SIMULATION OF GROUND-WATER-FLOW PATTERNS AND AREAS CONTRIBUTING RECHARGE TO STREAMS AND WATER-SUPPLY WELLS IN A VALLEY-FILL AND CARBONATE-ROCK AQUIFER SYSTEM, SOUTHWESTERN MORRIS COUNTY, NEW JERSEY

By Robert S. Nicholson and Martha K. Watt

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ILLUSTRATIONS

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Flow	
foot per year (ft/yr)	0.3048	meter per year
gallons per minute (gal/min)	0.06308	liters per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
million gallons per year (Mgal/yr)	3,785	cubic meters per year
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meters per day

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

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ABSTRACT

Regulatory programs to evaluate and control potential sources of contamination of public supply wells require knowledge of recharge mechanisms, flow patterns, and areas contributing recharge to wells. Ground-water-flow patterns and areas contributing recharge to wells and streams in a complex valley-fill and carbonate-rock aquifer system in southwestern Morris County, New Jersey, were simulated by using a three-dimensional numerical ground-water-flow model. Areas contributing recharge to supply wells under recent, projected 2005, and full-allocation pumping conditions were delineated and areas contributing recharge that reaches supply wells in 5- and 12-year time periods were identified. Limitations of the analysis include factors related to conceptual-model reliability, model discretization, and parameter error.

Withdrawals from the aquifer system are increasing in large part to meet growing water demands of communities in southwestern and central Morris County. As withdrawals increase, areas contributing recharge to wells expand, displacing areas that previously contributed recharge to streams.

The area contributing recharge to a shallow well typically is located near the well. The area contributing recharge to a deeper well typically consists of a highly irregular or fragmented area, parts of which can be located thousands of feet from the well. Ground-water travel time from distant contributing recharge areas to deep wells typically is many decades or hundreds of years, whereas travel time to shallow wells from local contributing recharge areas typically is shorter.

The aquifer system in the study area consists of three aquifers--an upper valley-fill aquifer, a lower valley-fill aquifer, and an underlying carbonate-rock aquifer. Recharge occurs as direct infiltration of precipitation through the valley floor and as seepage from surface water. Irregular aquifer boundaries and complex hydraulic gradients result in ground-water-flow patterns that are tortuous in places. Flow patterns in the upper valley-fill aquifer are dominated by the effects of surface-water features and aquifer boundaries, and most water in the upper valley-fill aquifer discharges to streams. Flow patterns in the lower valley-fill and carbonate-rock aquifers in the study area are dominated by the effects of supply wells, aquifer boundaries, and zones of varying aquifer permeability.

Withdrawals from the aquifer system in the study area averaged 4.2 Mgal/d during 1991-95 and are projected to increase by 38 percent, to about 5.8 Mgal/d, by 2005. If 1996 allocations were fully utilized, withdrawals would reach 6 Mgal/d, a 43-percent increase over recent (1991-95) withdrawals. The areas contributing recharge to wells under projected 2005 and full-

allocation conditions were larger than those under recent conditions. Areas contributing recharge to wells under projected 2005 and full-allocation conditions were generally similar because ground-water withdrawals under these respective conditions were similar. Differences in contributing areas and travel times under different conditions are attributable to differences in pumping rates.

INTRODUCTION

In the New Jersey Highlands, the **valley-fill**[1] and **carbonate-rock** aquifer system extending from Hoffmans to Picatinny Arsenal (fig. 1) has become an increasingly important source of water supply for communities in southwestern and central Morris County. The hydrogeology of the aquifer system and surrounding area were described in a previous investigation by Nicholson and others (1996), which included the development and application of a numerical ground-water-flow model (fig. 1). Eighteen water-supply wells tap the aquifer system in the present study area which includes the headwaters of Drakes Brook and the Lamington River (fig. 1). These wells provide water to communities in and east of the study area. As these communities continue to experience residential, commercial, and industrial growth, withdrawals from the aquifer system in the study area are expected to increase.

The study area includes several potential sources of ground-water contamination. Efforts to protect and monitor the quality of ground-water resources in the study area have been constrained by a limited understanding of recharge areas and flow patterns. This study was undertaken to improve this understanding.

The U.S. Environmental Protection Agency (USEPA) instituted the **Wellhead Protection Program** to provide a regulatory framework for the evaluation and control of potential sources of contamination of public water-supply wells. A critical element of such evaluations is the determination of the **areas contributing recharge** to supply wells. In hydrogeologically simple settings and circumstances, simplified **analytical-modeling** methods or arbitrary approaches are sometimes used to estimate these areas (U.S. Environmental Protection Agency, 1987; New Jersey Department of Protection and Energy, 1991). In complex hydrologic-flow systems, such as the valley-fill and carbonate-rock aquifer system in southwestern Morris County, New Jersey (fig. 1), areas contributing recharge to wells can be estimated more reliably by the application of **numerical-modeling** techniques.

The U.S. Geological Survey (USGS), in cooperation with Randolph Township, conducted a study of the aquifer system in which numerical-modeling techniques were used to estimate areas contributing recharge to all ground-water discharges from the study area. This study is part of the Alamatong Wellhead Protection Demonstration Project, which was administered by Randolph Township as part of the New Jersey Department of Environmental Protection (NJDEP) Wellhead Protection Program. The NJDEP Wellhead Protection Program was initiated under the auspices of the USEPA Wellhead Protection Program, which requires each state to implement programs to

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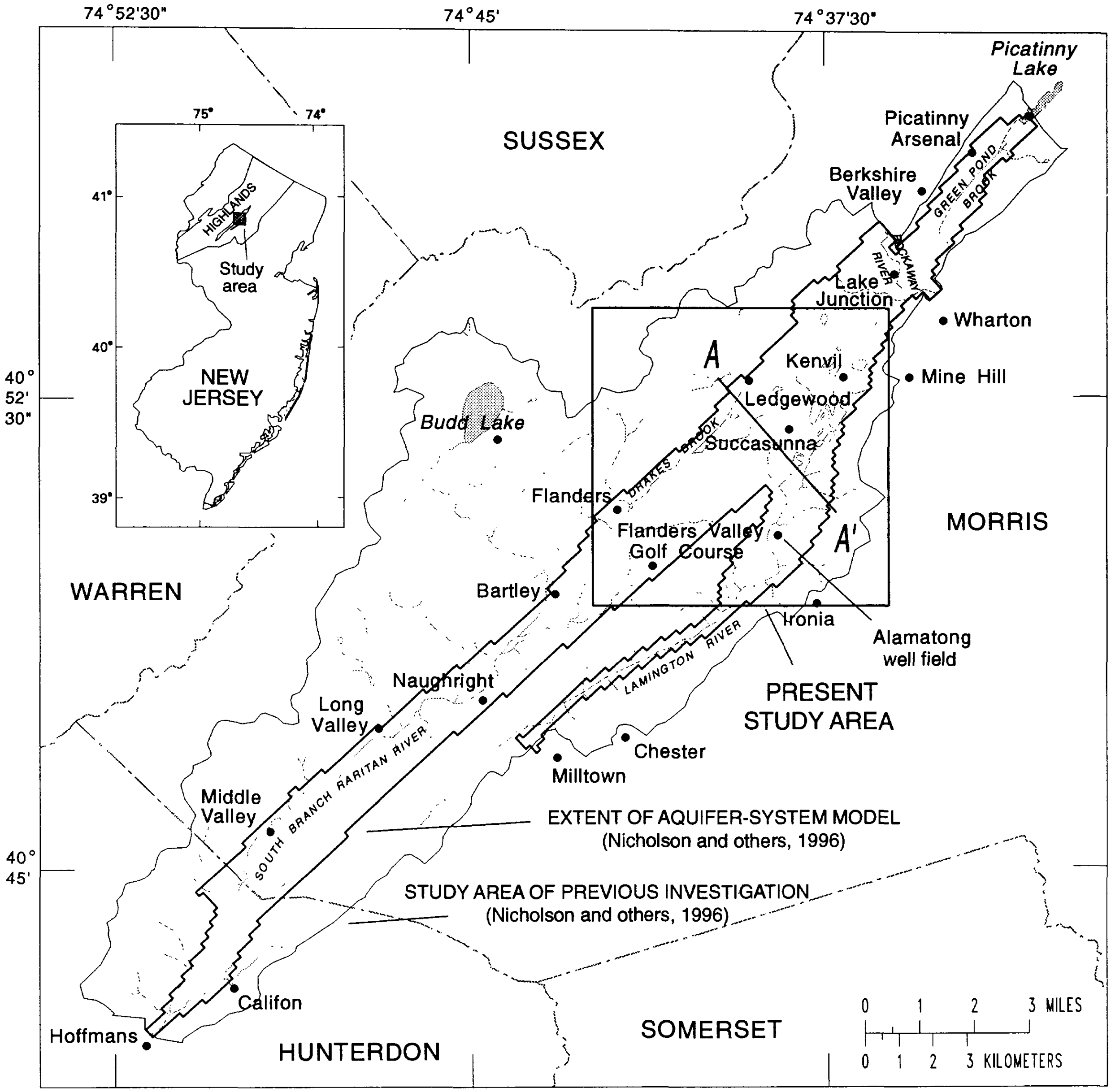
[1]Terms in bold are defined in the glossary.



EXPLANATION

A——A' TRACE OF GENERALIZED HYDROGEOLOGIC SECTION

Figure 1. Location of valley-fill and carbonate-rock aquifer study area, southwestern Morris County, in the New Jersey Highlands, extent of model grid, and trace of generalized hydrogeologic section.

delineate **wellhead protection areas**. Other participants in the Alamatong Wellhead Protection Demonstration Project include Chester Township, Roxbury Township, the Morris County Municipal Utilities Authority, and the Upper Raritan Watershed Association.

Purpose and Scope

This report presents the techniques and results of numerical simulations used to describe ground-water-flow patterns and to estimate areas contributing recharge to wells in the study area. Simulated ground-water-flow patterns in the three aquifer units are described, and a ground-water budget that quantifies ground-water flow into and out of the aquifer system in the study area is presented. Estimated areas contributing recharge to wells and streams under three alternative flow conditions--recent, projected 2005, and full allocation--are identified and compared. **Time-of-travel** from areas contributing recharge to water-supply wells is calculated, and the areas contributing recharge to the wells in 5- and 12-year time periods are presented. Assumptions and inherent limitations of the analysis are discussed.

Previous Investigations

The USGS, in cooperation with the NJDEP, conducted an investigation of the hydrogeology of the valley-fill and carbonate-rock aquifer system during 1987-91 (Nicholson and others, 1996) in which critical features of the aquifer system, including hydrogeologic framework (geometry), water levels, hydraulic characteristics, geochemistry, **base flow**, and supply-well pumping rates, were assessed. A three-dimensional numerical **ground-water-flow model** of the aquifer system was developed by using the USGS modular model (MODFLOW) code by McDonald and Harbaugh (1988). The model was calibrated and used to determine effects of withdrawals on water levels, ground-water-flow rates, and base flow. The calibrated model is suitable, with some limitations, for use in calculating ground-water-flow paths and for estimating areas contributing recharge to wells.

Acknowledgments

The authors gratefully acknowledge the input of the many State and local officials and nonprofit environmental organizations involved with the Alamatong Wellhead Protection Demonstration Project. In particular, we acknowledge the guidance and assistance of Allison Werry of Randolph Township, Russell Titus of Roxbury Township, Kimberly Cenno of NJDEP Office of Environmental Planning, and David Peifer and Douglas Schleifer of the Upper Raritan Watershed Association. Jennifer Myers, NJDEP Bureau of Water Allocation, provided information on ground-water withdrawals and allocations. Special thanks are extended to David Troast, Sparta Township Planning Director and former Randolph Township Planner, who initiated the planning of this project.

Description of the valley-fill and carbonate-rock aquifer system

The aquifer system extends along valleys of the Drakes Brook and Lamington River Basins in the New Jersey Highlands. The part of the aquifer system considered in this study extends from the Flanders area in the southwest to the Kenvil area in the northeast (fig. 1). The valley fill is a complex assemblage of stratified glacial drift, glacial till (unstratified glacial sediment), alluvium (sediment deposited by streams), and colluvium (sediment from an adjacent slope deposited by gravity). The valley-fill sediments are underlain in most areas by carbonate rock, which in many areas is folded, fractured, and highly weathered. In some areas, Paleozoic rock (primarily conglomerate) underlies the valley fill and overlies the carbonate rock. Paleozoic quartzite and Precambrian gneiss underlie and laterally bound the valley-fill and carbonate-rock units. The formation and characteristics of these geologic units are described in detail by Nicholson and others (1996). The geometries of these units were defined by L.J. Nicholson and Robert Canace (New Jersey Geological Survey, written commun., 1990) and are also documented by Nicholson and others (1996).

The aquifer system consists of upper and lower valley-fill aquifers, two valley-fill **confining units**, a Paleozoic-rock confining unit, and a carbonate-rock aquifer (fig. 2). The combined thickness of water-bearing units ranges from zero at the valley walls to several hundreds of feet along valley axes (L.J. Nicholson and Robert Canace, New Jersey Geological Survey, written commun., 1990). The **permeability** of the surrounding and underlying Paleozoic quartzite and Precambrian gneiss is low. All three aquifers are present in most of the valley areas in the study area, except near Flanders and south of the Alamatong wellfield where the upper valley-fill aquifer is absent. The valley-fill-aquifer materials are relatively permeable, with hydraulic conductivities ranging from 2 to 86 ft/d for both the upper and lower valley-fill aquifers, and ground water flows through them easily. In some areas the carbonate-rock aquifer is highly permeable, with hydraulic conductivities as high as 864 ft/d, and well yields are as high as 2,000 gal/min. As a result of the orientation of fracturing and subsequent weathering processes, the carbonate-rock aquifer is more permeable parallel to the valley (northeast-southwest) than in the cross-valley direction. The permeability of the confining-unit materials (silt, clay, and sedimentary rock) is several orders of magnitude lower than that of the aquifer materials, and ground water moves through the confining units relatively slowly.

Recharge to the aquifer system occurs as (1) direct infiltration of precipitation through the valley floor, (2) seepage from streams and lakes, and (3) infiltration of unchanneled runoff from adjacent bedrock upland areas (fig. 3). The sources of recharge to the aquifer system are also the sources of all water reaching supply wells. Water-quality data indicate that human activities have affected water quality in both valley-fill aquifers and the carbonate-rock aquifer (Nicholson and others, 1996, p. 120; R.A. Gallagher, New Jersey Department of Environmental Protection, written commun., 1992). Limited information on the age of ground water in the study area indicates that most ground water probably is less than a few decades old; tritium concentrations in ground-water samples collected during 1988-90 from 11 wells representing the three aquifers in the study area indicate that much of the sampled ground water entered the aquifer system as recharge after 1952 (Nicholson and others, 1996, p. 48).

Sources of Water to Wells

The withdrawal of water from a well causes **drawdown** in the aquifer, which causes water to flow through the aquifer to the well. The area contributing recharge to a well is defined in this report as the area on the land surface through which all ground-water recharge passes that eventually flows to the well and discharges (Reilly and Pollock, 1993). In some situations, the sole source of water to a shallow supply well may be the precipitation that infiltrates over the contributing recharge area (fig. 3a).

