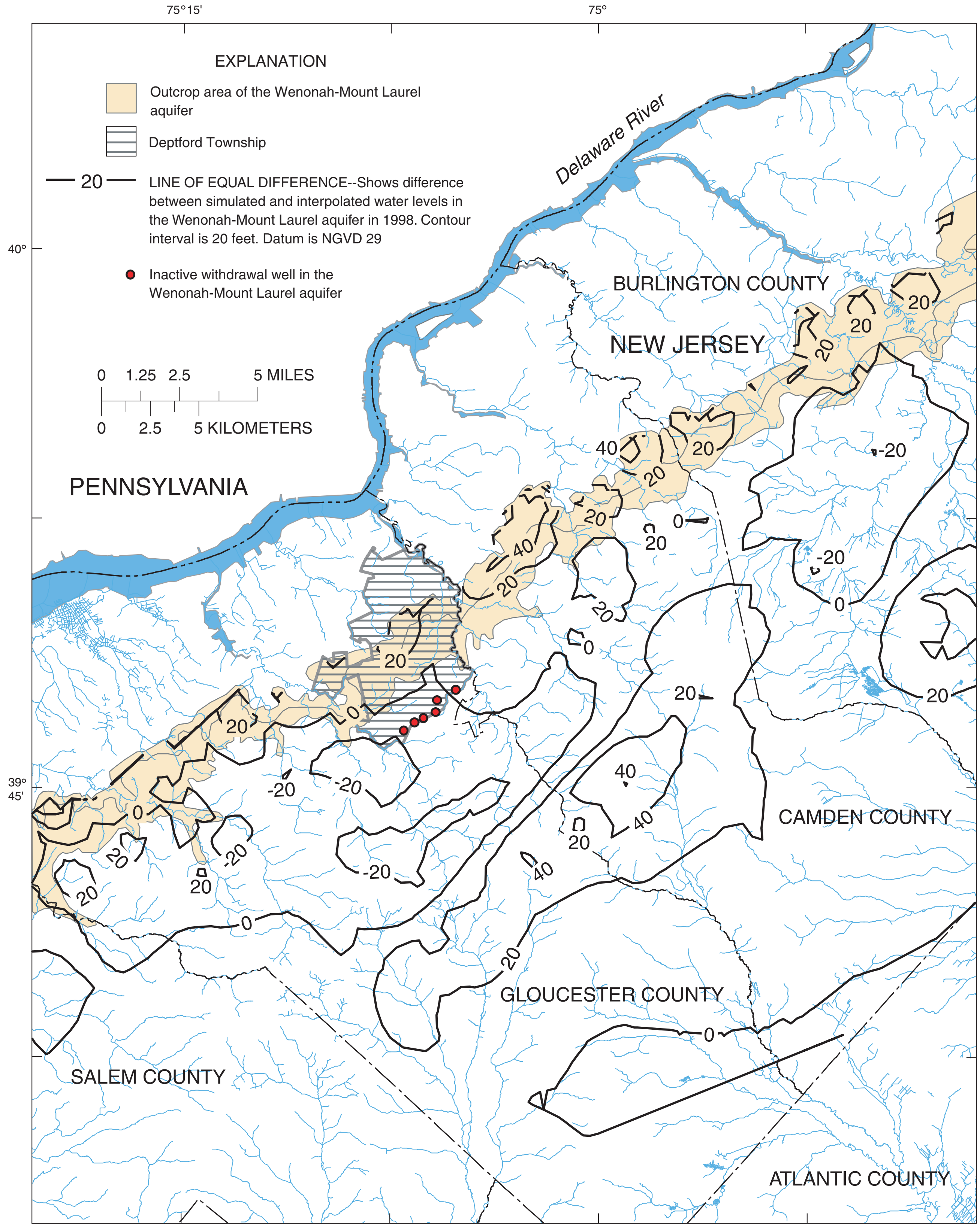
To quantify these errors, simulated water levels in the Wenonah-Mount Laurel aquifer under 1998 conditions (fig. 7) were compared with water levels interpolated from contours drawn from water levels measured during the Coastal Plain-wide synoptic water-level survey in the fall of 1998 (fig. 4). The median difference between simulated and interpolated water levels (water-level residuals) in 2,214 model cells in and around Deptford Township is 7.1 ft (range, –38 to 58 ft) (fig. 14), and 75 percent of the absolute differences are less than 17.6 ft. The mean difference between simulated and interpolated water levels is 7.6 ft, and the mean absolute difference is 12.3 ft. Even though the differences between simulated and interpolated heads are large in localized areas, both of these values are small in comparison to the range of water levels (-60 to 80 ft) that the model is intended to reproduce (fig. 4). In general, the model dampens both the extreme high and extreme low water levels. The simulated high water levels northeast and southwest of Deptford Township are as much as 20 ft lower than the interpolated water levels in some places. Similarly, the simulated cones of depression downdip from Deptford Township are as much as 40 ft higher than interpolated values, and simulated water levels in the outcrop generally are 20 to 40 ft higher than interpolated water levels. These differences between simulated and interpolated water levels may be a result of contour interpretation, interpolation errors, limited water-level data for the outcrop area and other parts of the study area, unreported ground-water withdrawals, model error, or a combination of these factors.

