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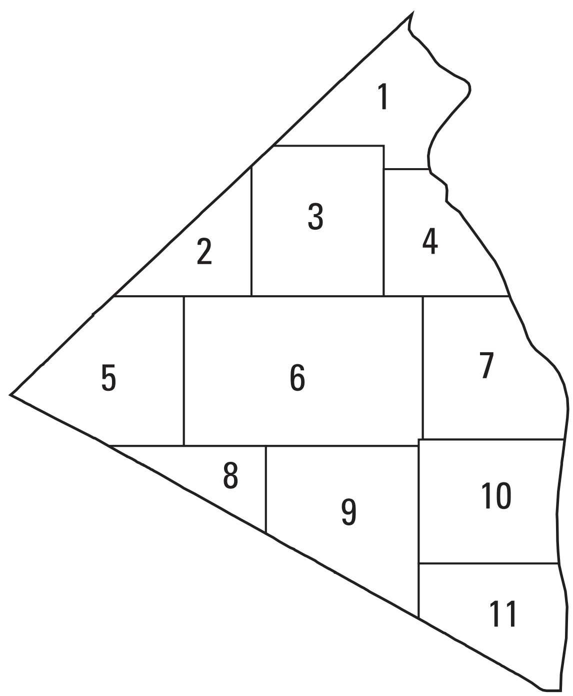
Water Resources of Rockland County, New York, 2005–07, with Emphasis on the Newark Basin Bedrock Aquifer

Scientific Investigations Report 2010-5245

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



1—Production well
2—Spring at Monsey Glen
3—Production well
4—Domestic well
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Cover. Photograph collage of Rockland County water resources.

Water Resources of Rockland County, New York, 2005–07, with Emphasis on the Newark Basin Bedrock Aquifer

By Paul M. Heisig

Prepared in cooperation with Rockland County and New York State Department of Environmental Conservation

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U.S. Department of the Interior
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U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2010

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Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
billion gallons (Ggal)	0.001382	cubic kilometer (km^3)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per month (ft/mo)	0.3048	meter per month (m/mo)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
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]
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
gallon per day per foot (gal/d/ft)	0.01242	cubic meter per day per meter ($m^3/d/m$)
gallon per day per square mile [(gal/d)/mi^2]	0.001461	cubic meter per day per square kilometer [(m^3/d)/km^2]
billion gallons per year (Ggal/yr)	0.001382	cubic kilometer per year (km^3/yr)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
million gallons per year (Mgal/yr)	3,785	cubic meter per year ($m^{3/yr}$)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s)/m]
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

*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.

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32)/1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88) unless specified as 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.

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

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations

GW ET	Groundwater Evapotranspiration
ET	Evapotranspiration
T	Transmissivity

Acronyms

USGS	U.S. Geological Survey
NYSDEC	New York State Department of Environmental Conservation
UWNY	United Water New York
WSA	Water Supply Application

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Water Resources of Rockland County, New York, 2005–07, with Emphasis on the Newark Basin Bedrock Aquifer

By P.M. Heisig

Abstract

Concerns over the state of water resources in Rockland County, NY, prompted an assessment of current (2005–07) conditions. The investigation included a review of all water resources but centered on the Newark basin aquifer, a fractured-bedrock aquifer over which nearly 300,000 people reside. Most concern has been focused on this aquifer because of (1) high summer pumping rates, with occasional entrained-air problems and an unexplained water-level decline at a monitoring well, (2) annual withdrawals that have approached or even exceeded previous estimates of aquifer recharge, and (3) numerous contamination problems that have caused temporary or long-term shutdown of production wells. Public water supply in Rockland County uses three sources of water in roughly equal parts: (1) the Newark basin sedimentary bedrock aquifer, (2) alluvial aquifers along the Ramapo and Mahwah Rivers, and (3) surface waters from Lake DeForest Reservoir and a smaller, new reservoir supply in the Highlands part of the county. Water withdrawals from the alluvial aquifer in the Ramapo River valley and the Lake DeForest Reservoir are subject to water-supply application permits that stipulate minimum flows that must be maintained downstream into New Jersey. There is a need, therefore, at a minimum, to prevent any loss of the bedrock-aquifer resource—to maintain it in terms of both sustainable use and water-quality protection.

A regional conceptual model of the aquifer framework was needed upon which other regional and local hydrogeologic data could be overlaid to define the regional groundwater flow system. From that perspective, water-resource questions could be addressed from a regional context.

The framework of the Newark basin bedrock aquifer included characterization of (1) the structure and fracture occurrence associated with the Newark basin strata, (2) the texture and thickness of overlying glacial and alluvial deposits, (3) the presence of the Palisades sill and associated basaltic units on or within the Newark basin strata, and (4) the streams that drain the aquifer system. The structure of the aquifer was in part defined by previous geologic mapping, including strike and dip measurements of the sedimentary strata that fill the basin, and lithologic mapping that shows westward coarsening from mudstones and siltstones to conglomeratic sandstones. Borehole geophysical surveys were conducted at 24 wells and provided critical subsurface structural data. Other data that contributed to the conceptual model of the aquifer framework included groundwater-level responses to pumping at production wells and groundwater and surface-water chemistry (particularly chloride). The strike of the tilted bedding constrains groundwater flow because the most productive water-bearing fractures are subparallel to bedding. The general strike of bedding is north-northeast and the dip is about 10 degrees to the northwest. The regional groundwater flow system was delineated by overlaying aquifer-wide groundwater-level data on the bedrock framework (bedding strike lines). Groundwater divides were identified, including a major southeast to northwest regional divide that partitions groundwater flow northeastward to discharge at the Hackensack River and its tributaries and southwestward to discharge in the Mahwah River, Pascack Brook, and Saddle River drainages.

Review of pumping-rate and water-level data from the bedrock aquifer during 1989–2004 suggests that there is not a year-to-year, aquifer-wide downward trend in water levels. There have been periods of several years where water levels at individual wells show declines, and groundwater levels have declined in response to new stresses as production wells have come online, especially if the wells have been used continuously. Once pumping is initiated, water levels decline toward a new equilibrium, if possible. In fact, water levels in a large area of the most productive west-central part of the bedrock aquifer have declined because of withdrawals and depths to water in this part of the aquifer are the greatest (100–150 feet).

The greatest concern regarding sustainability of groundwater resources is the aquifer response to the seasonal increase in pumping rates from May through October (an average increase of 25 percent in 2005). Investigation of pumping rates and water levels during these periods indicates that water levels in most wells decline beyond what is expected under natural conditions and that the effective aquifer yield can decrease as water levels drop or as entrained air from stressed aquifer conditions creates problems in the distribution system. Increases in pumping rates at certain productive well fields during summer result in water-level decline rates that

are not sustainable and that represent the greatest stresses on the aquifer. Extrapolation of water-level decline rates under conditions of continuous pumping (a worst-case scenario, although the assumption of no decrease in aquifer yield over the summer is a best case scenario) indicates that between 10 and 15 wells would not be able to pump through the entire high-water-use season (May 15 to October 1). In most cases, pump rates would have to be reduced as aquifer yield declines. This analysis underlines the fragility of the aquifer given the fact that recent years (2003–06) have been relatively wet. Large seasonal water-level fluctuations in the most productive part of the aquifer indicate that recharge during the non-growing season thus far has been enough to replenish the aquifer prior to the next growing season. Streams also are affected by seasonal increases in groundwater pumping rates; nearly all streams in the productive west-central area of the aquifer went dry during dry periods in late summer of 2005.

Impervious surfaces increase the amount of stormflow and decrease the amount of base flow in streams. Analysis of stormflows in watersheds with 11.9 and 17 percent impervious surface area increased the percentage of rainfall that becomes stormflow in streams by 7 to 8 percent and by 12.5 to 16.5 percent, respectively.