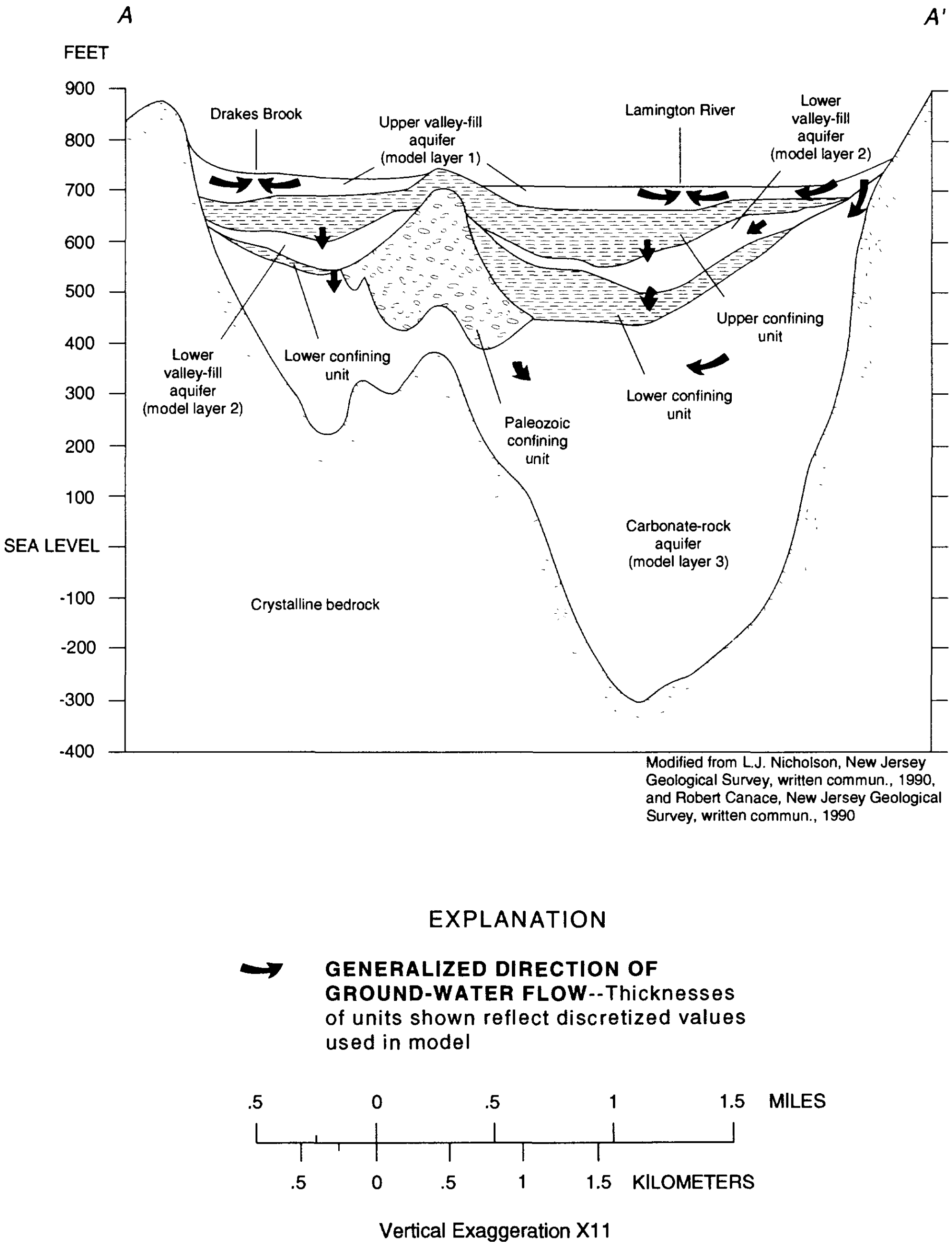


Figure 2. Generalized hydrogeologic section *A - A'*. (Line of section shown in fig. 1)

In typical valley-fill settings, surface water can be a significant source of water reaching wells. Examples of surface-water flow that recharges the aquifer system are (1) tributaries with headwaters in adjacent upland areas that flow into valleys and lose water to the aquifer system; (2) unchanneled runoff from adjacent uplands areas that flows into valleys and recharges the aquifer system; and (3) valley rivers that lose water to the aquifer system, either naturally or as a consequence of ground-water withdrawals. If surface water infiltrates in an area contributing recharge to the well, then water originating as surface runoff will eventually reach the well. Consider the example of a shallow well located near a stream that is hydraulically connected with the aquifer. If the well is pumped at a sufficiently high rate, then the resulting drawdown will induce surface water to flow into the aquifer and to the well (fig. 3b). The entire **source area** contributing either surface runoff or ground water to the stream above the point of infiltration potentially contributes flow to the well. Results of the analysis presented in this report were used to estimate areas contributing recharge; the determination of the source areas contributing unchanneled runoff from upland areas and direct runoff to streams is beyond the scope of this report.

If the well draws water from water-bearing zones beneath a confining layer, the area contributing recharge to the well will tend to be spread over a wide area and may not include the location of the **wellhead** itself (fig. 3c). Tributary seepage and unchanneled runoff from adjacent upland areas also may contribute flow to the well (fig. 3c).

Factors Affecting Contributing Recharge Areas

The size, shape, and location of the area that contributes recharge to a well is determined by many interrelated hydrogeologic factors that affect flow patterns. These factors can be grouped into three categories: (1) aquifer-system boundaries, (2) hydraulic properties of earth materials, and (3) characteristics of the pumped well.

Aquifer-system boundaries determine the distribution of flow into or out of the aquifer system. Examples of aquifer boundaries are the **water table** through which recharge occurs (a recharge boundary), a stream (a recharge or a discharge boundary), other supply wells (discharge boundaries), and the aquifer contact with bounding low-permeability bedrock (a no-flow boundary). The hydraulic properties of earth materials in buried-valley settings can vary greatly. Ground water flows preferentially through more permeable materials, and so flow patterns are affected by the distribution of high- and low-permeability materials. Well characteristics that affect the area contributing recharge to wells include pumping rate; well depth and length of open interval; and proximity to significant hydrogeologic features such as recharge boundaries, zones of high or low permeability, and other pumped wells.

Hydrogeologic factors affecting areas contributing recharge to wells in valley-fill settings are discussed in detail, with many illustrative examples, by Morrissey (1989), Reilly and Pollock (1993, 1995), and Risser and Madden (1994).

DESCRIPTION OF THE GROUND-WATER-FLOW MODEL

A three-dimensional computer model of the aquifer system (Nicholson and others, 1996) was developed by using the USGS modular ground-water-flow model (MODFLOW) computer code by McDonald and Harbaugh (1988). The model consists of a series of equations governing

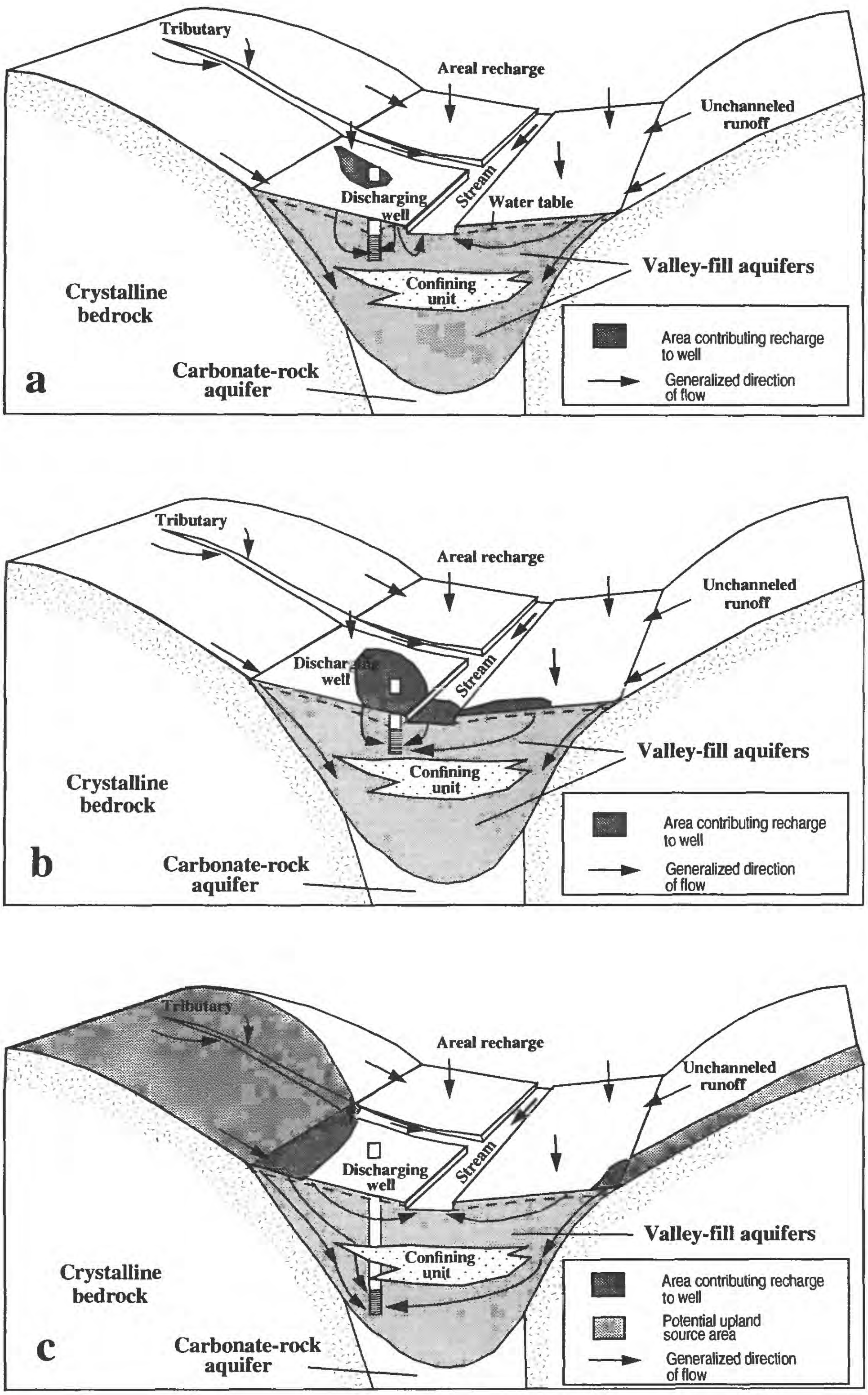


Figure 3. Sources of water to wells: (a) area contributing recharge to a shallow well; (b) area contributing recharge to a shallow well that induces infiltration of surface water; (c) areas contributing recharge to a deep well and potential upland source areas of runoff.

the flow of ground water in a discretized (gridded) representation of the aquifer system under average conditions. The series of equations is solved simultaneously, resulting in a **steady-state simulation** of the distribution of **hydraulic head** and ground-water flow. Each of the three aquifers is represented in the model as a separate layer with variable thickness, and each layer is discretized by using a uniform lateral grid spacing of 500 ft. The overall model grid consists of 44 rows and 256 columns, and is oriented along strike (northeast-southwest, fig. 1). Lateral model boundaries coincide with valley walls where the aquifer system contacts low-permeability crystalline bedrock.

The model output is the simulated distribution of average hydraulic head and flow at discrete points. During model **calibration**, model **parameters** were adjusted within a reasonable range until the simulated hydraulic heads and flows were consistent with field data. The field data used in the calibration included water levels measured in 236 wells and base-flow gain measured in 8 stream reaches. Model development, calibration, and application to water-supply-planning issues are discussed in detail by Nicholson and others (1996).

With minor modifications, the calibrated model was considered to represent the flow system adequately for the purpose of determining flow patterns and areas contributing recharge to wells and streams. One of the modifications was to represent the upper valley-fill aquifer by using two model layers rather than one in order to better define flow paths near streams.

Once the distribution of hydraulic head and flow were determined with the calibrated flow model, **pathlines** were determined by using MODPATH, a **particle-tracking** computer program documented by Pollock (1989, 1994). The particle-tracking technique employed by MODPATH is conceptually simple; a hypothetical particle is positioned at a particular location within the modeled system, and then the position of the particle is calculated at successive intervals of simulation time. Particle movement is thus simulated or "tracked" through the flow field. Taken together, the successive particle positions describe a simulated pathline. In order to calculate successive particle positions, estimates of aquifer and confining-unit **porosity** are required. Porosity values of 0.25 for the upper and lower valley-fill aquifers and 0.15 for the carbonate-rock aquifer were assumed. A porosity value of 0.35 was assumed for confining units.

Groups of particles were positioned strategically and tracked simultaneously in order to generate groups of pathlines. Analyses of different groups of pathlines generated by using variations of the particle-tracking procedure were used to illustrate flow patterns within specific aquifer units and to determine areas contributing recharge to streams and wells.

GROUND-WATER-FLOW PATTERNS

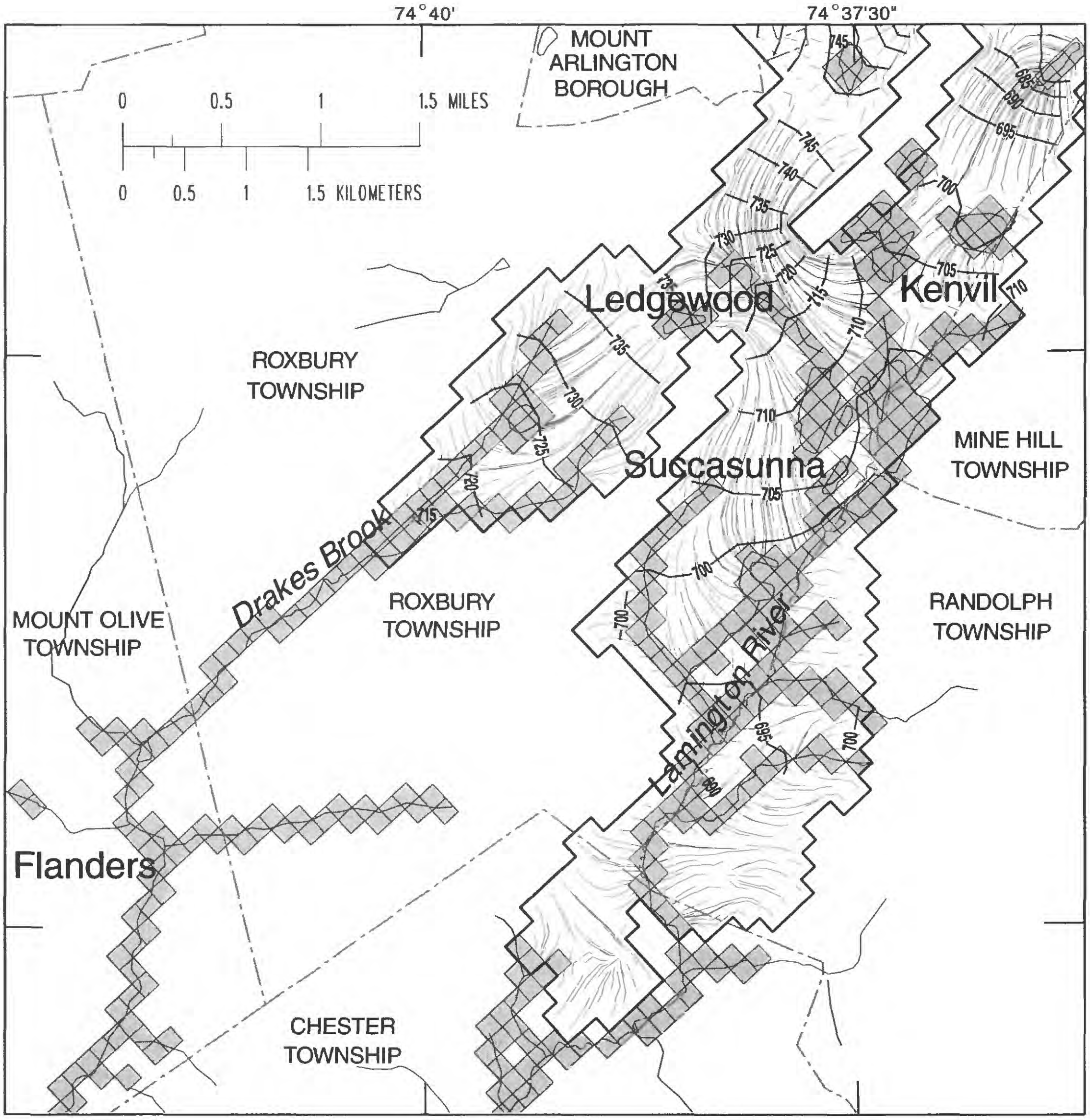
In order to illustrate the concept of contributing recharge areas and their relation to ground-water-flow patterns, an analogy between the aquifer system and a metropolitan transportation system can be drawn: Commuters can travel from home along specific routes to the workplace downtown. Similarly, ground water flows from a contributing recharge area through aquifer-system materials along specific routes, or **flow paths**, that lead to the discharge point (the water-supply well). The area contributing recharge to the well is analogous to the metropolitan commuting area, and the water-supply well is analogous to the location of the workplace. Just as a road map is a useful aid in the understanding of a metropolitan commuting area, a map showing ground-water-flow paths is a useful aid in the understanding of a contributing recharge area. Although ground-water flow is diffuse, a map showing flow patterns can reveal zones of preferential flow, akin to major highways.

The road-map analogy, however, is imperfect. Roadway networks are essentially two-dimensional systems at the land surface, whereas ground-water-flow systems are three-dimensional, and vertical components of flow can be significant. Also, unlike roads, which remain at fixed locations, flow paths can change course as conditions in the aquifer change. When water levels change--in response to additional pumping from a new well, for example--flow paths in the zone of influence of the well change.