In this study, simulations were conducted with the revised RASA model, which has been used successfully to evaluate the regional effects of increases in ground-water withdrawals on water levels in confined aquifers (Battaglin and Hill, 1989; Navoy, 1994; Martin, 1998; Voronin, 2003). The simulated effects of a local well field on the regional flow system and the resulting estimate of the sources of water to wells are considered to be reasonable because (1) the area of influence of the proposed withdrawals (fig. 6) is regional in extent, and (2) the degree of discretization in the revised RASA model, both at the inactive Deptford Township wells and between the wells and their source areas, is sufficiently small. The actual effects of withdrawals from the Deptford Township wells on local water levels and flow, however, are uncertain until verified by water-level and base-flow measurements. Therefore, although simulated water levels and flows in the outcrop cannot be considered well documented or precise, differences in simulated water levels and in the magnitude and direction of flows between the full-allocation and additional-withdrawal scenarios are considered to be reliable and to provide a reasonable estimate of the sources of water to wells.

Summary and Conclusions

Since 1996, when the NJDEP restricted ground-water withdrawals from the Potomac-Raritan-Magothy aquifer system in the southern New Jersey Coastal Plain as a result of excessive drawdown, Coastal Plain communities have been interested in developing alternate sources of water supply for their residents. The use of ground water from areas near the updip parts of the overlying confined aquifers where withdrawals are not restricted is being considered to meet the demand for drinking water. Three aquifers that potentially could be used for water supply in the southern New Jersey Coastal Plain are the Vincentown aquifer, the Wenonah-Mount Laurel aquifer, and the Englishtown aquifer system; of these three, the Wenonah-Mount Laurel aquifer is the thickest and most coarse grained in the study area. Currently (2005), all production wells that tap the Wenonah-Mount Laurel aquifer between northern Burlington County and Salem County are within 10 mi of the downdip (southeastern) extent of the Wenonah-Mount Laurel aquifer outcrop. In 1998, water withdrawn for public supply from the Wenonah-Mount Laurel aquifer—most from wells 3 to 10 mi from the downdip extent of the aquifer outcrop—totaled 9.01 Mgal/d. Interest in developing new sources of water has raised questions however, concerning the sources of water to wells that would withdraw from the updip portions of the aquifer, 1 to 3 mi from the downdip extent of the aquifer outcrop. Therefore, the USGS, in cooperation with the NJDEP, conducted a study to examine the effects of increased withdrawals from the updip portion of the aquifer on ground-water flow to streams and wetlands, and (or) downdip to deeper, confined portions of the Wenonah-Mount Laurel aquifer. Of particular interest is whether the primary source of water withdrawn from updip wells is likely to be the downdip, confined part of the aquifer or the aquifer outcrop. The results of this study will be useful in aiding water managers to understand the effects of withdrawals near the outcrops of regional confined aquifers in other parts of the Northern Atlantic Coastal Plain.

The study area includes Gloucester and Camden Counties and adjacent portions of Salem and Burlington Counties in the Coastal Plain of New Jersey. Deptford Township is in the northeastern part of Gloucester County, bordering Camden County. The Wenonah-Mount Laurel aquifer outcrop covers nearly 8 mi^{2}, or about 46 percent of Deptford Township's 17.56-mi^2 area. Deptford Township Municipal Utilities Authority (MUA) owns six currently inactive withdrawal



Base from U.S. Geological Survey digital line graph files, 1:24,000

Figure 14. Difference between simulated and interpolated water levels in the Wenonah-Mount Laurel aquifer in and around Deptford Township, N.J., 1998.

wells in the Wenonah-Mount Laurel aquifer at the southeastern boundary of Deptford Township, 1.25 mi from the Wenonah-Mount Laurel aquifer outcrop. These wells were included in the model simulation to examine the effects of their potential withdrawals on the ground-water and surface-water-flow systems and to determine the sources of water to these wells.