Recharge was estimated from streamflow data and from groundwater-level data. Estimates from across the county in 1961 ranged from 24.8 inches in the northwest (New York Highlands area) to 14.7 inches in the southeast. Recharge largely parallels the annual amount of precipitation. Recharge is probably highest in the Highlands because of high precipitation, despite crystalline bedrock that acts as a relatively poor aquifer. Across the county, the thickness of glacial deposits that mantle bedrock also appeared to be a major control on the amount of recharge. The distribution of monthly recharge was documented, including substantial recharge during the growing season in 2006.

Water budgets were generated for three basins with streamflow data. During1959–94 and in 2006, groundwater pumpage for public supply accounted for 12 to 24 percent of recharge within the Mahwah River near Suffern, NY, watershed. Public-supply pumpage as a percentage of recharge in 2006 at the two other currently gaged watersheds (Pascack Brook and Saddle River) was 18 and 21 percent, respectively.

About 12.9 billion gallons of water was used in Rockland County in 2005. The majority (63 percent) was for base-line domestic supply (non-growing season rates of use); of this amount, about 6 percent was from domestic wells and 94 percent was from production wells and reservoirs. Commercial, industrial, and institutional users made up 10 percent of total water use, and growing-season increases accounted for 18 percent.

Sanitary sewers serve much of Rockland County and the majority of treated wastewater is discharged to the Hudson River, which is an estuary with brackish water adjacent to Rockland County. Inflow of stormwater and infiltration of groundwater constitute a significant additional contribution of water to the sanitary sewer system.

Introduction

Rockland County has undergone major suburban development since the mid-1950s when access to New York City, about 15 mi south, was greatly improved with the completion of the New York State Thruway and the Palisades Interstate Parkway. The county population has increased from about 89,000 in 1950 to nearly 295,000 in 2005 (http://quickfacts.census.gov/qfd/states/36/36087lk.html, accessed October 3, 2007). Development has been concentrated in the lowland parts of the county, which are underlain by a fractured-sedimentary bedrock aquifer that has historically served as the primary source of water supply for the county. Glacial deposits of variable thickness overlie the bedrock and offer limited protection from contamination by human activities. Some aspects of groundwater quality have degraded over the last 50 years, and during that time, at least 13 well fields have been abandoned or fitted with treatment systems because of contamination from gasoline, organic solvents, and other organic compounds.

Concerns over the quantity of water available from the bedrock aquifer in particular but also the alluvial aquifer and reservoir have also come to light during dry, hot summer periods over the past decade. Many instances of reduced pumping rates at production wells have occurred in response to low groundwater levels in late summer. Because irrigation of lawns is a major component of the increase in water use during the summer, outdoor water use has been periodically restricted. The Rockland County Department of Health compared annual withdrawals from the bedrock aquifer with estimates of annual recharge (Leggette, Brashears & Graham, Inc., 1979) and determined that withdrawals in 2001–02 were between 88 and 145 percent of recharge (D. Miller, Rockland County Department of Health, written commun., 2003). The Department of Health determined that if the recharge estimates were correct, the aquifer was not being managed at a sustainable rate. An additional concern was a decline of the groundwater level at bedrock monitoring well Ro-1274, located within a heavily pumped area of the aquifer.

Rockland County has a long history of commercially owned, rather than municipal, public water supplies. The current water supplier, United Water New York (UWNY), a subsidiary of Suez, a multinational corporation (now Suez Environment), serves most of Rockland County. United Water New Jersey, another subsidiary of Suez, operates in adjoining areas in Bergen County, NJ.

The U.S. Geological Survey (USGS), in cooperation with Rockland County and the New York State Department of Environmental Conservation (NYSDEC), undertook a 5-year study of the water resources of Rockland County to provide information on current water-resource conditions in the sedimentary bedrock aquifer and to consider possible additional resources. Information from this study can be used by local, State, and Federal agencies, water suppliers, consultants, and the general public in the management and protection of potable and ecological water resources within the county. The second part of this investigation was the development of a numerical computer flow model of the aquifer. A numerical model can incorporate a number of factors that affect recharge and simulate recharge across the aquifer surface. Model simulation of pumping conditions provides a consistent means of estimating contributing areas to major supply wells. This information is particularly useful for protection of aquifer water quality–for example, identifying which wells might be affected by groundwater contamination from hazardous waste sites or from a hazardous-waste spill. Documentation and results of the aquifer simulation are presented in Yager and Ratcliffe (2011).

Purpose and Scope

This report describes the current (2005–2007) state of water resources in Rockland County, NY. The report details the hydrogeology of the sedimentary bedrock aquifer (hereafter referred to as the Newark basin aquifer), including a conceptualization of the groundwater flow system. Specifically, this report documents the water sources and water use in the county; describes the components of the hydrogeologic framework, including the thickness of unconsolidated deposits, and the orientation of bedrock structure; and superimposes streamflow, groundwater-level, and water-quality data on that framework to present a conceptual model of the groundwater flow system. Three hydrogeologic sections and 10 groundwater-level hydrographs are included. Borehole geophysical logs from 24 wells, groundwater-level measurements from 4 synoptic surveys, stream and groundwater chemistry data, and water-use data are presented in figures, tables, and maps. This report also describes streamflow conditions and examines the effect of impervious surfaces on the stormflow and base-flow components of streamflow. Annual and monthly recharge estimates are presented from analyses of streamflow and groundwater levels. Recharge estimates from the Highlands area of the county are also provided. A conceptual water budget for the sedimentary bedrock aquifer is included, with changes related to suburban development. Water budgets for currently gaged watersheds are presented.

The structure of the sedimentary bedrock was based on:

1. Measurements of strike and dip at bedrock outcrops,
2. Measurements of strike and dip from geophysical borehole logs at 22 wells,
3. Correlation of geophysical logs between nearby wells,
4. Hydraulic interconnection of wells from aquifer test and groundwater-level data,
5. Water-quality distribution across the aquifer,
6. Linear features, such as stream alignments,
7. Regional groundwater-level maps, and
8. Lithologic variations (primarily carbonate content) of bedrock.

The findings of this investigation provide a basis for answering the following questions regarding water resources in Rockland County, which are addressed at the end of the report:

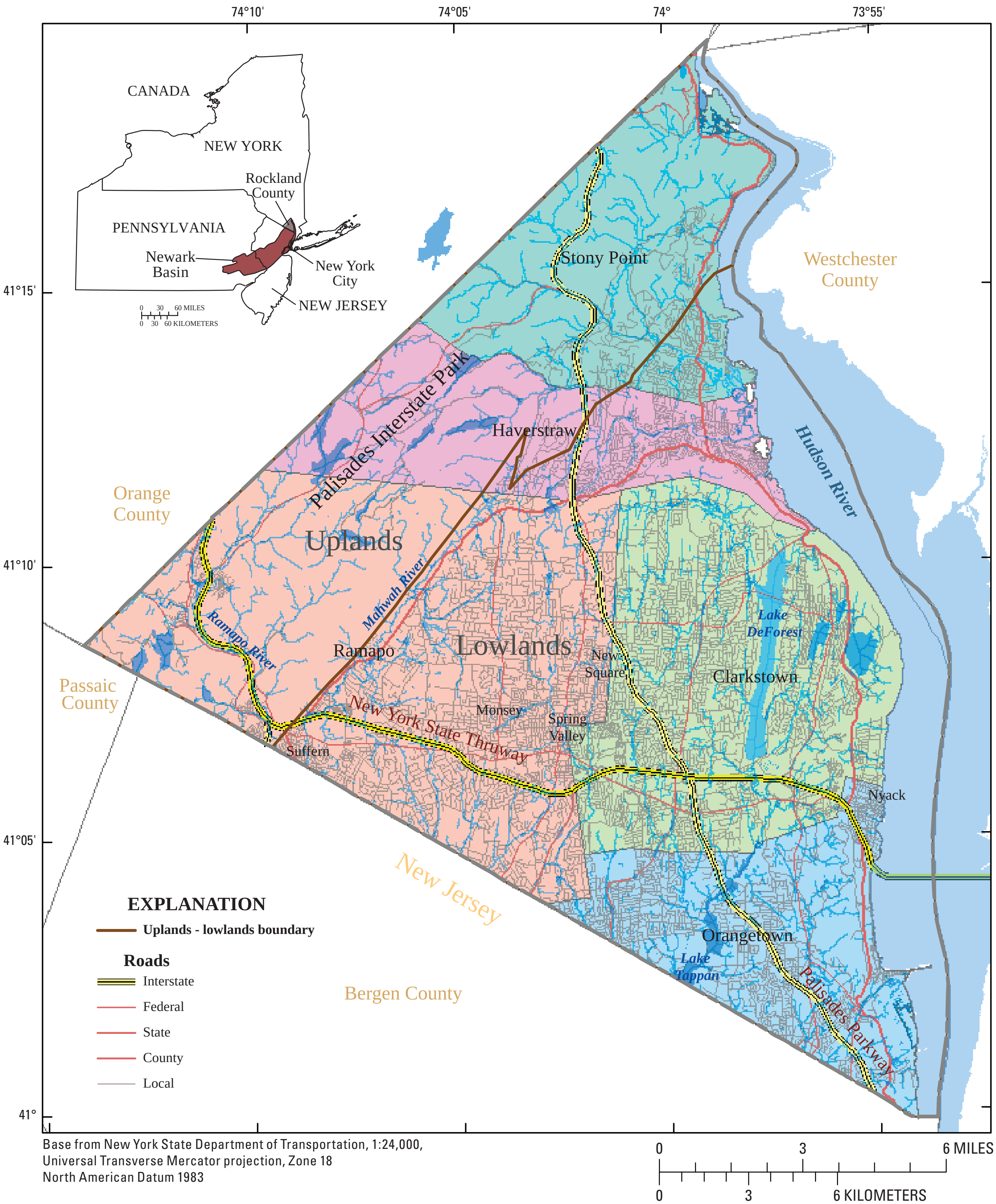
1. Are current groundwater withdrawal rates depleting aquifer storage?
2. Can rainfall data serve as a guide for determination of sustainable withdrawal rates for different climatic conditions? If so, what are sustainable rates for well fields that tap the aquifer?
3. Does induced infiltration of streamflow contribute water to supply wells?
4. Does leakage from water-supply mains and sanitary sewers contribute recharge to the aquifer?
5. What are the shape and extent of land-surface areas that contribute recharge to production wells?
6. What is the distribution and amount of groundwater pumped from domestic wells?
7. What are the annual amounts of precipitation that fall across the county, and how much of that water recharges the bedrock aquifer?
8. Are there additional water resources in the county that might be utilized?

Study Area

Rockland County covers an area of about 174 mi^2 in the metropolitan area of southeastern New York State, about 15 mi north of New York City (fig. 1). Roughly triangular in shape, the county is bordered on the east side by the Hudson River (Westchester County), on the northwest by Orange County, and on the southwest by New Jersey (Bergen and Passaic Counties). The county is divided into five townships (fig. 1)—Ramapo, Orangetown, Clarkstown, Haverstraw, and Stony Point. Most of the population is concentrated in the suburban lowland area of the county (about 134 mi^2). Much of the upland area of the county is parkland—part of the Palisades Interstate Park and several county and State parks.

Development History and Associated Hydrologic Changes

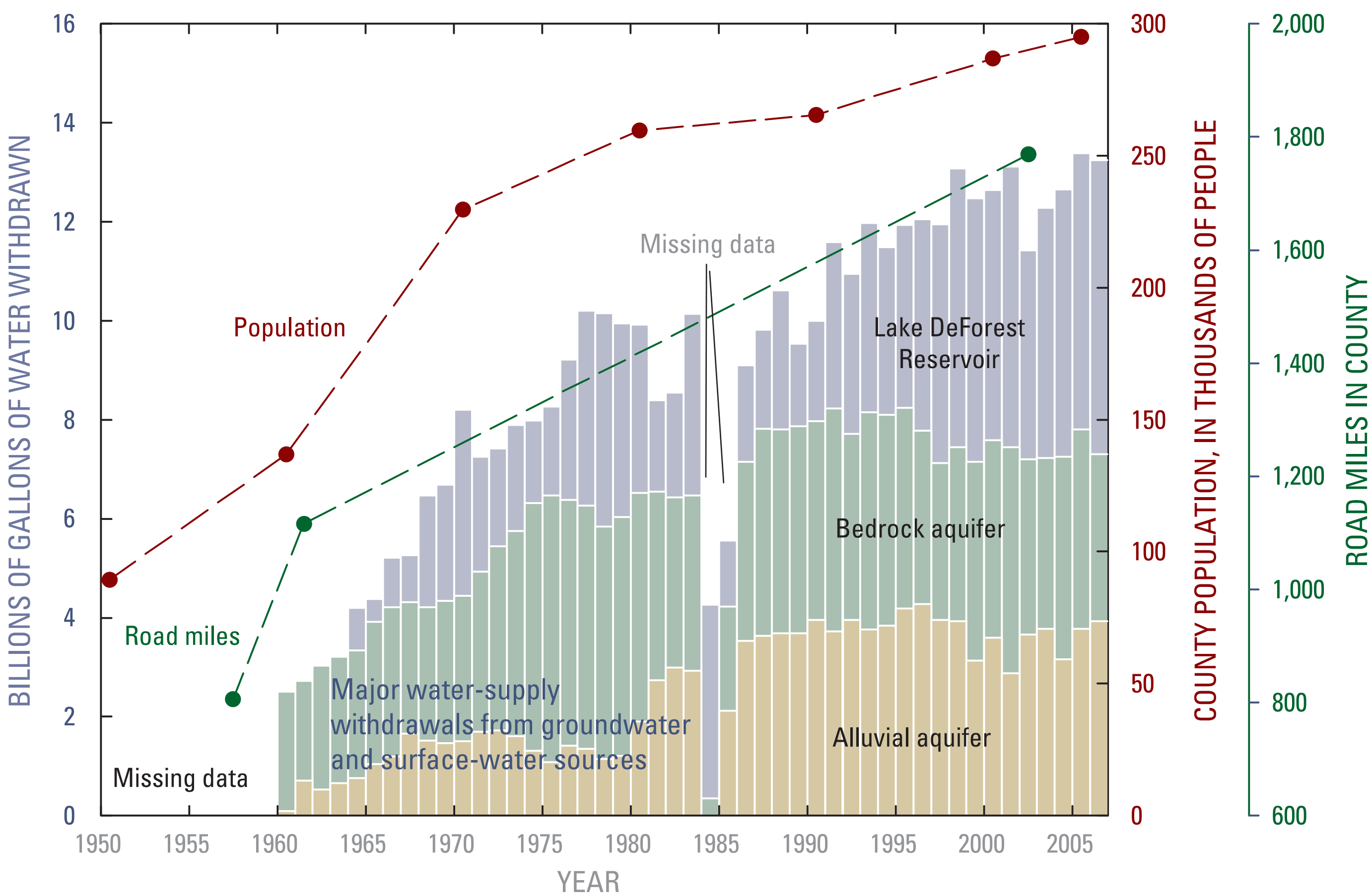
Prior to World War II, Rockland County was mostly rural and agricultural in character. Domestic water supplies were primarily individual or small-group supplies from springs,



Fgure 1. Rockland County, New York, study area, including towns, roads, hydrography, and upland and lowland areas.