Ground-water-flow patterns are typically described by using maps that show contour lines of equal hydraulic head. For unconfined aquifers, these contour lines represent the water table. For confined aquifers, these contour lines represent the **potentiometric surface** of the aquifer. Ground water flows in the direction of decreasing head values, and, in relatively simple hydrologic settings in which flow is primarily lateral and unidirectional, flow paths can be assumed to be perpendicular to contour lines. In more complex settings in which flow is more tortuous or in which the vertical component of flow is significant, however, flow paths cannot be discerned easily from contour maps alone. Maps showing simulated pathlines as well as head contours can help in visualizing flow from areas of high hydraulic head to areas of low hydraulic head in complex settings. For this illustrative purpose, representative pathlines in each of the three aquifers under unstressed (prepumping) conditions were generated, and are shown in figures 4-6.

To generate the pathlines shown in figure 4, one particle was positioned at the center of the top face of each model cell in model layer 1, representing the top part of the upper valley-fill aquifer, and was **forward-tracked** through the simulated flow field. Tracking was terminated when a particle either discharged from the aquifer system, passed vertically into an underlying aquifer, or passed across a study-area boundary. The procedure was repeated for the underlying model layer 3, representing the lower valley-fill aquifer (fig. 5). For model layer 4, representing the carbonate-rock aquifer (fig. 6), the procedure was repeated with one particle positioned at the center of the top of adjacent nine-cell blocks to achieve a lower particle density and a clearer illustration of flow paths. For model layers 3 and 4, particle tracking was terminated when a particle passed vertically into an overlying aquifer. Pathline coordinates were translated into Geographic Information System (GIS) coverages by using the computer program package MODTOOLS by Leonard Orzol (1997).

Flow patterns in the upper valley-fill aquifer are dominated by the effects of surface-water features and aquifer boundaries. As shown in figure 4, most pathlines terminate at streams. Some ground water converges on a buried gap in the bedrock ridge near Ledgewood, passes through the gap, and then diverges toward various surface-water features. Some pathlines are very short and terminate before reaching a surface-water boundary, indicating vertical flow into an underlying aquifer. Several short pathlines indicating downward vertical flow are evident near the aquifer boundary east of the Lamington River in Randolph Township.



EXPLANATION

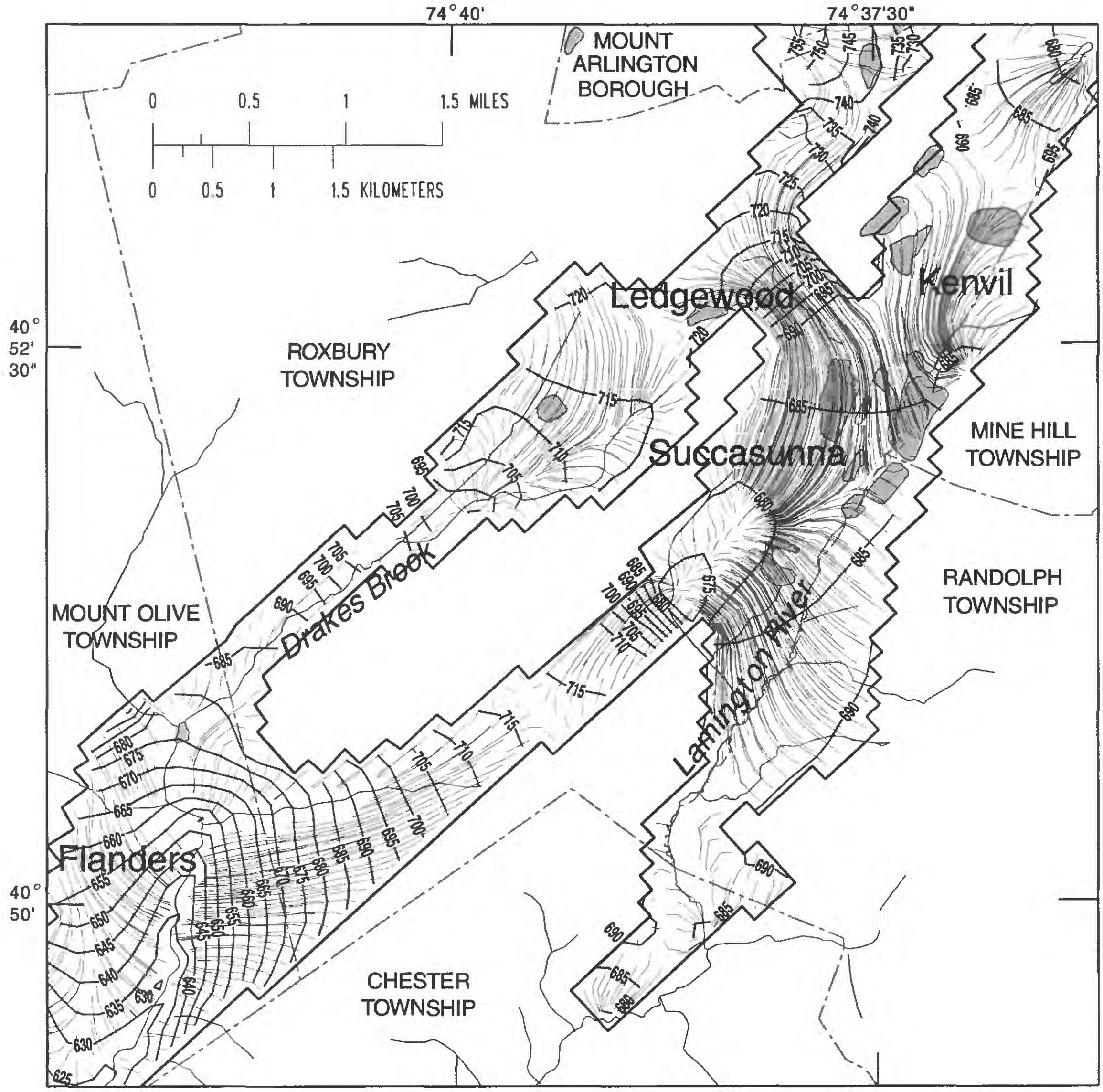
SURFACE-WATER-BOUNDARY CELL

PATHLINE--Shows flow path from recharge area to discharge area or underlying aquifer

730 WATER-TABLE CONTOUR --Shows altitude of water table. Contour interval 5 feet. Datum is sea level

MODEL BOUNDARY

Figure 4. Water levels and flow paths under unstressed (prepumping) conditions in the upper valley-fill aquifer in the study area, southwestern Morris County, New Jersey.



EXPLANATION

PATHLINE--Shows flow path from recharge area to discharge area, overlying aquifer, or underlying aquifer

730 POTENTIOMETRIC CONTOUR--Shows altitude at which water would have stood in tightly cased wells, in feet above sea level. Contour interval 5 feet. Datum is sea level

MODEL BOUNDARY

Figure 5. Water levels and flow paths under unstressed (prepumping) conditions in the lower valley-fill aquifer in the study area, southwestern Morris County, New Jersey.

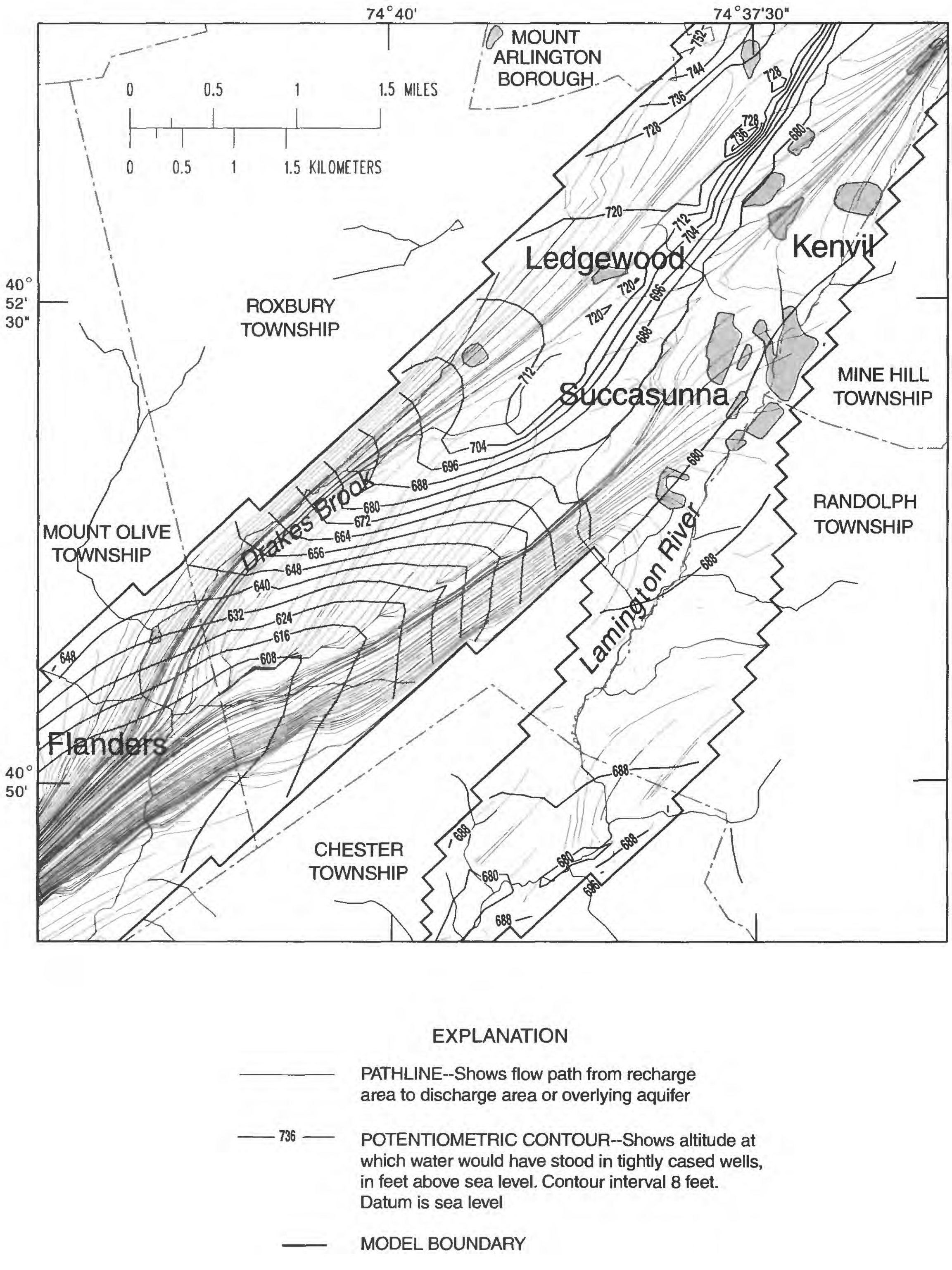


Figure 6. Water levels and flow paths under unstressed (prepumping) conditions in the carbonate-rock aquifer in the study area, southwestern Morris County, New Jersey.

Flow patterns in the lower valley-fill aquifer near Flanders where the aquifer is unconfined are dominated by the effects of surface water and ground water discharges directly from the aquifer to Drakes Brook and its tributaries (fig. 5). Near Succasunna and Kenvil, where the aquifer is confined, pathlines converge on areas where the lower valley-fill aquifer is well-connected hydraulically to the carbonate-rock aquifer. In these areas, ground water flows vertically into the carbonate-rock aquifer.

In the carbonate-rock aquifer (fig. 6), ground water flows preferentially through fractures and solution openings that trend along strike, parallel to the valley axis (northeast-southwest). Preferential flow pathways along the valley from Ledgewood and Kenvil to Flanders are evident. Many flow lines converge on and flow through high-permeability zones in the carbonate rock in Roxbury Township and Mount Olive Township (Nicholson and others, 1996, p. 36).

AREAS CONTRIBUTING RECHARGE TO STREAMS AND WELLS

In order to determine areas contributing recharge to streams and wells, particles were forward-tracked from the simulated water table to discharge locations. A dense grouping of particles was used, composed of a 3x3 array of particles positioned at the top face of each uppermost model cell. Particle-tracking results were analyzed to identify pathlines that terminated at specific discharge locations, including streams and wells. The starting positions of all pathlines were recorded and these locations were translated into GIS point coverages. The area enclosing all of the starting points of pathlines that terminated at a particular well is an estimate of the area contributing recharge to the well. Likewise, the area enclosing all of the starting points of pathlines that terminated at a particular stream segment is an estimate of the area contributing recharge to that stream segment. Maps showing contributing recharge areas to streams and water-supply wells can help to illustrate the relations between the sources of water to streams and the sources of water to wells.

Limitations of Model Application

The reliability of estimates of the areas contributing recharge that are made by using numerical- modeling techniques is a function of several factors relating to conceptual model reliability, model **discretization**, and parameter error. The overall conceptual model of the flow system (described earlier) forms the basis for the numerical model used in this analysis. This conceptual model is grounded in many field observations and studies of other, similar systems. As in any modeling exercise, the true system response in areas where field data are unavailable (and in areas where available field data do not uniquely define the system) may be different from the simulated response. Actual contributing areas, therefore, may be affected by aquifer-system features that are not represented accurately in simulations.

Numerical-model discretization imposes a limitation on estimated pathline resolution; the termination point of pathlines that enter model cells representing discharge boundaries such as wells or streams may be indeterminate in some instances. For these cells, there is no way to determine whether an entering particle of water represents discharge to the well or stream, or whether it represents flow into an adjacent cell. As a result of this limitation, contributing recharge areas described in this report should be regarded as potential contributing recharge areas, or areas from which ground water probably flows to the vicinity of a well or stream.

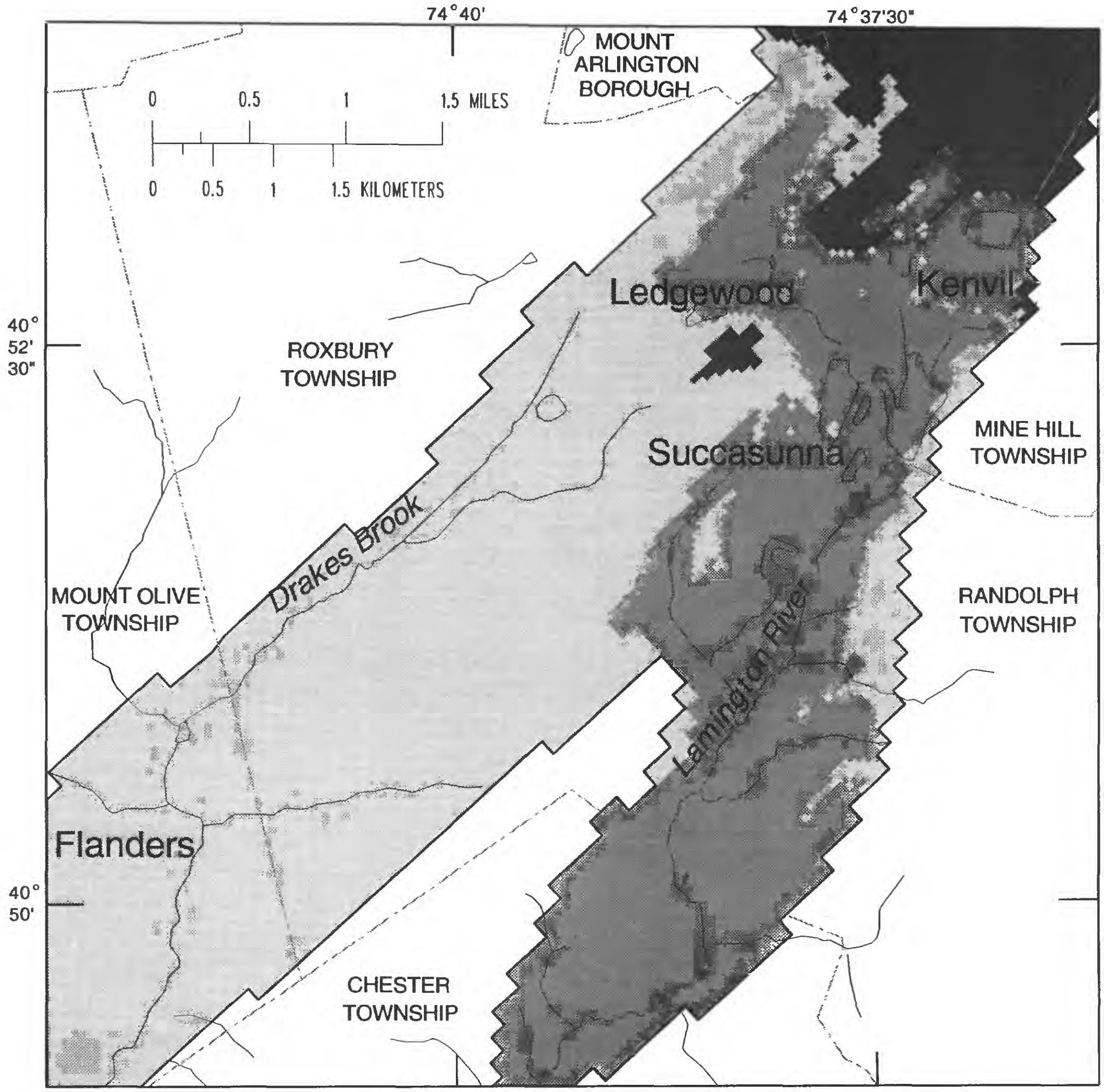
The model determines the distribution of hydraulic head and flow throughout the aquifer system, and these model outputs are dependent on the selected values of model parameters, such as recharge and the permeabilities of aquifer, confining-unit, and streambed materials. Any errors in parameter estimates will contribute to errors in simulated hydraulic head, flow, and areas contributing recharge to wells and streams. Sensitivity analysis can be used to demonstrate the effect of parameter error on simulation results. Results of a sensitivity analysis showed that a selected range of plausible alternative models in which different parameter values were used results in estimated contributing recharge areas with boundaries that deviate from those determined by using the calibrated model. Eight model parameters were independently adjusted upward and downward by the largest amount possible without disrupting model calibration. (Model calibration was considered to be disrupted if simulated water levels increased or decreased more than 10 ft anywhere in the model domain.)