An existing ground-water-flow model was used to simulate steady-state water levels in and around Deptford Township in 1998, as well as two alternative ground-water withdrawals scenarios. Initially, steady-state water levels were simulated using 1998 withdrawals. The results of this simulation provide a baseline with which to compare the results of the other simulations and the synoptic water levels measured in the Coastal Plain in 1998. The first of the two alternative withdrawal scenarios (full allocation) is a simulation of water levels that could occur if 1998 conditions were modified so that ground-water withdrawals from 45 wells in and around the Deptford Township area were equal to the maximum allocated withdrawals. The second withdrawal scenario (additional withdrawals) is a simulation of water levels resulting from 1998 withdrawals and full-allocation withdrawals from the 45 wells plus an additional 1.62 Mgal/d pumped from the six inactive Deptford Township MUA withdrawal wells screened in the Wenonah-Mount Laurel aquifer near its updip limit in Deptford Township.

Simulated steady-state water-level altitudes in Deptford Township in 1998 are 30 to 40 ft above NGVD 29. Small cones of depression (20 to 40 ft below NGVD 29) are present downdip from Deptford Township. The model simulated relatively high water levels (40 to 80 ft above NGVD 29) in areas northeast and southwest of Deptford Township, possibly because the Wenonah-Mount Laurel aquifer in this area is hydraulically connected to the overlying unconfined aquifer.

Simulated drawdown in the full-allocation scenario, which is the changes from the simulated 1998 water levels to the simulated full-allocation water levels, is zero or near zero in Deptford Township. Changes are greatest in a broad area downdip from Deptford Township, where drawdowns of 5 to 10 ft are common; maximum drawdown at the center of the cone of depression is 20 ft. Water levels declined as much as 10 ft around individual wells whose current withdrawals are only a small percentage of their allotted allocation.

Simulated drawdown in the additional-withdrawal scenario, which is the changes from the full-allocation water levels to the additional-withdrawal water levels, is greater than 40 ft and is centered around the six inactive withdrawal wells in Deptford Township. Drawdown is 5 ft approximately 3.75 miles downdip from the wells and 2 miles updip, into the outcrop.

A computer program was used to calculate water budgets from the full-allocation and additional-withdrawal simulation results. The budgets for the two model scenarios were compared, with particular focus on budget zone 2, which represents the outcrop of the Wenonah-Mount Laurel aquifer and the area surrounding the inactive Deptford Township withdrawal wells. Results of the comparison show that 46 percent of the Deptford Township withdrawals in the additional-withdrawal scenario would originate from reduced stream base flow in the Wenonah-Mount Laurel outcrop and 35 percent would result from increased downward flow from the overlying Vincentown aquifer. Five percent would originate from a decrease in flow to the downdip areas of the Wenonah-Mount Laurel aquifer, and 5 percent would be derived from a decrease in flow to the underlying Englishtown aquifer system. Four percent would result from an increase in flow from the downdip areas of the Wenonah-Mount Laurel aquifer to the pumped wells. The remaining 4 percent represented decreased upward flow to the Vincentown aquifer.

Three streamflow-gaging stations and four low-flow partial-record stations in the Deptford Township area were analyzed to determine mean annual base flow for comparison to the water-budget values. Statistics from only one station, Still Run near Mickleton, N.J., were selected for use in the estimation of base-flow reduction because the outcrop of the Wenonah-Mount Laurel aquifer occupies nearly 76 percent of the drainage basin's area. Mean annual base flow at this station was assumed for all streams draining the Wenonah-Mount Laurel aquifer outcrop. Using this base-flow value, the outcrop area within budget zone 2 would yield 23.7 ft^3/s of base flow. For budget zone 2, model results include a 1.15-ft^3/s decrease (a 4.9-percent reduction) in ground-water flow to streams from the full-allocation scenario to the additional-withdrawal scenario.

On the basis of the simulations, the primary sources of the water withdrawn from the Wenonah-Mount Laurel aquifer when the inactive withdrawal wells in Deptford Township are pumped are the Wenonah-Mount Laurel aquifer outcrop and the Vincentown aquifer rather than the downdip parts of the Wenonah-Mount Laurel aquifer. The relatively low transmissivity of the Wenonah-Mount Laurel aquifer and the proximity of the wells to the outcrop area are the primary factors controlling the source of water for the withdrawals.

The accuracy of simulation results depends largely on the accuracy with which the model represents local parameters such as stream base flow, stream leakance, and the transmissivity of the unconfined aquifer. Although the simulations in this study were conducted with the revised RASA model, a regional model, the simulated effects of a local well field on the regional flow system and the resulting estimate of the sources of water to wells are considered to be reasonable because (1) the area of influence of the proposed withdrawals is regional in extent, and (2) the degree of discretization in the model, both at the inactive Deptford Township wells and between the wells and their source areas, is sufficiently small. The actual effects of withdrawals from the Deptford Township wells on local water levels and flow, however, are uncertain until verified by water-level and base-flow measurements. Therefore, although simulated water levels and flows in the outcrop cannot be considered well documented or precise, differences in simulated water levels and in the magnitude and direction of flows between the full-allocation and additional-withdrawal scenarios are considered to be reliable and to provide a reasonable estimate of the sources of water to wells.

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