dug wells, and shallow bedrock wells. Some villages, such as Spring Valley, were supplied by privately owned production wells that tapped the bedrock aquifer as far back as the 1890s (http://www.unitedwater.com/uwny/whony.htm, accessed August 20, 2007). Suburban development in Rockland County began after World War II. From 1950 to 1960, the county population increased by about 48,000 people (fig. 2). From 1960 to 1970, the population increased by 92,000 people. Suburban development was spurred in the mid-1950s by the completion of the Palisades Interstate Parkway and the New York State Thruway, which bisect the county north to south and east to west, respectively. These roads greatly improved accessibility to New York City. Domestic wells continued to be drilled as the population increased, but many new housing developments were supplied by new public supplies: (1) deep bedrock-aquifer production wells, (2) the Lake DeForest Reservoir, an impoundment of the Hackensack River in the eastern part of the county (built in the late 1950s, with diversions for water supply starting in 1965), and (3) alluvial-aquifer well fields in the Mahwah River (1961) and the Ramapo River (1979) valleys, which tap deposits of sand and gravel and induce flow from the respective rivers into the aquifers and to the wells (fig. 1). The mid-1960s drought spurred exploration for additional water supply from the bedrock aquifer; the greatest increases in new production wells in Rockland County were during the late 1960s to mid -1970s.

Suburban development has affected the water resources of the county more than simply increases in water use. Installation of sanitary sewers and increases in impervious surface and storm sewers have reduced the groundwater resource by exporting wastewater from the county, reducing recharge, and shifting the streamflow regime toward higher stormflows and lower base flows. Installation of sanitary sewers and drainage infrastructure has generally occurred in conjunction with development across the county. About 42 percent of the population was served by public sewerage systems in the early 1960s (Ayer and Pauszek, 1963); today, nearly the entire county is sewered. Wastewater is routed to treatment plants and exported out of the county to the Hudson or Ramapo Rivers. An additional loss of water from the local hydrologic system is inflow and infiltration of storm runoff and shallow groundwater into sanitary sewers, especially during wet periods. The loss of water through sanitary sewers in 2005 was about 14.6 billion gallons— roughly equivalent to



Fgure 2. Changes in population, road miles, and water-supply withdrawals in Rockland County, New York.

double the annual flow of the Mahwah River at the streamgage near Suffern, NY (01387450). Prior to sanitary sewering, about 90 percent of water pumped by domestic wells was returned to the local soil/aquifer system through onsite septic systems or cesspools (Pebbles, 2003). Storm sewers rapidly route storm runoff from paved surfaces and sloped lawns to local streams and ultimately out of the county. Increases in storm runoff from paved surfaces decrease aquifer recharge and evapotranspiration (ET).

Climate

The climate of Rockland County is classified as humid continental (Koppen-Geiger Classification), with winters that are cold but not long. Data from Suffern, NY, published in the Soil Survey of Rockland County (U.S. Department of Agriculture, Soil Conservation Service, 1990) show mean monthly air temperatures below 40°F only from December through March and freeze dates with temperatures below 28°F generally from late October to mid-April. Annual snowfall averages about 26 in.

Annual precipitation totals vary locally with the tracks of individual summer thunderstorms and more regionally through orographic (altitude) effects (fig. 3). Mean annual precipitation (2005–07 averages) was generally highest in the uplands area of the county (about 58 in.) and decreased toward the southeast in the lowlands (about 47 in.). The maximum annual difference among nine measurement stations was 11.8 in. Differences in annual precipitation across the central part of the lowland area, however, were small.

Suffern, West Point, and Spring Valley weather stations have precipitation records beginning in the 1940s or 1950s, but none of the stations have complete data records. The longest, most complete precipitation record in the county was measured from 1940 to 2002 at the Letchworth water-treatment plant in the uplands (fig. 3). Mean annual precipitation for that period was 49.27 in. (median = 48.42 in.). Mean annual precipitation values at the other sites are 47.12 in. (1956–82) at Suffern (U.S. Department of Agriculture, Soil Conservation Service, 1990) and 48.14 in. (1940–62) at Spring Valley (Ayer and Pauszek, 1963).

Precipitation is distributed relatively evenly throughout the year; monthly means are between 3 and 4.5 in. at the Letchworth and Suffern stations (fig.4). February, however, exhibited the narrowest range and lowest median value of monthly precipitation at the Letchworth streamgage (fig. 4). Despite these relatively constant mean and median monthly values, monthly totals can vary by 8 to 15 in. Severe thunderstorms, northeasters, and hurricanes periodically occur, and the Letchworth data reflect these events. Deficits in precipitation also occur, and monthly totals of less than 1 in. have been recorded for every month except April.

Evapotranspiration, the return of precipitation to the atmosphere through evaporation and transpiration (the uptake and release of soil water to the atmosphere by plants), was