The model parameters were the hydraulic conductivity of each aquifer, lateral anisotropy in the carbonate-rock aquifer, confining-unit leakances, recharge, and streambed hydraulic conductivity. Among the parameter sensitivities evaluated in this manner, the parameter with the greatest effect on contributing recharge areas was the hydraulic conductivity of the upper valley-fill aquifer. Adjusted values of this parameter resulted in subtle differences in simulated flow directions, which in turn resulted in different boundaries of contributing recharge areas to wells. Because the uncertainty associated with this model parameter is relatively high, the reliability of estimates of contributing recharge areas may be limited more by uncertainty in this parameter than by uncertainty in other parameters.

Among the contributing recharge areas simulated by using the alternative models, the greatest deviation was typically about 300 ft (but exceeded 300 ft in some areas) from the contributing-recharge-area boundaries simulated by using the calibrated model. The results of the sensitivity analysis provide an indication of the reliability of the contributing-recharge-area determinations. The reader is cautioned that this sensitivity analysis was not exhaustive, and that other alternative models using different parameter values may result in areas contributing recharge to wells that deviate from the calibrated-model estimates more than those simulated with the alternative models selected for the sensitivity analysis.

Unstressed Conditions

Analysis of areas contributing recharge under unstressed (non-pumping) conditions can help in understanding contributing recharge areas under stressed (pumping) conditions. Average, unstressed flow conditions were simulated by using parameters identical to those used in the calibrated model, but with pumping stresses removed. Results of the simulation were used, in conjunction with the particle-tracking techniques described previously, to estimate the contributing areas to streams under unstressed conditions, as shown in figure 7. Part of the area contributing recharge to Drakes Brook is situated east of the neighboring Lamington River. Ground water recharged in this area flows into the lower valley-fill aquifer and beneath the Lamington River, and into the underlying carbonate-rock aquifer (fig. 5). Much of the flow in the carbonate-rock aquifer follows long flow paths to the southwest (fig. 6), and discharges to either Drakes Brook or the South Branch Raritan River outside the study area to the southwest. This analysis of complex pathlines helps to explain why areas contributing recharge to streams may be substantially different from drainage areas (areas contributing surface runoff to streams).



EXPLANATION

- Area contributing recharge to Rockaway River
- Area contributing recharge to Lamington River
- Area contributing recharge to Drakes Brook (tributary to South Branch Raritan River)
- Model boundary

Figure 7. Simulated areas contributing recharge to streams under unstressed (prepumping) conditions in the study area, southwestern Morris County, New Jersey.

Stressed Conditions

Ground-water flow under three different stressed (pumping) conditions was simulated to estimate areas contributing recharge to wells. The locations of water-supply wells in the study area are shown in figure 8. The three conditions simulated represent (1) average pumping rates during 1991-95 (4.2 Mgal/d), (2) pumping rates projected for the year 2005 (5.8 Mgal/d), and (3) pumping rates assuming full utilization of allocations that were in place in 1996 (6.0 Mgal/d) (table 1). Information regarding full-allocation pumping rates was provided by the NJDEP Bureau of Water Allocation (Jennifer Myers, New Jersey Department of Environmental Protection, written commun., 1996). Withdrawals by public-supply purveyors and industries under these three conditions are summarized in figure 9. Water withdrawn from the aquifer system in the study area for public supply is provided by two purveyors, the Roxbury Water Company (RWC) and the Morris County Municipal Utilities Authority (MCMUA). Withdrawals for industrial use by Alliant Tech Systems (formerly Hercules) and Schindler Elevator (formerly Westinghouse Elevator) also were included in the simulations.

Recent Conditions

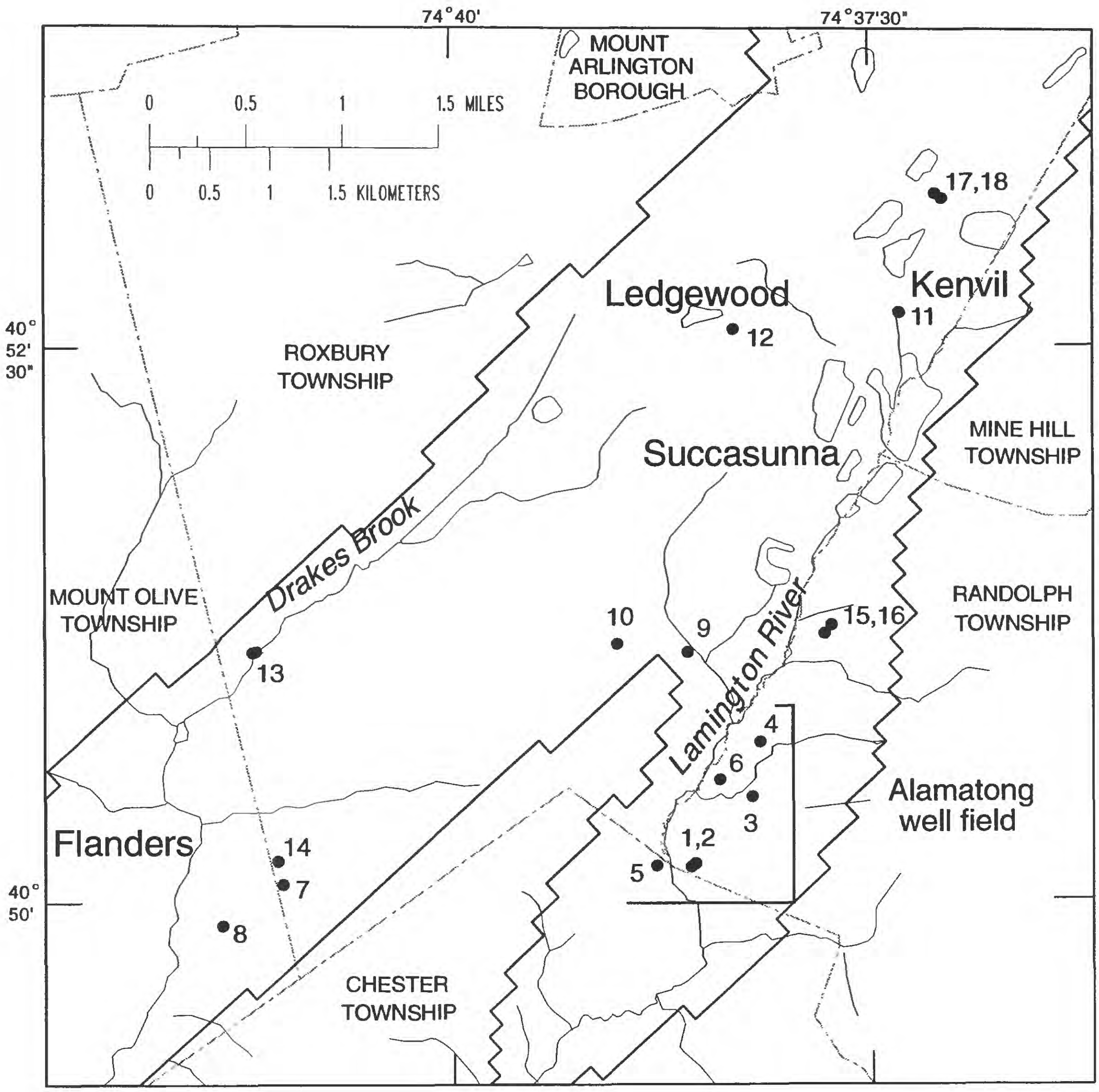
Total withdrawals during 1991-95 averaged 1,524 Mgal/yr, or 4.2 Mgal/d. The distribution of these withdrawals is shown in figure 10. Simulated contributing recharge areas to streams and supply wells under steady-state conditions at recent (1991-95) pumping rates are shown in figure 11. The areas contributing recharge to wells no longer contribute flow to streams as they did under unstressed conditions; therefore, the area contributing recharge to streams--the Lamington River, for example--is smaller under recent conditions (fig. 11) than under predevelopment conditions (fig. 7). A smaller contributing recharge area to a stream results in less base flow to the stream. Base-flow reduction in study-area streams is discussed in detail in Nicholson and others (1996).

Ground-water flow into and out of the aquifer system can be summarized by an equation that represents the ground-water budget, in which the sum of average annual inflows equals the sum of average annual outflows. Budgets for stressed and unstressed conditions can be compared to explain and quantify the sources of water to wells. For the part of the aquifer system located within the boundaries of the study area, the budget is stated as:

$$R + S + I = B + W + O,$$

where R = recharge (infiltration of incident precipitation),
S = infiltration from surface water,
I = lateral inflow from adjacent parts of the aquifer system,
B = base flow,
W = discharge to wells, and
O = outflow to adjacent parts of the aquifer system.

The ground-water budgets for the aquifer system in the study area under recent (1991-95) conditions, 2005 conditions, and full-allocation conditions are shown graphically in figure 12. The largest inflow is recharge, which was assumed to be about 16 Mgal/d for all three conditions. As ground-water withdrawals increase to meet future demand, infiltration from surface water and



EXPLANATION

—— Model boundary

• 8 Supply well (number is well number listed below and in table 1)

NUMBER	WELL IDENTIFIER	NUMBER	WELL IDENTIFIER
1	MCMUA ALAMATONG 1	10	ROXBURY WATER COMPANY 2
2	MCMUA ALAMATONG 2	11	ROXBURY WATER COMPANY 3
3	MCMUA ALAMATONG 3	12	ROXBURY WATER COMPANY 6
4	MCMUA ALAMATONG 4	13	ROXBURY WATER COMPANY 7/7A
5	MCMUA ALAMATONG 5	14	ROXBURY WATER COMPANY 8
6	MCMUA ALAMATONG 6	15	SCHINDLER ELEVATOR 1
7	MCMUA FLANDERS 1	16	SCHINDLER ELEVATOR 2
8	MCMUA FLANDERS 2	17	ALLIANT TECH 1
9	ROXBURY WATER COMPANY 1A	18	ALLIANT TECH 2

MCMUA = Morris County Municipal Utilities Authority

Figure 8. Location of water-supply wells in the study area, southwestern Morris County, New Jersey.

Table 1. Well-construction data for water-supply wells located in the southwestern Morris County, New Jersey, study area, and pumping rates for three water-use alternatives

[USGS, U. S. Geological Survey; MUA, Municipal Utilities Authority; Co., Company; NJDEP, New Jersey Department of Environmental Protection; 112SFDF, Stratified drift; 374LSVL, Leithsville Formation; --, no data; 00, date unknown; *, map number 13 corresponds to two wells at same location]

Map number (shown in fig. 8)	USGS well number	Owner	NJDEP local well name	Date of well construction	Depth to top of open interval (feet below land surface)	Depth to bottom of open interval (feet below land surface)	Aquifer	Model layer	Average 1991-95 pumping rate (million gallons per day)	Projected 2005 pumping rate (million gallons per day)	Maximum expected rate under 1996 allocation (in million gallons per day)	NJDEP permit number
1	27-1314	Morris County MUA	Alamatong 1	06-00-68	52.83	80.83	112SFDF	3	0.083	0.08	0.12	25-14790
2	27-1315	Morris County MUA	Alamatong 2	08-01-73	50	70	112SFDF	3	.11	.09	.16	25-17050
3	27-1323	Morris County MUA	Alamatong 3	11-00-74	163.5	180.5	112SFDF	3	.091	.095	.03	25-17733
4	27-1324	Morris County MUA	Alamatong 4	03-29-82	103	156.9	112SFDF	3	.63	.56	.37	25-22600
5	27-1090	Morris County MUA	Alamatong 5	11-04-85	325	514	374LSVL	4	.38	.55	.53	25-25610
6	27-1707	Morris County MUA	Alamatong 6	12-23-92	440	530	374LSVL	4	0	.59	.55	25-41766
7	27-1728	Morris County MUA	Flanders 1	09-18-90	161	245	374LSVL	4	.52	.77	.85	25-41497
8	27-1727	Morris County MUA	Flanders 2	08-00-90	164	288	374LSVL	4	.81	1.14	1.15	25-41592
9	27-1733	Roxbury Water Co.	RWC 1A	01-04-90	130	700	374LSVL	4	.15	.18	.19	25-34457
10	27-1710	Roxbury Water Co.	RWC 2	02-27-56	118	160	374LSVL	4	.16	.26	.21	25-05279
11	27-1711	Roxbury Water Co.	RWC 3	11-00-59	--	--	112SFDF	2	.0005	0	0	45-00314
12	27-1177	Roxbury Water Co.	RWC 6	03-15-85	45	55	112SFDF	2	.084	.017	.11	25-25540
13*	27-1173	Roxbury Water Co.	RWC 7	--	161.7	175	374LSVL	4	.20	0	0	25-29720
	27-1807	Roxbury Water Co.	RWC 7A	06-08-93	170	182	374LSVL	4	.08	.48	.37	25-44470
14	27-1308	Roxbury Water Co.	RWC 8	06-05-87	163	245	374LSVL	4	.06	.086	.078	25-29660
15	27-1317	Schindler Elevator	Schindler Elevator 1	03-14-57	47	65	112SFDF	2	.0004	0	.065	25-05732
16	27-1316	Schindler Elevator	Schindler Elevator 2	11-01-85	50	75	112SFDF	2	.0004	0	.065	25-26977
17	27-1087	Alliant Tech	Alliant Tech 1	02-16-40	75	105	112SFDF	3	.61	.62	.88	45-00310
18	27-1713	Alliant Tech	Alliant Tech 2	00-00-42	--	--	112SFDF	3	.21	.25	.304	45-00311
TOTAL									4.2	5.8	6.0	