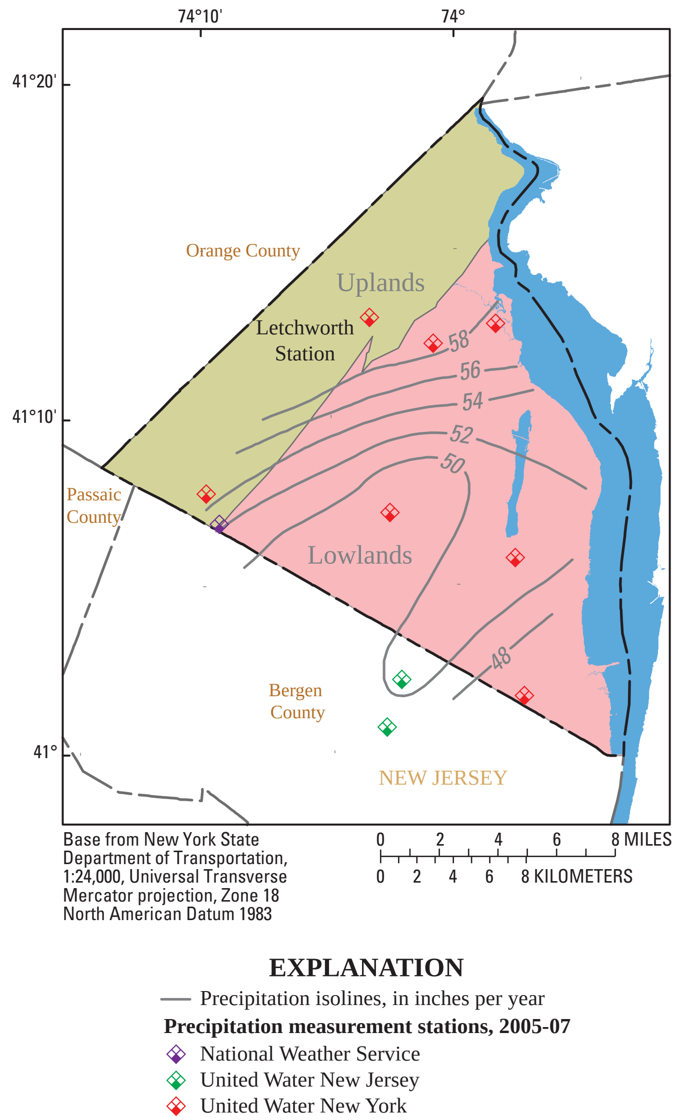
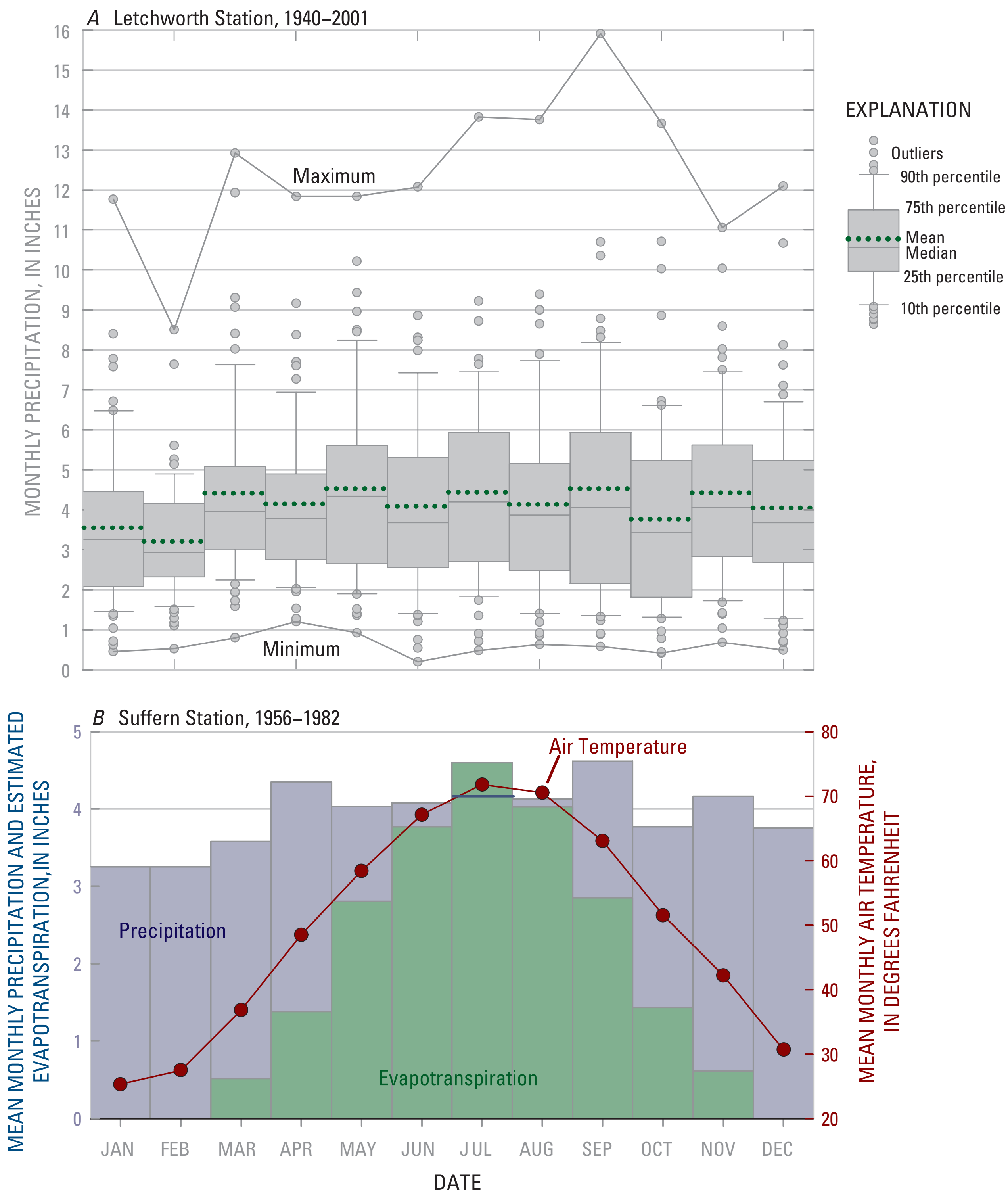


Figure 3. Distribution of annual precipitation, in inches, across Rockland County, New York, 2005–07.

estimated to average about 22 in/yr in Rockland County (Randall, 1996). The annual distribution of ET mostly depends on the growing season (plant activity), the type of vegetation, temperature, and soil type. The average percentage of ET in each month was estimated from temperature data collected at the Suffern, NY, streamgage from 1956 to 1982, using the method of Thornthwaite and Mather (1957). This method produced monthly estimates that were based on single soil and vegetation types, which is an oversimplification of conditions in the area. The estimated annual value from this method was deemed too high relative to Randall (1996), so the monthly percentage of annual ET was applied to the 22-in. total from Randall (1996) and apportioned to each month. The results are shown in figure 4 with average monthly precipitation and temperature from the Suffern streamgage (U.S. Department of Agriculture, Soil Conservation Service, 1990). The



Fgure 4. Climatic data for Rockland County: *A,* monthly precipitation at the Letchworth precipitation station in northern Rockland County, 1940–2001; *B,* mean monthly precipitation, estimated evapotranspiration, and air temperature at the Suffern, New York, streamgage, 1956–82.

figure depicts the seasonal nature of ET and its dependence on temperature and the growing season. On average, ET nearly equals or exceeds precipitation during June, July, and August, which leaves little excess water for aquifer recharge or streamflow.

Drainage

Streams and rivers in Rockland County are tributaries to four large drainages: the Hudson River, the Hackensack River, the Ramapo River, and the Passaic River (in New Jersey). The Ramapo River is a tributary to the Passaic River farther south in New Jersey. The largest streams originating within the county are the Hackensack River in the east and the Mahwah River, which joins the Ramapo River just south of the New York-New Jersey border, in the west (fig. 5).

The Hudson River bounds the eastern side of the county and receives tributary flow from Cedar Pond Brook and Minisceongo Creek in the northern part of the county and Sparkill Creek in the extreme southern part of the county. Both northern streams are impounded in several places in the uplands and have been used for water supply in the past. The Hudson River is a major East Coast estuary that is brackish in the reach adjacent to Rockland County with a local tidal fluctuation of about 3 ft (Perlmutter, 1959; http://xtide.ldeo.columbia.edu/hudson/tides/predictions.html, accessed November 16, 2010).

The Hackensack River drains about 48 mi^2 of the eastern lowland part of the county and is bounded on the east and north by the Palisades sill and its western extension (South Mountain). The upper Hackensack River has a minor impoundment at Lake Lucille and major impoundments downstream at the Lake DeForest Reservoir and at the Lake Tappan Reservoir, which straddles the State border with New Jersey (fig. 5). Lake DeForest is a source of water supply for Rockland County and provides downstream releases to New Jersey as stipulated by the New York State Department of Environmental Conservation (NYSDEC) Water Supply Application (WSA) no. 2189. Water from the Hackensack River below Lake DeForest supplies the village of Nyack. United Water New Jersey uses the Lake Tappan Reservoir as a source of water supply. Large tributary streams of the Hackensack River in Rockland County include the Demarest Kill (also known as New City Brook), Demarest Mill Brook, East Branch Hackensack River, and Nauraushaun Brook (fig. 5).

The Ramapo River is an important water source despite its relatively short reach in the southwest corner of Rockland County. Most of the headwater drainage area of the Ramapo River (86.9 mi^2 at the Ramapo River at Ramapo, NY, streamgage; 01387400) is to the north in Orange County. The reach in Rockland County cuts through and across the uplands, and the valley fill is a highly permeable sand and gravel that forms a productive alluvial aquifer[1] tapped by well fields operated by UWNY and the village of Suffern. Tributary streams that enter the Ramapo River from the uplands include the following: from the north, Stony Brook and Torne Brook, and from the south (in part from New Jersey), the drainage of Cranberry and Potake Ponds. NYSDEC WSA permit no. 6507 stipulates minimum flow in the Ramapo River that must be maintained downgradient from the well field into New Jersey.

The Mahwah River is the largest headwater drainage of the Ramapo River in Rockland County. The drainage course follows the boundary between the crystalline uplands and the lowlands (sedimentary rock); the drainage area includes parts of each of these areas (fig. 5). The sand and gravel deposits within the Mahwah River valley are not as widespread and well-sorted as in the Ramapo River valley, but three well fields, two of which are capable of pumping more than 600 gal/min, induce infiltration from the river.

The Saddle River and Pine Brook drainages are headwater reaches of the Passaic River in south-central Rockland County (fig. 5). Both streams are deeply incised relative to most other streams in the lowland area of the county. Both streams have small impoundments along their lengths and have bedrock supply wells along their lower reaches. The Saddle River valley across the State boundary in New Jersey contains sand and gravel deposits that are tapped by two production wells about 1 mi south of the border. Pumping at this well field is also subject to maintenance of minimum downstream flows.

Pascack Brook drains the central and south-central parts of the lowland area of the county and joins the Hackensack River a few miles into New Jersey. The drainage basin is widest in the headwater area around Spring Valley and narrows to the south (fig. 5). The southern section of the drainage area includes the Muddy Brook tributary, which received a 1992–2004 average discharge of about 1.2 Mgal/d of spent cooling water from industry in its headwater area (S. Vogler, New York State Department of Environmental Conservation, written commun., 2005). There are no sand and gravel wells in this drainage, although such deposits are at least 25 ft deep in the reach of Muddy Brook at Pearl River.

Current and historic streamgages are presented in table 1. Streamgages on unregulated streams in or near Rockland County are currently limited to one long-term streamgage on the Mahwah River and two recent (since 2005) streamgages on the Saddle River and Pascack Brook just over the State border in New Jersey. Three other streamgages measure streamflows from regulated watersheds: one on the Hackensack River below the Lake DeForest Reservoir and two on the Ramapo River—one upstream and one downstream of the alluvial well field. Treated wastewater discharges add to streamflow at the upstream streamgage. Historic short-term streamflow records in Rockland County include 1 or 2 years during 1959–61 from 15 streamgages (Ayer and Pauszek, 1963).

[1] Alluvial aquifer is defined in this report as a valley-fill aquifer (sand and gravel) in which pumping wells derive at least part of their water from the stream or river that flows through the valley (through induced infiltration). The sand and gravel of alluvial aquifers in Rockland County is glaciofluvial in origin.

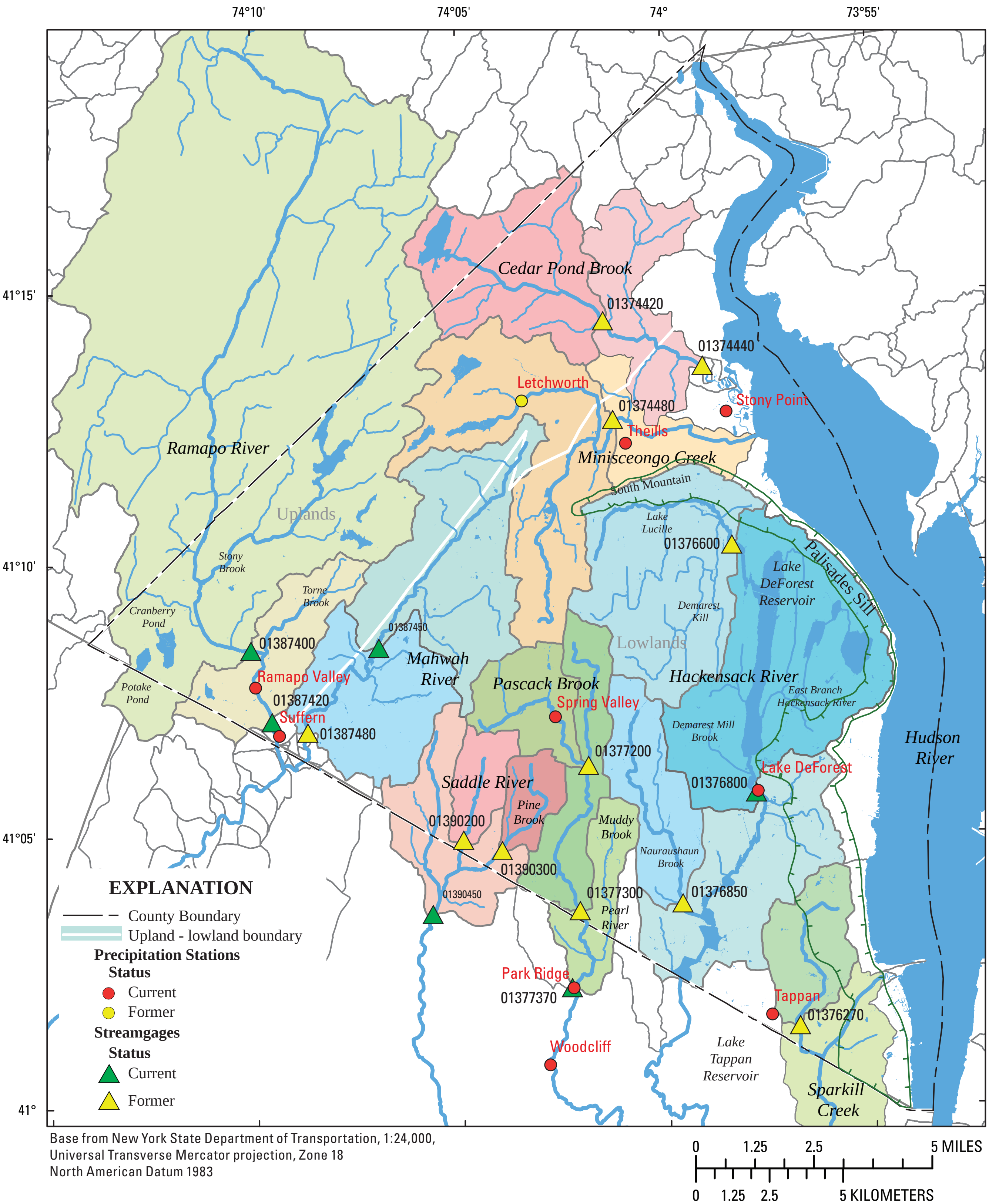


Figure 5. River and stream drainages in Rockland County, New York, with current and former precipitation stations and streamgages (denoted with U.S. Geological Survey site identification number).

Table 1. Current and historic streamflow-measurement gages in or near Rockland County, New York.

[Shaded areas indicate currently operating streamgages. NY, New York; NJ, New Jersey]

Streamgage name	USGS streamgage number	Drainage area, (mi²)	Period of record	Comment	Underlying bedrock type in Rockland County	Major watershed
Lake Tiorati Brook at Cedar Flats, NY	01374420	10.6	10/1/59–12/31/61		crystalline	Hudson
Cedar Pond Brook at Stony Point, NY	01374440	17.4	11/1/59–12/31/61		crystalline / sedimentary	Hudson
Minisceongo Creek at Theills, NY	01374480	15.0	10/1/59–12/31/61		crystalline / sedimentary	Hudson
Sparkill Creek at Tappan, NY	01376270	4.9	10/1/59–12/31/61		crystalline / sedimentary	Hudson
Hackensack River at Brookside Park, NY	01376600	12.9	10/1/59–12/31/61		crystalline / sedimentary	Hackensack
Nauraushaun Brook at Nauraushaun, NY	01376850	5.9	2/1/60–9/31/61		sedimentary	Hackensack
Pascack Brook Trib. at Spring Valley, NY	01377200	4.2	10/1/59–12/31/61		sedimentary	Hackensack
Pascack Brook at Pearl River, NY	01377300	10.0	9/1/59–12/31/61		sedimentary	Hackensack
Mahwah River near Suffern, NY	01387450	12.3	8/1/58–3/31/95, 10/1/05–present		crystalline / sedimentary	Ramapo-Passaic
Mahwah River at Suffern, NY	01387480	20.9	8/1/59–12/31/61		crystalline / sedimentary	Ramapo-Passaic
Saddle River near Spring Valley, NY	01390200	2.0	7/1/60–12/31/61		sedimentary	Passaic
Pine Brook near Spring Valley, NY	01390300	2.3	8/1/59–12/31/61		sedimentary	Passaic
Pascack Brook at Park Ridge, NJ	01377370	13.6	4/1/04–present	Precipitation measured at station	sedimentary	Hackensack
Saddle River at Upper Saddle River, NJ	01390450	11.0	1/1/04–present	Air temperature measured at streamgage	sedimentary	Passaic
Stony Brook at Sloatsburg, NY	01387300	18.2	10/1/59–12/31/61		crystalline	Ramapo-Passaic
Sparkill Creek at Tappan, NY	01376270	11.1	9/1/59–12/31/61		crystalline / sedimentary	Hudson
Hackensack River at West Nyack, NY	01376800	30.7	12/1/58–present		crystalline / sedimentary	Hackensack
Hackensack River at Nauraushaun, NY	01376900	44.9	12/1/59–12/31/61		crystalline / sedimentary	Hackensack
Ramapo River at Sloatsburg, NY	01387250	60.9	9/1/59–12/31/61		crystalline / sedimentary	Passaic
Ramapo River at Ramapo, NY	01387400	86.9	6/1/79–present		crystalline / sedimentary	Ramapo-Passaic
Ramapo River at Suffern, NY	01387420	93.0	6/1/79–present		crystalline / sedimentary	Ramapo-Passaic