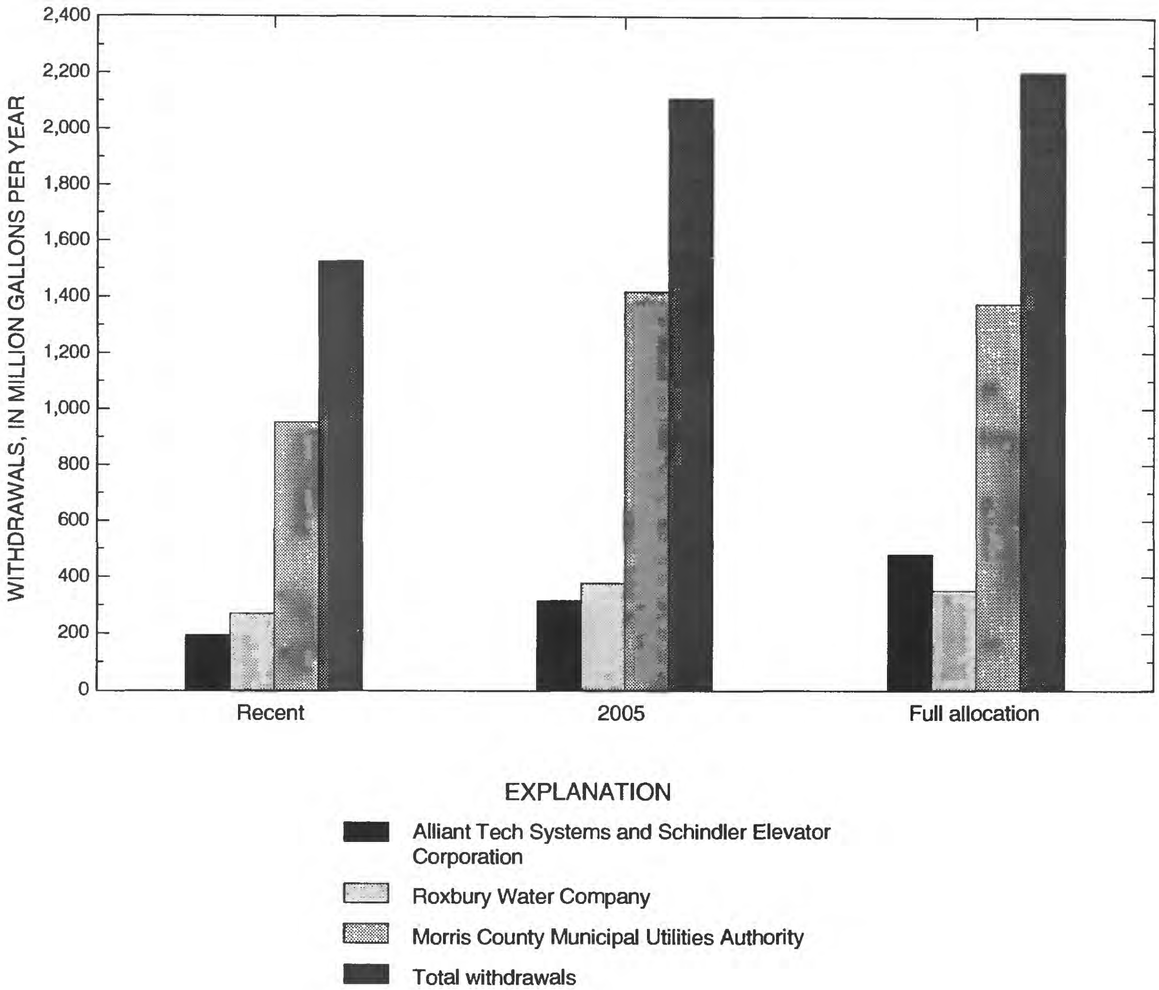


Figure 9. Summary of withdrawals for recent (1991-95), projected 2005, and full-allocation conditions in the study area, southwestern Morris County, New Jersey.

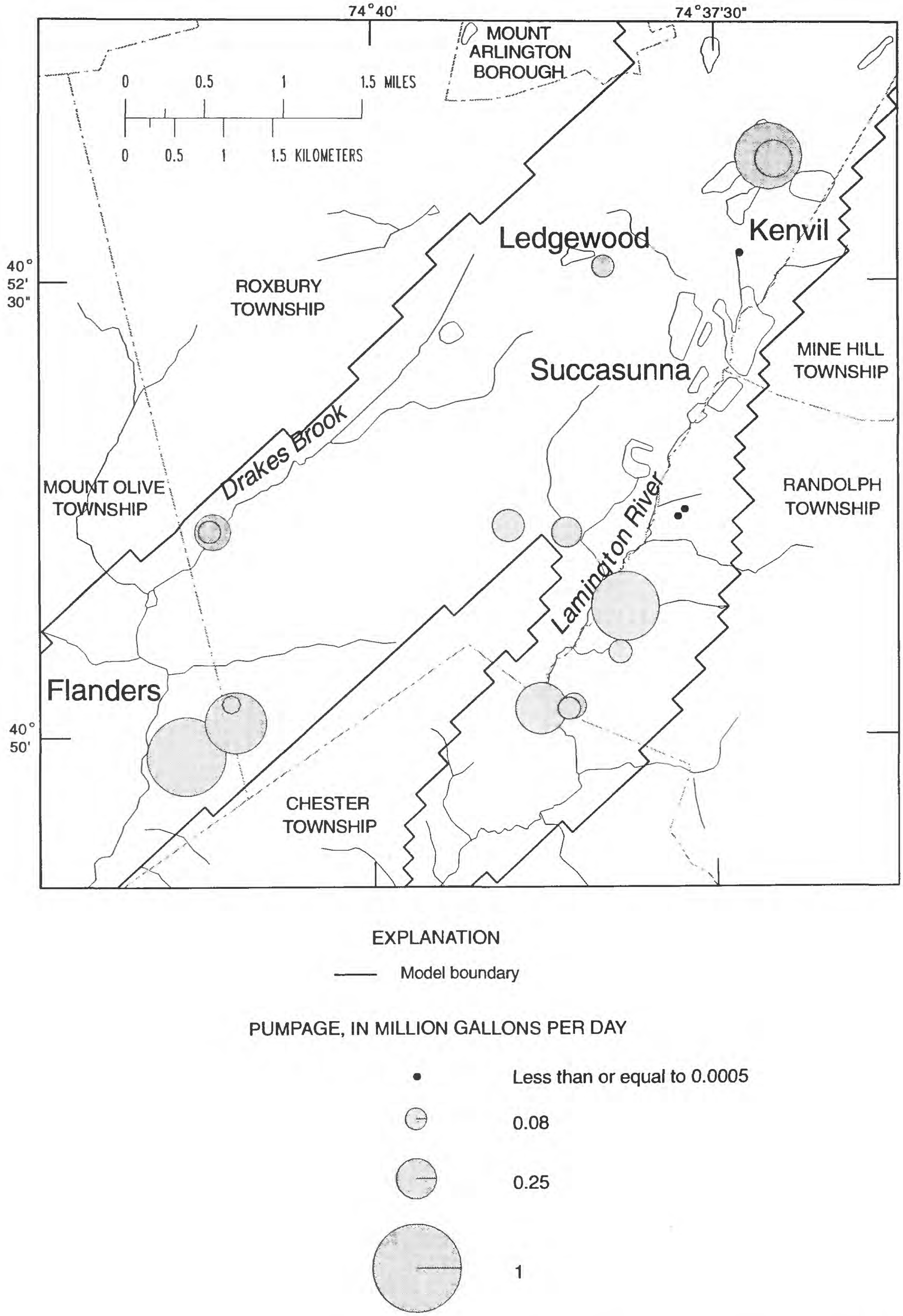


Figure 10. Average recent (1991-95) pumping rates from water-supply wells in the study area, southwestern Morris County, New Jersey.

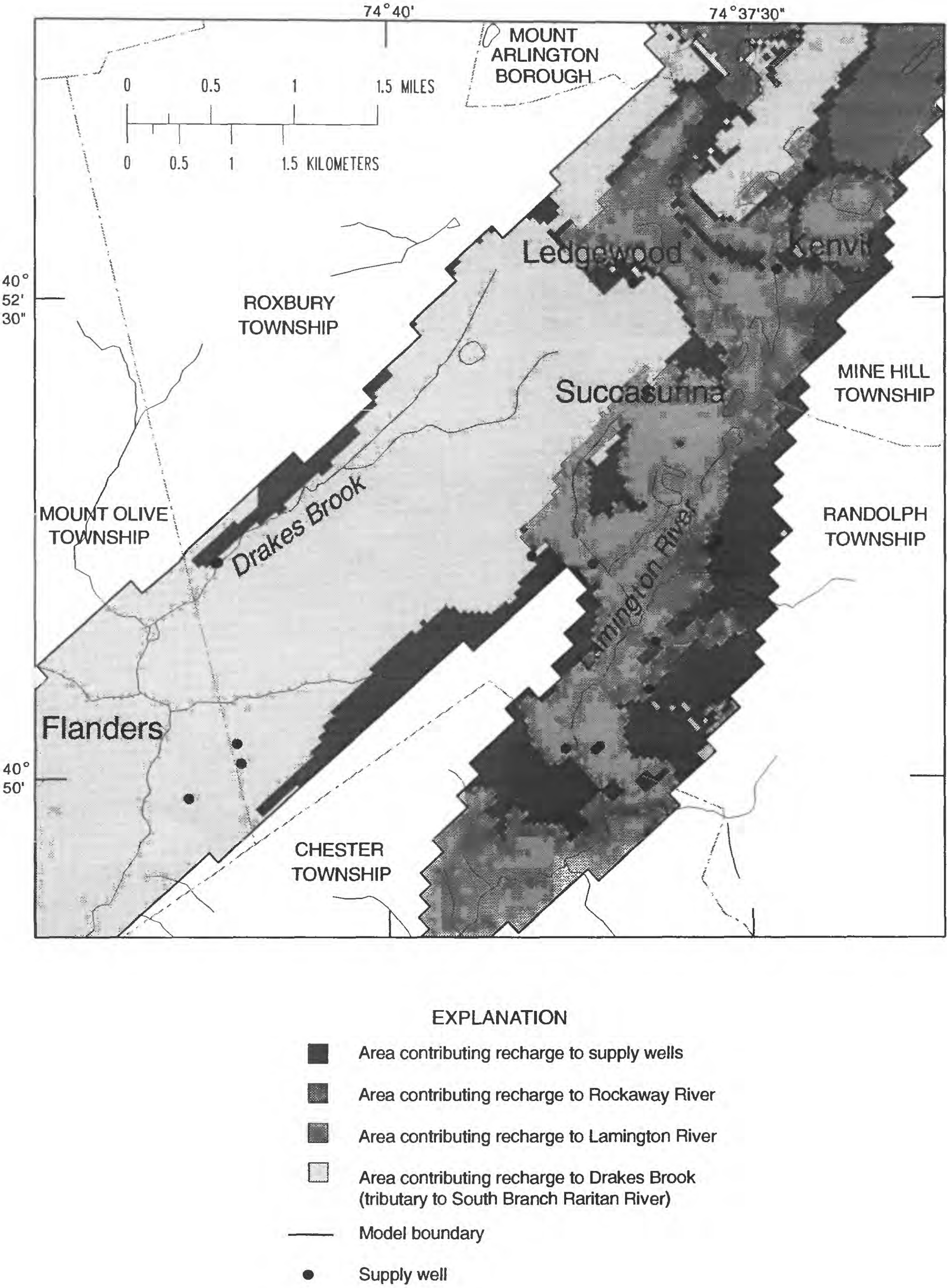


Figure 11. Simulated areas contributing recharge to streams and wells under recent (1991-95) pumping conditions in the study area, southwestern Morris County, New Jersey.

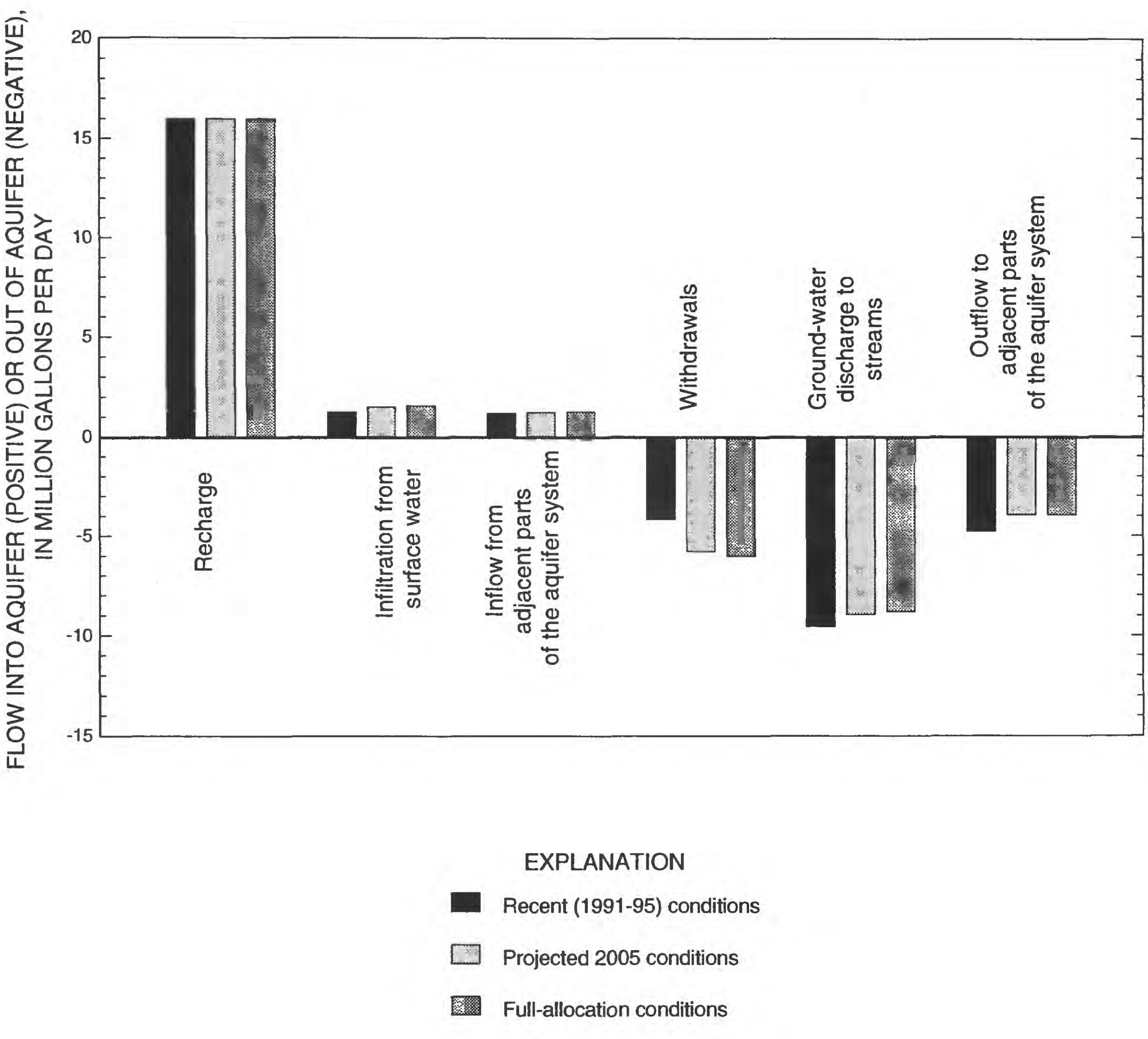


Figure 12. Ground-water budgets under recent, projected 2005, and full-allocation conditions for the study area, southwestern Morris County, New Jersey.

inflow from adjacent parts of the aquifer system increase slightly. Additionally, base flow to streams and outflow to adjacent parts of the aquifer system decrease because the additional withdrawals intercept some of this flow. Streamflow reduction resulting from ground-water withdrawals can be illustrated in terms of changes in the ground-water budget (fig. 12) and contributing recharge areas (figs. 7 and 11).

Simulated contributing recharge areas to individual wells under recent conditions are shown in figure 13. Only wells that are pumping under the conditions being discussed are shown. For example, MCMUA Alamatong 6 was not being pumped during 1991-95; therefore, it does not appear in figure 13. Some contributing recharge areas to shallow wells, such as Roxbury Water Company 6 and the two Schindler Elevator wells, for example, are contiguous areas located near the respective wells. In contrast, contributing recharge areas to many deeper wells, such as MCMUA Flanders 1 and MCMUA Alamatong 5, for example, are fragmented, with some areas located many thousands of feet from the well.

The analytical limitation imposed by model discretization (described earlier) is illustrated by an explanation of the contributing recharge areas to wells between Succasunna and Flanders. The Roxbury Water Company 2 (number 10 in figure 13) well is pumped at an insufficient rate to capture all the water entering the model cell representing it. For consistency, the origins of particles entering such cells were attributed to the contributing area of the first well cell encountered. As a result, the contributing recharge areas of the first well encountered can be overestimated, and those of downgradient wells can be underestimated. In this particular example, water originating at indeterminate parts of the contributing recharge area shown for the Roxbury Water Company 2 well would probably flow downvalley to the southwest and discharge to one of the three wells at Flanders (numbers 7,8, and 14 in figure 13). Therefore, the boundary lines defining the areas contributing recharge to all wells (shown in figure 11) are more reliable than the boundaries lines that distinguish areas contributing recharge to individual wells (shown in figure 13).

Ground-water velocities typically are on the order of tens of feet per year through moderately permeable, sandy, unconsolidated sediments, and are much lower through low-permeability materials such as silt and clay. Time-of-travel from point of recharge to supply wells can range from days to centuries, depending on the length of the flow path and the average velocity along the flow path. Simulated travel times associated with areas contributing recharge to the shallow wells in the study area are on the order of days to a few years. In contrast, simulated travel times associated with distant areas contributing recharge to the deeper wells are on the order of decades or centuries.

The New Jersey Wellhead Protection Program (New Jersey Department of Environmental Protection, 1991) incorporates time-of-travel (TOT) as a critical factor in determining areas contributing recharge to wells, and identifies TOT thresholds of 200 days, 5 years, and 12 years for specific program objectives. Contributing recharge areas associated with travel times to wells of 12 years or less were estimated by using results of simulations and particle-tracking analyses. Although the scale of model resolution limits the reliability of flow paths predicted over short time periods, 5-year contributing recharge areas were delineated to demonstrate the relative distribution of travel times in contributing recharge areas. Results of simulations conducted by using the available flow model are not meaningful in determinations of 200-day contributing recharge areas because of limitations imposed by the scale of the model.

The discrete representation of the aquifer system in the model is reflected in the "stair-step" pattern of boundaries of simulated contributing recharge areas that is evident in previous figures. For practical relation to real-world geographic features, simulated areas contributing recharge to wells and those areas associated with 5- and 12-year travel times were interpreted and adjusted (smoothed) to conform with actual hydrogeologic boundaries. The adjusted boundaries are shown in figure 14.

The simulated 5-year contributing recharge areas are useful in helping to understand the relative distributions of travel time in contributing recharge areas. In many cases, the 5-year contributing recharge areas coincide with a part of the 12-year contributing recharge area that is closest to the well. In some situations, however, the 5-year contributing recharge area may include some areas that are farther from the well than other parts of the 12-year contributing recharge area. An example of such a situation is the well screened in the carbonate-rock aquifer adjacent to Drakes Brook, just north of Flanders (fig. 14). Ground water that reaches the carbonate-rock aquifer moves at a high velocity relative to ground water that flows through less permeable overlying sediments. Ground water that reaches the carbonate-rock aquifer quickly may reach the well sooner than ground water that flows a shorter distance through the less permeable sediments.

Some of the water-supply wells withdraw water from aquifer zones that are overlain by relatively extensive valley-fill confining layers. These wells include MCMUA Flanders 1, MCMUA Flanders 2, Roxbury Water Company 1A, Roxbury Water Company 8, and Alliant Tech Wells 1 and 2 (fig. 13). Because ground water takes more than 5 years to reach these respective wells under recent pumping conditions, no associated 5-year contributing recharge areas for these wells are shown in figure 14. At the Alamatong wellfield, the upper and lower valley-fill confining units are less extensive (Nicholson and others, 1996, p. 26, 31), so that ground water flows relatively rapidly from the water table into lower aquifers. Simulation results indicate that some ground water reaches the deeper MCMUA Alamatong wells (wells 3, 4, and 5), as well as the shallower Alamatong wells 1 and 2, within 5 years. Ground-water age-dating techniques could be applied to samples from these and other wells to estimate the age of the water reaching the wells and the vulnerability of the wells to contamination from sources at the land surface.

Projected Conditions: Year 2005

Withdrawals from the aquifer system in the study area are projected to increase to meet increasing demand. The year 2005 was selected as a planning horizon for projecting ground-water withdrawals. Population forecasts (Raymond Zabihach, Morris County Planning Board, written commun., 1996) were used to update purveyor-supplied demand forecasts reported in the New Jersey Statewide Water Supply Master Plan (CH2M Hill, 1994). Updated demand forecasts for the municipalities in respective purveyor service areas were used to extrapolate pumping rates for individual wells to the year 2005. Water Conservation Plans filed at the NJDEP Bureau of Water Allocation by the two purveyors were also taken into consideration in the extrapolation of pumping rates. Total withdrawals are projected to reach 2,110 Mgal/yr (5.8 Mgal/d), representing a 38-percent increase over recent (1991-95) withdrawals (fig. 9). The distribution of these projected withdrawals is shown in figure 15.

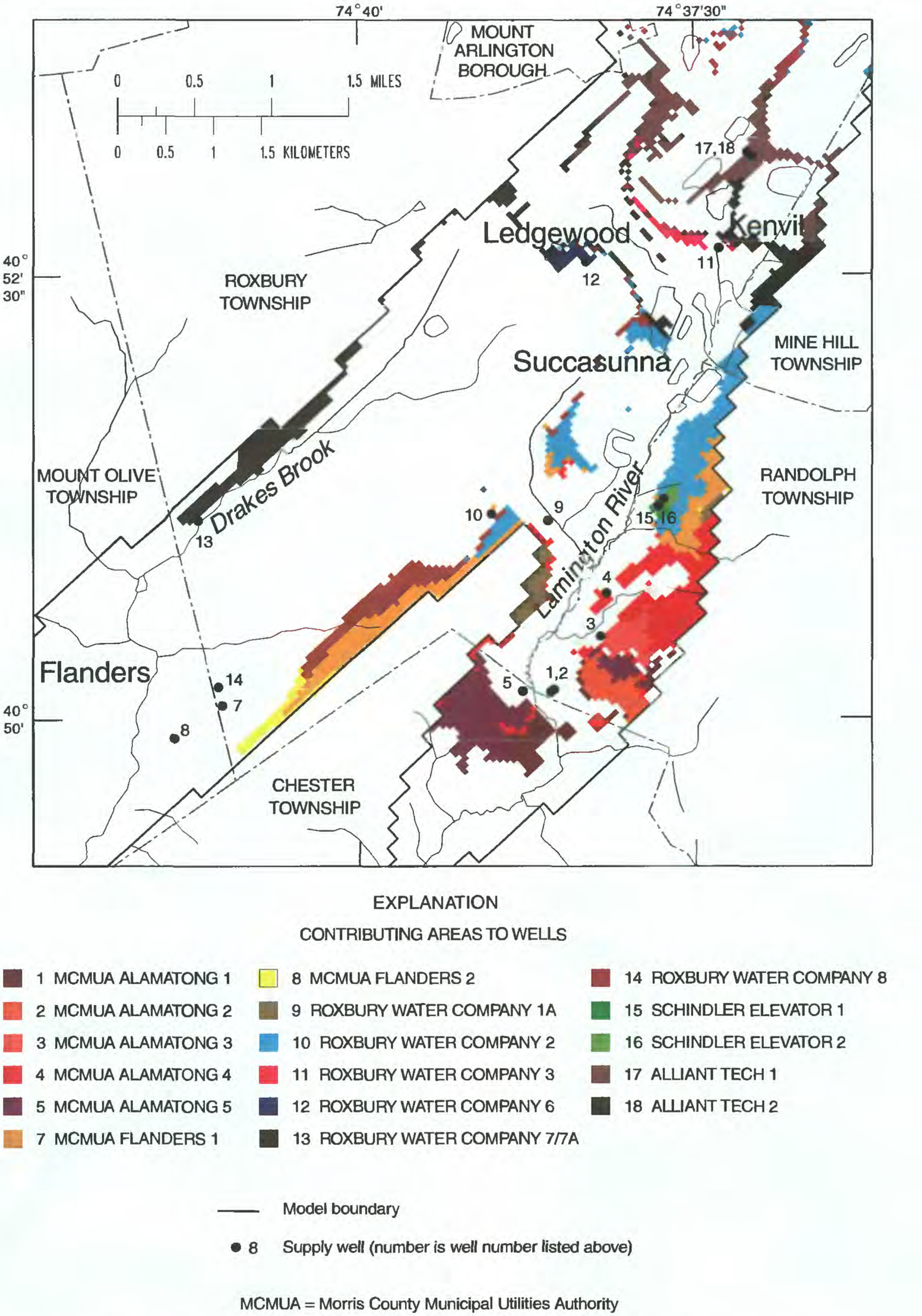
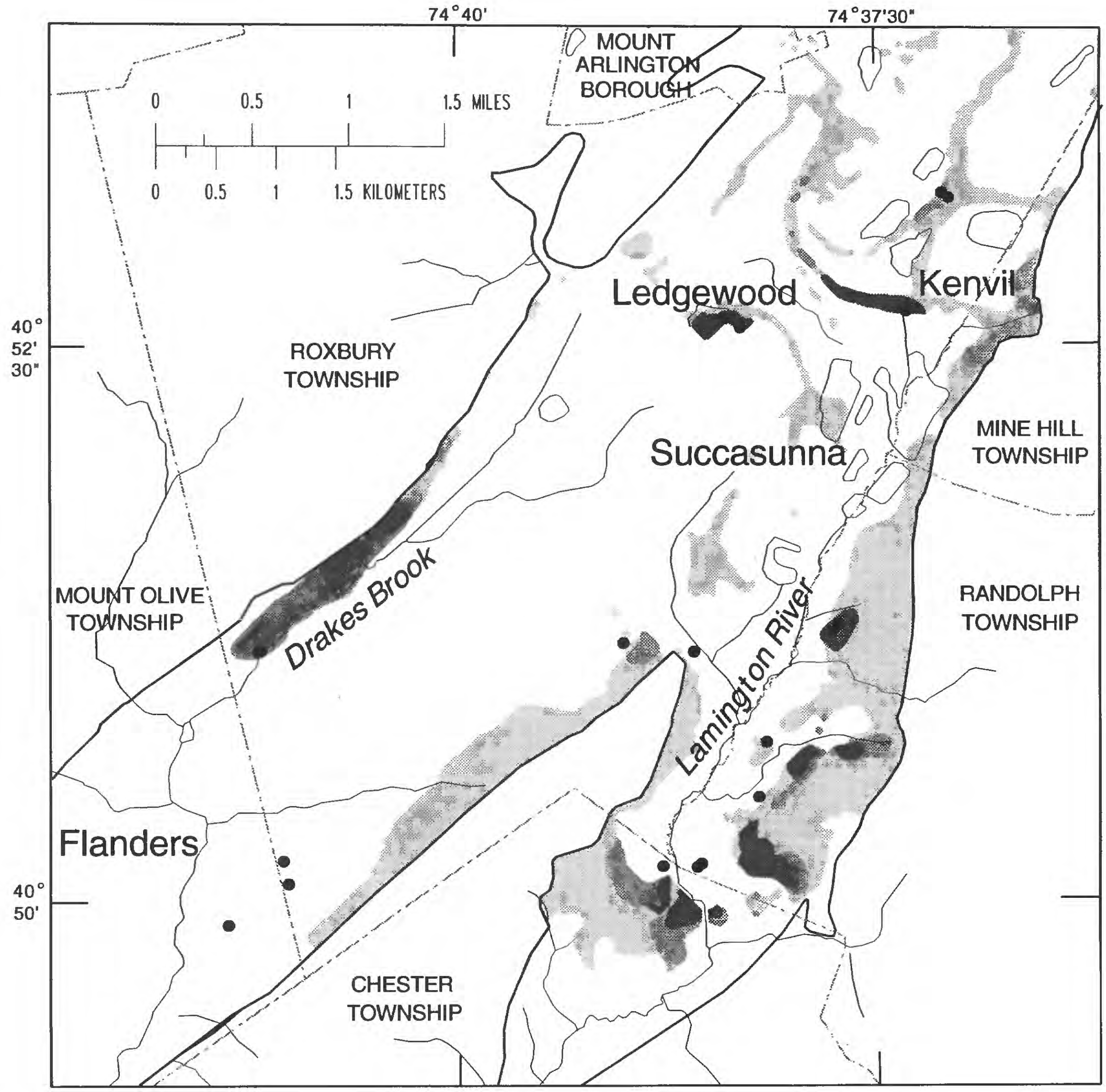


Figure 13. Simulated areas contributing recharge to individual wells under recent (1991-95) pumping conditions in the study area, southwestern Morris County, New Jersey.



EXPLANATION

TRAVEL TIME FROM CONTRIBUTING RECHARGE AREA TO WELL, IN YEARS

- $\leq$ 5 years
- > 5 years to $\leq$ 12 years
- > 12 years
- Aquifer-system boundary
- Supply well

Figure 14. Estimated areas contributing recharge to wells that are associated with travel times of 5 years or less, greater than 5 years to less than or equal to 12 years, and greater than 12 years under recent (1991-95) pumping conditions in the study area, southwestern Morris County, New Jersey.

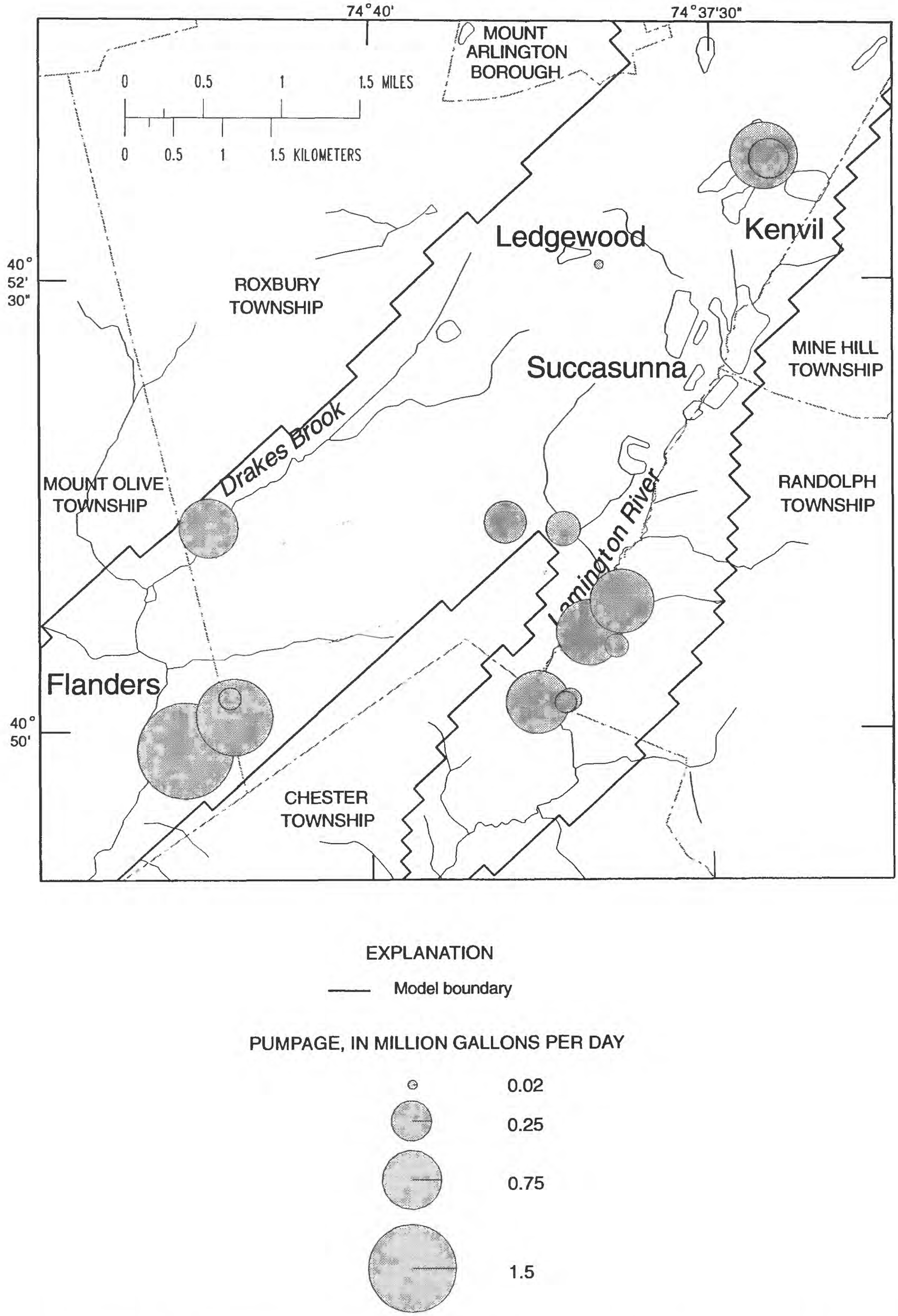


Figure 15. Average pumping rates from water-supply wells projected for year 2005 in the study area, southwestern Morris County, New Jersey.

Areas contributing recharge to surface water and wells under projected conditions for the year 2005 are shown in figure 16. Because pumping rates assumed in this simulation are generally higher than those represented in the simulation of recent conditions, projected contributing recharge areas to wells shown in figure 16 are slightly larger than those shown in figure 11. For the same reason, the projected contributing areas to streams are smaller than those under recent conditions as a result of decreased ground-water flow to streams, as shown in the water budget (fig. 12).

Simulated areas contributing recharge to wells and those areas associated with 5- and 12-year travel times were interpreted and adjusted to conform with actual hydrogeologic boundaries, and are shown in figure 17. In addition to overall size of the contributing recharge areas to wells, several differences between these areas and those estimated for recent conditions (fig. 14) are evident. Areas contributing recharge to wells that are associated with travel times of less than 12 years are generally larger under projected 2005 conditions, indicating that water reaches wells more quickly when pumping rates are greater. An exception is the area between Kenvil and Ledgewood, where travel time is less than 5 years under recent conditions. Under projected conditions, the pumping rate of Roxbury Water Company well 3 is zero because the well is no longer used as a result of contamination by volatile organic carbon compounds and has been sealed (Jack Hosking, Roxbury Water Company, oral commun., 1996). The area that contributed recharge to this well in the past will contribute to other discharge points in the future.

Another important difference between areas contributing recharge to wells under recent and projected conditions is that under the projected conditions simulated, surface water along a short segment of the Lamington River in northeastern Chester Township would be induced to flow into the aquifer system and to the MCMUA Alamatong 1 well within 5 years. This is evident in figure 17, where the 5-year contributing recharge area intersects the Lamington River. In contrast, the contributing recharge areas to wells under recent conditions (fig. 14) straddle (but do not intersect) the river in this area, indicating that the river gains flow through the reach. Additional testing of the aquifer system could be conducted to determine more conclusively the likelihood of induced infiltration of streamflow in this area.

Full-Allocation Conditions

If 1996 water allocations were fully utilized, total withdrawals would reach 2,204 Mgal/yr (6.04 Mgal/d), representing a 43-percent increase over recent (1991-95) withdrawals (fig. 9). The distribution of these withdrawals is shown in figure 18. Total withdrawals under full-allocation conditions are only slightly higher than those projected for the year 2005. For some wells, the full-allocation pumping rate is less than the rate projected for the year 2005.

Projected contributing recharge areas to surface water and wells under full-allocation pumping conditions are shown in figure 19. Simulated contributing recharge areas to wells associated with 5- and 12-year travel times were smoothed to conform with actual hydrogeologic boundaries, and are shown in figure 20.

Areas contributing recharge to wells for different travel times (fig. 20) are similar to those estimated for conditions projected for the year 2005 (fig. 17). This result is expected because pumping rates for these two conditions are similar. Some notable differences, attributable to

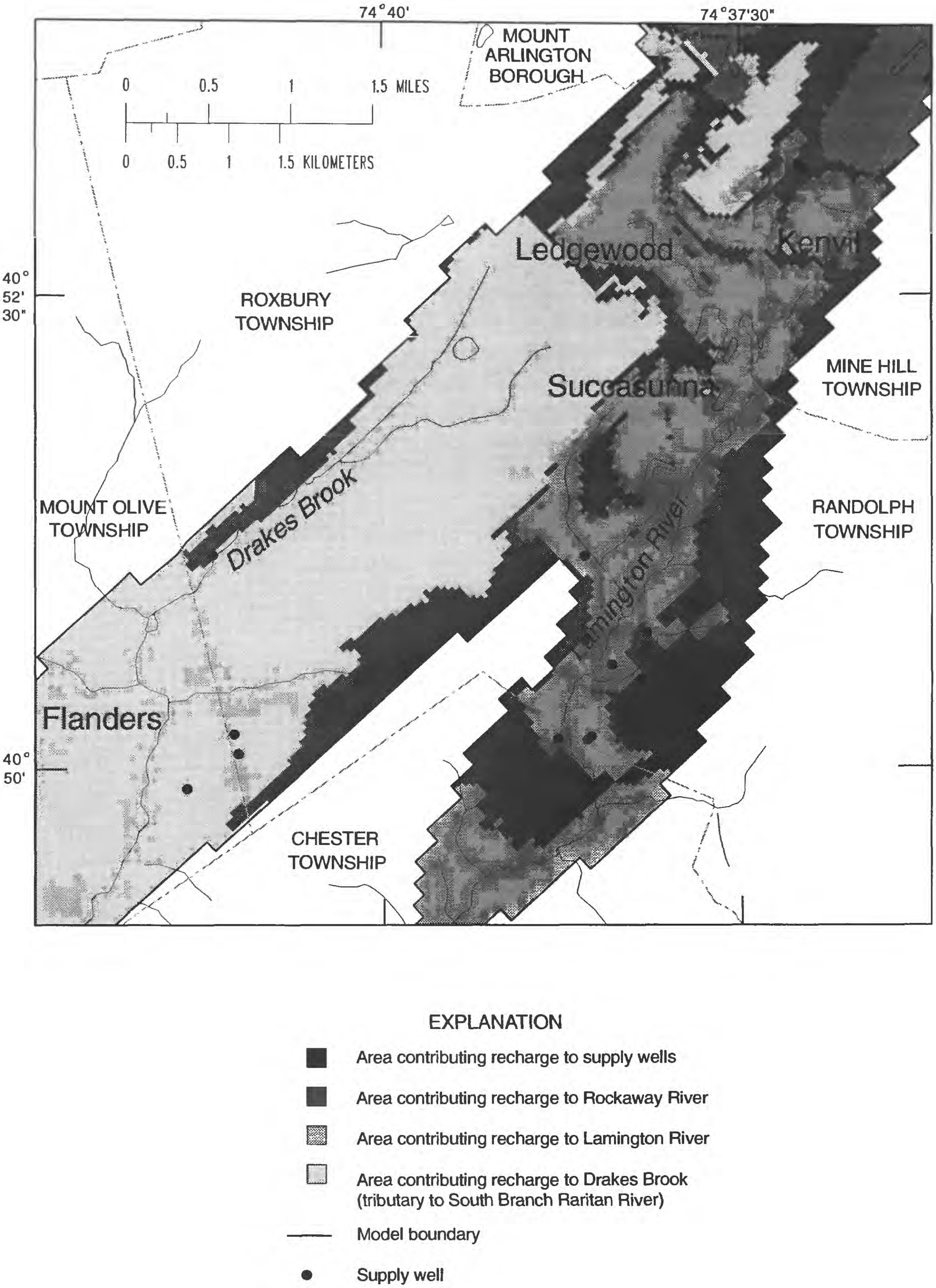
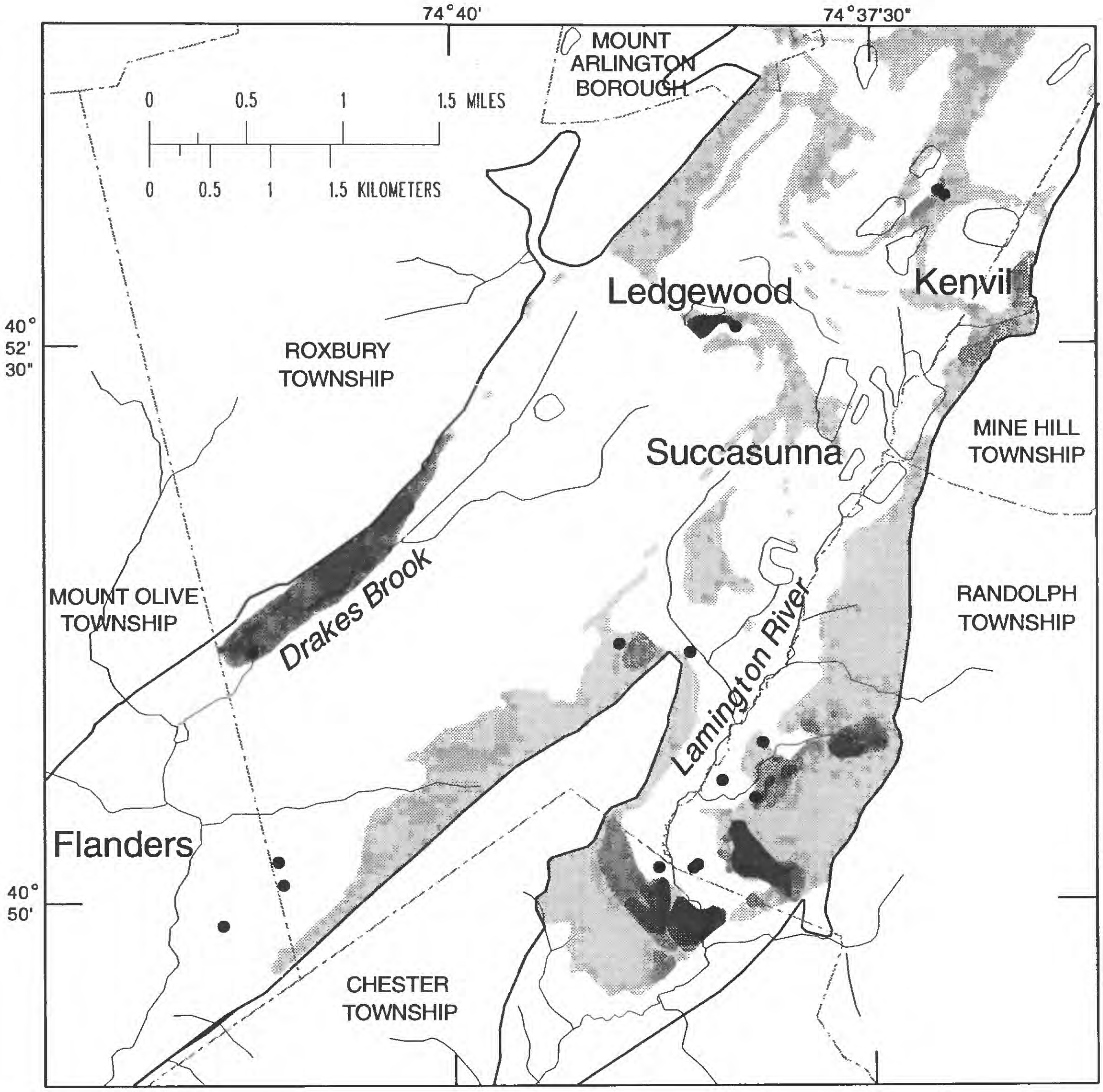


Figure 16. Simulated areas contributing recharge to streams and wells under projected 2005 pumping conditions in the study area, southwestern Morris County, New Jersey.



EXPLANATION

TRAVEL TIME FROM CONTRIBUTING RECHARGE AREA TO WELL, IN YEARS

- $\leq$ 5 years
- > 5 years to $\leq$ 12 years
- > 12 years
- Aquifer-system boundary
- Supply well

Figure 17. Estimated areas contributing recharge to wells that are associated with travel times of 5 years or less, greater than 5 years to less than or equal to 12 years, and greater than 12 years under projected 2005 pumping conditions in the study area, southwestern Morris County, New Jersey.

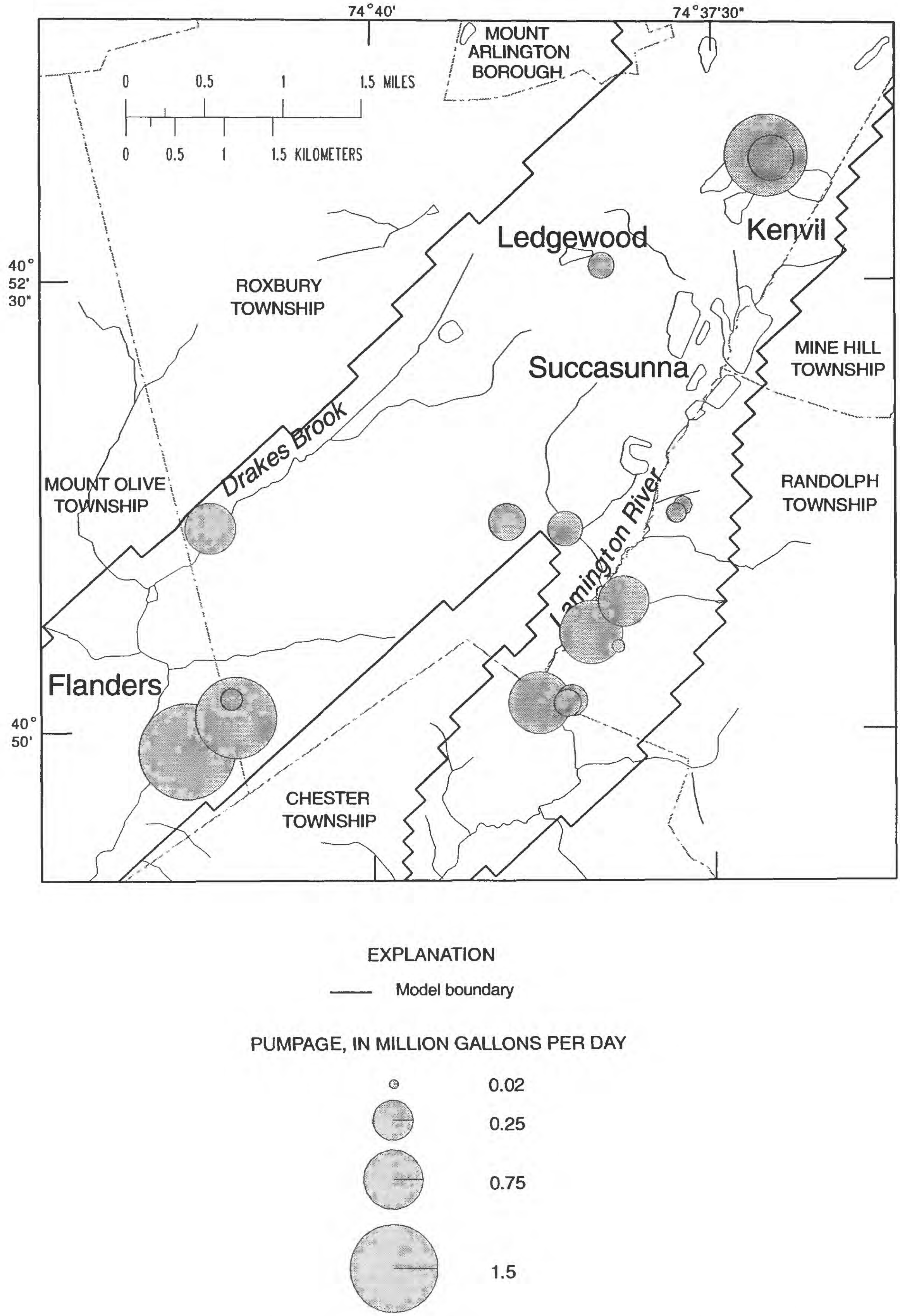
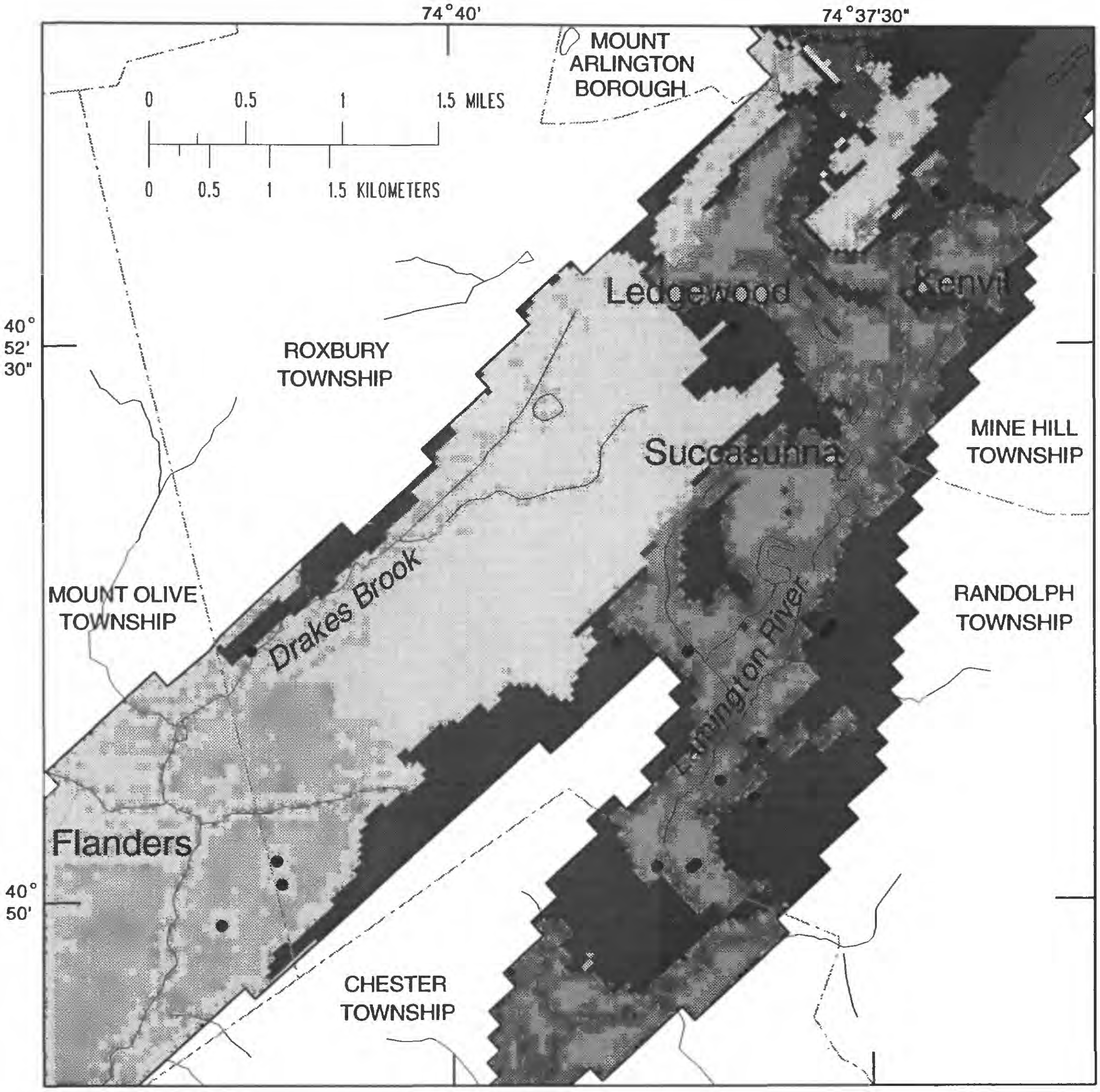


Figure 18. Maximum expected average pumping rate under 1996 full-allocation conditions in the study area, southwestern Morris County, New Jersey.



EXPLANATION

- Area contributing recharge to supply wells
- Area contributing recharge to Rockaway River
- Area contributing recharge to Lamington River
- Area contributing recharge to Drakes Brook (tributary to South Branch Raritan River)
- Model boundary
- Supply well

Figure 19. Simulated areas contributing recharge to streams and wells under full-allocation pumping conditions in the study area, southwestern Morris County, New Jersey.

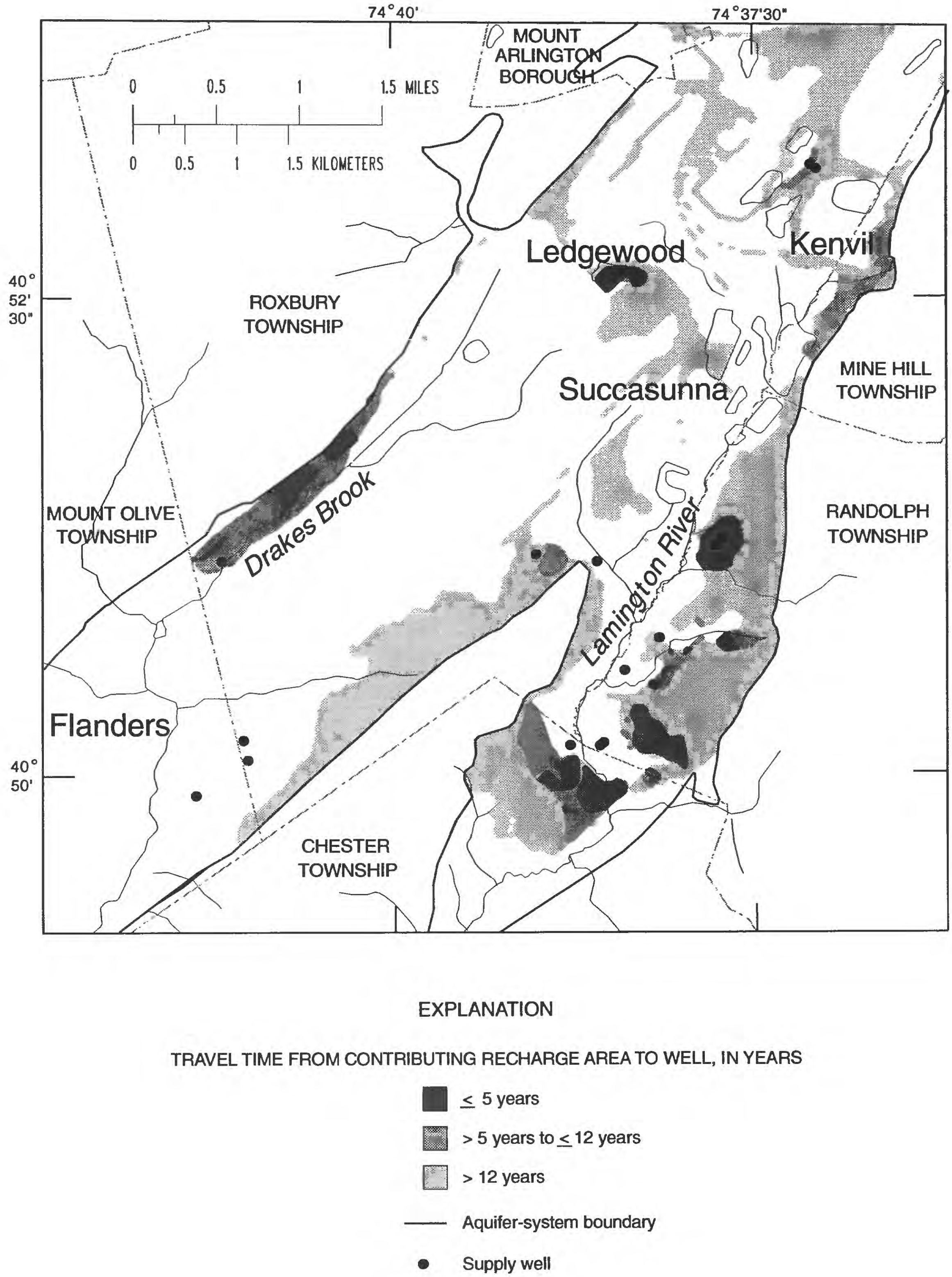


Figure 20. Estimated areas contributing recharge to wells that are associated with travel times of 5 years or less, greater than 5 years to less than or equal to 12 years, and greater than 12 years under full-allocation pumping conditions in the study area, southwestern Morris County, New Jersey.

minor differences in pumping rates, are evident, however. Between Ledgewood and Succasunna, the area contributing recharge to wells with travel time exceeding 12 years under full-allocation conditions is larger than that estimated for 2005 conditions. Along an unnamed tributary east of the Lamington River, the area contributing recharge to wells with travel time between 5 and 12 years under full-allocation conditions is smaller than that estimated for 2005 conditions. These differences illustrate the sensitivity of contributing recharge areas and travel time to pumping rate.

SUMMARY AND CONCLUSIONS

The valley-fill and carbonate-rock aquifer system near Succasunna in the New Jersey Highlands is an important source of water supply for many communities in Morris County, New Jersey. The aquifer system is an assemblage of alluvium, colluvium, stratified and unstratified glacial sediments, low-permeability rock, and permeable carbonate rock underlain and bounded by low-permeability crystalline bedrock. Recharge occurs as direct infiltration of precipitation through the valley floor and as seepage from surface water. Surface-water sources of recharge include natural and induced infiltration from rivers in the valleys, seepage from tributary streams, and unchanneled runoff from adjacent upland areas. Ground-water-flow patterns are tortuous in places. Flow patterns in the uppermost valley-fill sediments are dominated by the effects of surface-water features and aquifer boundaries, and most flow in this aquifer discharges to surface water. Flow patterns in the deeper valley-fill and carbonate-rock aquifers are dominated by the effects of supply wells and of zones characterized by either high aquifer permeability or good vertical hydraulic connection between aquifers.

Withdrawals from the aquifer system in the study area averaged 4.2 Mgal/d during 1991-95, and are projected to increase by 38 percent to about 5.8 Mgal/d by the year 2005. If 1996 allocations were fully utilized, withdrawals would reach 6 Mgal/d, representing a 43-percent increase over recent (1991-95) withdrawals. Withdrawals are increasing in large part to meet water demands of communities in southwestern and central Morris County. As withdrawals increase, areas that contribute recharge to wells increase, and areas that contribute recharge to surface water decrease, resulting in streamflow reduction.

The area contributing recharge to a shallow well is typically located near the well. The area contributing recharge to a deeper well typically consists of highly irregular or fragmented areas, parts of which can be located thousands of feet from the well. The travel time of ground water from distant contributing recharge areas to deeper wells is typically many decades or hundreds of years, whereas travel time to shallow wells from local contributing recharge areas is typically shorter. Some ground water may reach the deeper wells at the Alamatong wellfield within 5 years.

Total areas contributing recharge to supply wells under different pumping conditions were estimated, as well as areas contributing recharge that flows to supply wells in 5- and 12-year periods. Simulation results show that the part of the contributing recharge area that is closest to the well may or may not correspond with the shortest travel time, depending on the local permeability distribution of aquifer and confining- unit materials. Under the recent (1991-95) conditions simulated, some ground water recharging the aquifer system would reach each of the active MCMUA Alamatong wells within 5 years. Contributing recharge areas to wells under the 2005 and full-allocation conditions generally were larger than those under recent conditions. Contributing recharge areas under the 2005 and full-allocation conditions generally were similar because ground-water withdrawals in most areas were similar. Differences in contributing recharge areas and travel times under different conditions are attributable to differences in pumping rates. Under the projected conditions simulated, surface water along a short segment of the Lamington River in northeastern Chester Township would be induced to flow into the aquifer system and to the MCMUA Alamatong 1 well within 5 years.

REFERENCES CITED

CH_2M Hill; Metcalf and Eddy, Inc.; and New Jersey First, Inc., 1994, New Jersey Statewide water supply master plan--Final water supply database: Prepared for the New Jersey Department of Environmental Protection and Energy, August 1994, 10 volumes revised periodically on a rotating basis.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 586 p.

Morrissey, D.J., 1989, Estimation of the recharge area contributing water to a pumped well in a glacial-drift, river valley aquifer: U.S. Geological Survey Water-Supply Paper 2338, 41 p.

New Jersey Department of Environmental Protection and Energy, 1991, New Jersey Well Head Protection Program plan: Trenton, New Jersey, 84 p.

Nicholson, R.S., McAuley, S.D., Barringer, J.L., and Gordon, A.D., 1996, Hydrogeology of, and ground-water flow in, a valley-fill and carbonate-rock aquifer system near Long Valley in the New Jersey Highlands: U.S. Geological Survey Water-Resources Investigations Report 93-4157, 159 p., 3 pl.

Orzol, L.L., 1997, User's guide for MODTOOLS: Computer programs for translating data of MODFLOW and MODPATH into geographic information system files: U.S. Geological Survey Open-File Report 97-240.

Pollock, D.W., 1989, Documentation of computer programs to compute and display pathlines using results from the U.S. Geological Survey modular three-dimensional finite-difference ground-water-flow model: U.S. Geological Survey Open-File Report 89-381, 188 p.

_____ 1994, User's guide for MODPATH/MODPATH-PLOT, Version 3.0: A particle-tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water-flow model: U.S. Geological Survey Open-File Report 94-464, 234 p.

Reilly, T.E., and Pollock, D.W., 1993, Factors affecting areas contributing recharge to wells in shallow aquifers: U.S. Geological Survey Water-Supply Paper 2412, 21 p.

_____ 1995, Effect of seasonal and long-term changes in stress on sources of water to wells: U.S. Geological Survey Water-Supply Paper 2445, 25 p.

Risser, D.W., and Madden, T.M., 1994, Evaluation of methods for delineating areas that contribute water to wells completed in valley-fill aquifers in Pennsylvania: U.S. Geological Survey Open-File Report 92-635, 82 p.

U.S. Environmental Protection Agency, 1987, Guidelines for delineation of wellhead protection areas: Office of Ground Water Protection, U.S. Environmental Protection Agency, June 22, 1987, 131 p.

GLOSSARY

AQUIFER--A rock unit (which may consist of unconsolidated sediments or consolidated rock) that will yield water in a usable quantity to a well or spring.

ANALYTICAL MODELING-- A class of mathematical modeling techniques in which an analytical solution of a governing partial differential equation is obtained. Analytical solutions are available only for highly simplified problems. The usefulness of analytical models in the evaluation of ground-water flow in most real-world systems is limited.

AREA CONTRIBUTING RECHARGE --Area on the land surface through which all ground water passes that eventually flows to a well, stream, or other discharge area.

BASE FLOW--The ground-water contribution of flow to a stream.

CARBONATE ROCK--A rock consisting primarily of limestone or dolomite. Carbonate rock can be highly permeable.

CALIBRATION--Adjustment of model input until the model output adequately resembles the observed conditions in the real aquifer system.

CONFINING UNIT--A unit of rock or unconsolidated sediment with low permeability.

DISCRETIZATION--A process whereby the representation of an aquifer system is divided into a grid consisting of a finite number of cells or elements; hydraulic properties and stresses within each cell or element are assumed to be uniform.

DRAWDOWN--The decline in ground-water level in response to pumping from a well.

FLOW PATH--The subsurface course a water molecule or contaminant would follow in a given ground-water-velocity field. Ground-water models can be used to describe flow paths.

FORWARD TRACKING--A particle-tracking mode in which particles are tracked in the direction of simulated flow (forward direction) in order to define pathlines. In contrast, back-tracking mode involves tracking particles backward, opposite to the direction of simulated flow, to define pathlines.

GROUND-WATER-FLOW MODEL--A representation of relations between and among components of the ground-water system and the rest of the hydrologic system. A conceptual ground-water-flow model can be as simple as a diagram illustrating these relations qualitatively. Mathematical ground-water-flow models can be used to quantify these relations.

HYDRAULIC HEAD--The energy of a water mass, which is a function of elevation, pressure, and velocity. A measure of hydraulic head in an aquifer is the level to which water rises in a well. Differences in hydraulic head over distance cause ground water to flow.

NUMERICAL MODELING--A class of mathematical modeling techniques in which a solution to governing equations is obtained by using numerical methods. Numerical methods involve the replacement of governing partial differential equations with a system of algebraic equations, which are then solved simultaneously by using any of a variety of mathematical procedures. Properly constructed numerical models can represent aquifer systems characterized by irregular boundaries, heterogeneities, and other complexities.

PARTICLE TRACKING--A technique for determining ground-water-flow lines from results of a ground-water-flow simulation. In the application of this technique, the position of a hypothetical water molecule within the model volume is calculated at successive time intervals.

PARAMETER--A quantifiable characteristic of the system being modeled. In the ground-water-flow model presented in this report, the model parameters are hydraulic conductivity, porosity, aquifer and confining-unit thicknesses, recharge, and streambed conductance.

PATHLINE--The trace of a flow path.

PERMEABILITY--A property of a rock unit that determines the rate at which a fluid, such as water, can move through it. Sands and gravels have high permeabilities; silts and clays have low permeabilities.

POROSITY--The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment.

POTENTIOMETRIC SURFACE--A surface that represents the level to which water will rise in tightly cased wells. The water table is the potentiometric surface of an unconfined aquifer.

RECHARGE--The addition of water to the zone of saturation. Recharge can result from the infiltration of precipitation, from the flow of water from a surface-water body into an aquifer, or from the injection of water through an injection well.

SOURCE AREA--In this report, the land-surface area and subsurface volume from which water flows as either surface water or ground water to a stream or point of withdrawal.

STEADY-STATE SIMULATION--A mathematical model solution in which the distributions of hydraulic head and flow do not change through time. The average condition of a system typically can be represented adequately by using steady-state simulation.

TIME OF TRAVEL (TOT)--The time required for a contaminant to move through an aquifer from a specific recharge point to a specific discharge point (such as a well or stream).

VALLEY FILL--A body of unconsolidated sediment deposited within a valley.

WATER TABLE--The upper surface of the zone of saturation at which the water pressure equals atmospheric pressure.

WELLHEAD--The physical structure, facility, or device at the land surface from or through which ground water flows or is pumped from aquifers.

WELLHEAD PROTECTION AREA-- An aquifer volume described in plan view around a well, from which ground water flows to the well and ground-water pollution, if it occurs, poses a significant threat to the water quality of the well (New Jersey Department of Environmental Protection and Energy, 1991, Appendix C).

WELLHEAD PROTECTION PROGRAM--A Statewide effort to enhance protection of water supplies through integration and enhancement of existing programs and new initiatives. Each state is required by USEPA to plan a Wellhead Protection Program (1986 Federal Safe Drinking Water Act Amendments (Section 1428)).