Geologic and Topographic Setting

Rockland County is underlain by a variety of bedrock types that are mantled by as much as 325 ft of unconsolidated glacial deposits and recent alluvium (stream deposits). The principal bedrock types include 1) metamorphic and igneous (crystalline) rocks of late Precambrian age, 2) metasedimentary rock of Cambrian and Ordovician age, 3) clastic sedimentary rock of late Triassic age, and 4) igneous intrusive and extrusive rocks of early Jurassic age (fig. 6). The topography of Rockland County is largely controlled by the underlying bedrock type.

The crystalline bedrock that underlies the upland area of the county is primarily composed of resistant gneisses and granitic rocks that form a mountainous plateau about 4 mi wide along the northwest border of the county. This area is part of the Reading Prong section of the New England Physiographic Province (Fenneman, 1938) and is known as the New York–New Jersey Highlands. Hereafter in this report, the upland area of the county will be referred to as the "Highlands." The southern part of the Highlands is known as the Ramapo Mountains, and the northern part is known as the Hudson Highlands. The summits of this area are generally 900 to 1,200 ft in altitude and are about 200 to 500 ft higher than the highest points of the lowland part of the county. The Highlands are deeply incised at the Ramapo and Hudson River valleys at the southwest and northeast corners of the county, respectively. The boundary between the Highland crystalline rocks and the remainder of the county is an escarpment that follows the traces of the Ramapo and Theills faults (Ratcliffe, 1980).

A remnant of lower Paleozoic metasedimentary bedrock is variably preserved along the Theills fault (fig. 6) as a sliver of quartzite, limestone, dolomite, and phyllite (Perlmutter, 1959). It is generally 0.25 mi or less wide, except at the north end at Tomkins Cove, where the limestone-dolomite bedrock is nearly 1 mi wide.

The lowland area of Rockland County is the northernmost extent of the Newark basin, one of a series of rift basins that formed during the late Triassic and early Jurassic Periods along the east coast of North America as it separated from Northern Africa to ultimately form the Atlantic Ocean. The Newark basin is a half-graben structure (fig. 6) that stretches from Rockland County, NY, through New Jersey, and into Pennsylvania. It is bounded on the west by a series of normal faults and on the east by an erosional surface of onlapped sedimentary units (Schlische and Olsen, 1990). The eastern boundary lies under the Hudson River about three-fourths of the distance across the river from Nyack, NY, at the Tappan Zee Bridge crossing (Perlmutter, 1959).

The Newark basin progressively filled with sediment during the late Triassic and early Jurassic Periods as displacement along the boundary faults increased in response to extension of the Earth's crust. Maximum sediment thickness of about 30,000 ft has been estimated in New Jersey (Goldberg and others, 1994), whereas thicknesses in Rockland County are estimated between about 2,000 ft in the east to more than 6,000 ft in the west (N. Ratcliffe, U.S. Geological Survey, written commun., 2005). Bedrock generally dips about 10 degrees to the northwest.

The Newark basin sedimentary rocks in Rockland County are divided into the Stockton Formation (Kummel, 1899; Savage, 1967) and the overlying Passaic Formation (Olsen, 1980), formerly known as the lower Brunswick Formation (fig. 6). Both formations are fluvial in origin, and the boundary between them is transitional. The Stockton Formation is limited to outcrops along the eastern edge of the county, largely below and locally above the Palisades sill (Savage, 1967). The Passaic Formation makes up the remainder of the Newark basin strata in Rockland County.

The Lockatong Formation, composed of gray and black cyclic lacustrine deposits, separates the Stockton and Passaic Formations in New Jersey but is absent in Rockland County (Parker and others (1988). However, Parker (1993) reclassified the Stockton Formation above the Palisades sill in northern New Jersey as an arkosic sandstone facies of the Lockatong Formation. This unit likely extends into Rockland County as a narrow band above the Palisades sill but has not been mapped.

The Stockton Formation consists mostly of light colored (gray, pinkish gray, tan, and white) arkosic sandstones. The upper part of the formation consists of interbedded red mudstone, siltstone, and fine sandstone that are transitional with the overlying Passaic Formation (Parker and others, 1988). Parker and others (1988) operationally defined the boundary between the Stockton and Passaic Formations as the change from dominantly light tan to white arkosic sandstone in the Stockton to dominantly red-brown sandstone and siltstone of the overlying Passaic Formation. Some evidence of this transition has been observed in geologic and borehole geophysical logs from some water wells, but spatial and depth coverage is limited in the county.

The Passaic Formation coarsens from east to west and from bottom to top. Erosionally resistant coarse-grained strata underlie the highest altitude areas of the Newark basin in Rockland County.

Savage (1967, 1968) divided the Passaic Formation, then known as the lower part of the Brunswick Formation, into four mappable lithofacies in Rockland County that were incorporated into the New York State Geologic Map (Fisher and others, 1970; fig. 6). The upper boundary of the Passaic Formation (Olsen, 1980) is defined by the contact with the overlying Orange Mountain Basalt (in New Jersey). More recently, Parker and others (1988) delineated and detailed four mappable lithofacies in the Passaic Formation in northern New Jersey and southern Rockland County that parallel those of Savage (1968) but with different criteria for the lower boundary between the Stockton and Passaic Formations. From east to west, the lithofacies units include (1) siltstone, mudstone, sandstone; (2) sandstone and mudstone; (3) pebbly sandstone; and (4) conglomeratic sandstone. Noteworthy characteristics of these lithofacies (Parker and others, 1988) are as follows:

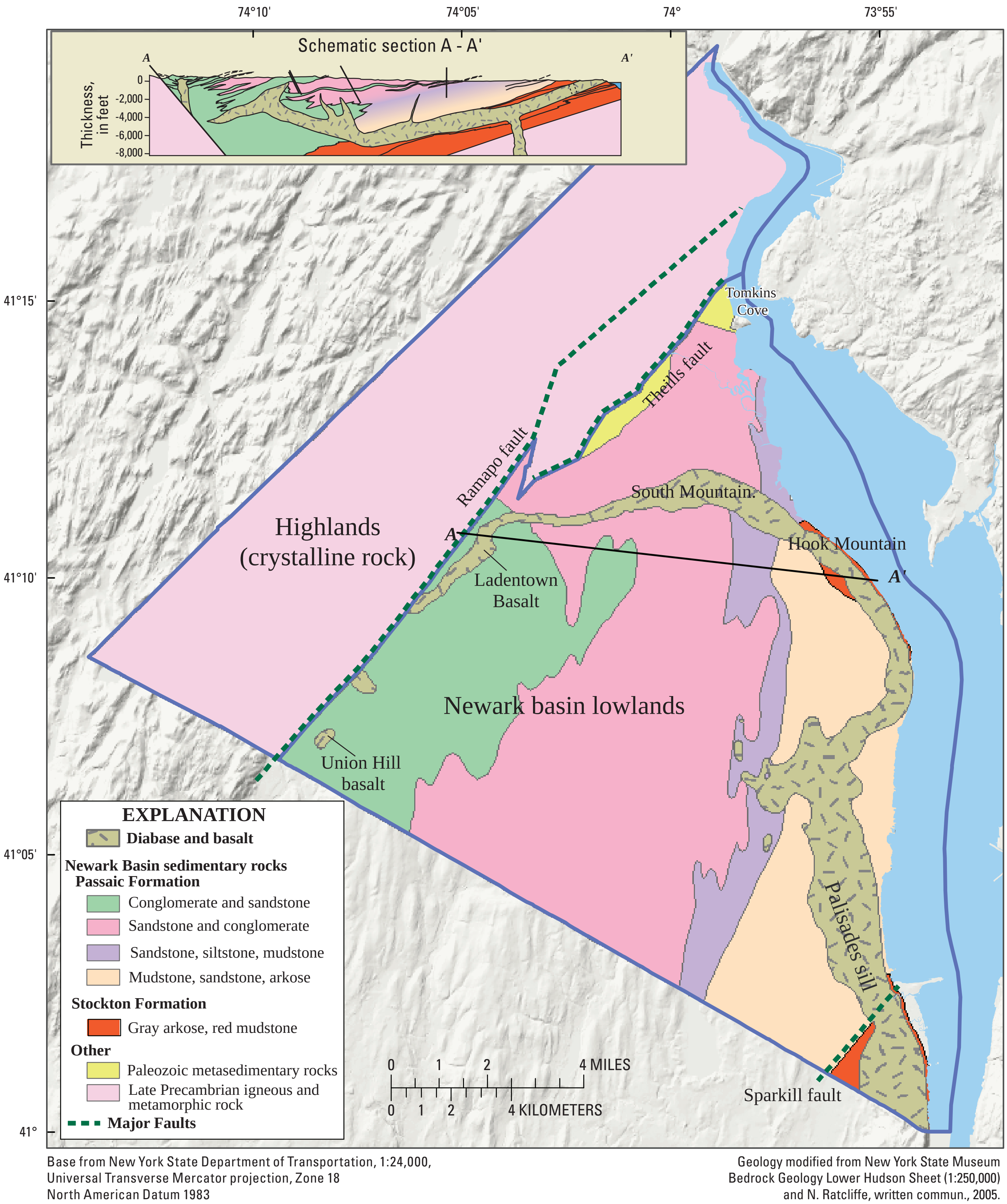


Figure 6. Generalized bedrock geologic map with schematic section, Rockland County, New York.

1. The two lower, finer-grained lithofacies (1 and 2) are micaceous.

2. Mudstones are minor in pebbly sandstone lithofacies 3 and are largely absent from the conglomeratic sandstone lithofacies 4.

3. Lithofacies 1 has calcareous cement in some siltstone beds and carbonate nodules in some mudstone beds. Lithofacies 2 has *no* carbonate, and lithofacies 3 and 4 both contain limestone rock fragments. This finding is in agreement with the carbonate-content data of Savage (1967).

4. Localized areas of matrix-supported debris flows are present in lithofacies 4 near the northwest fault boundary of the basin.

Early Jurassic volcanism resulted in the emplacement of intrusive (diabase) and extrusive (basalt) units within and on the Newark basin sediments in Rockland County (fig. 6; Darton, 1890; Kummel, 1899). These igneous units are more resistant than the sedimentary rocks and typically form local topographic highs in the basin. The Palisades sill is the diabase unit in Rockland County; it forms the prominent cliffs along the Hudson River and along Hook and South Mountains as it curves inland. The diabase is roughly subparallel to bedding along the Hudson River but cuts across bedding as it trends inland. Two extrusive units (basalt) crop out along the Ramapo fault near Ladentown (Ladentown basalt) and in Suffern (at Union Hill). Ratcliffe (1988) linked the basalts at Ladentown and Union Hill to the Palisade Diabase source magma using chemical data and core data between Hook Mountain and Ladentown.

Unconsolidated sediments overlying bedrock are mostly glacial in origin (fig. 7), with generally thin, recent alluvium in stream valleys. Glacial till, an unsorted mixture of sediments deposited by the ice sheet, is the most widespread glacial deposit with thicknesses up to 190 ft. Stratified glacial deposits are largely limited to the major stream valleys, including those of the Ramapo, Mahwah, and Hackensack Rivers and Minisceongo and lower Sparkill Creeks. Coarse-grained (sand and gravel) stratified deposits predominate in the Ramapo and Mahwah River valleys and at the lower reach of Sparkill Creek, and thicknesses in the center of these valleys are typically about 70 ft but as much as 140 ft. Fine-grained (fine sand, silt, clay, and peat) stratified lacustrine deposits overlie coarse-grained deposits in the north-south reach of the Hackensack River valley and the South Branch of the Minisceongo Creek valley; thicknesses are as much as 90 ft.

Water-Resource Use and Potential

The amount and type of water resources available to the county are largely dependent on the underlying geology. The alluvial aquifers in the Ramapo and Mahwah River valleys and the coarse-grained part of the Newark basin sedimentary bedrock in the western half of the lowlands support the most productive supply wells in the county. Maximum 2007 daily average pumping rates at individual supply wells ranged from 200 to 1,300 gal/min in the Ramapo valley aquifer, 180 to 950 gal/min in the Mahwah valley aquifer, and 75 to 800 gal/min in the Newark basin sedimentary bedrock. The Newark basin sedimentary bedrock (Stockton and Passaic Formations), forms a regional aquifer, herein referred to as the Newark basin aquifer.

All bedrock units, with the exceptions of some areas of diabase and crystalline rock, are capable of supplying domestic wells. Some domestic wells that failed to obtain adequate water in the diabase have been drilled completely through it to tap the more permeable Newark basin sedimentary bedrock beneath. Perlmutter (1959) reported median well yields (domestic and public or industrial supply), in gallons per minute (gal/min), for each glacial and bedrock unit as follows:

- Stratified drift (glacial sand and gravel), 183 gal/min (18 wells)
- Newark basin (Stockton and Passaic Formations), 30 gal/min (265 wells)
- Palisade Diabase, 5 gal/min (10 wells)
- Cambrian and Ordovician metasedimentary rocks, 9 gal/min (7 wells)
- Precambrian igneous and metamorphic (crystalline) rocks, 12 gal/min (32 wells)

Maximum yields of wells completed in the crystalline rocks rarely exceed 70 gal/min, and limited aquifer storage in crystalline rock makes such wells susceptible to decreased yields during dry periods unless they are in hydraulic connection with surface water. Therefore, surface-water reservoirs are the most viable source of public water supply from the crystalline rock of the Highlands area. UWNY recently (2008) began using a series of three reservoirs on Minisceongo Creek for this purpose.

The Ramapo River valley alluvial aquifer in the western part of the county is a limited resource, despite the high yield of the well field. This well field and the well fields that tap the Mahwah River valley alluvial aquifer supply about 3.73 Ggal/yr (31 percent) of UWNY public water supply (1990–2006 average; fig. 2). The Ramapo valley well field derives much of its water by inducing infiltration of Ramapo River water through the permeable sand and gravel to the supply wells. Withdrawals are subject to a permit between NYSDEC and UWNY that requires maintenance of minimum flow in the Ramapo River (8 Mgal/d or 12.6 ft^3/s) down river from the well field to New Jersey (NYSDEC WSA no. 6507). When flows are below that threshold, pumping must be stopped. Thus, if summer precipitation is low in the Ramapo River drainage area, this resource may be unavailable when water demand is greatest. This resource has been extended for limited periods through flow augmentation (releases of water

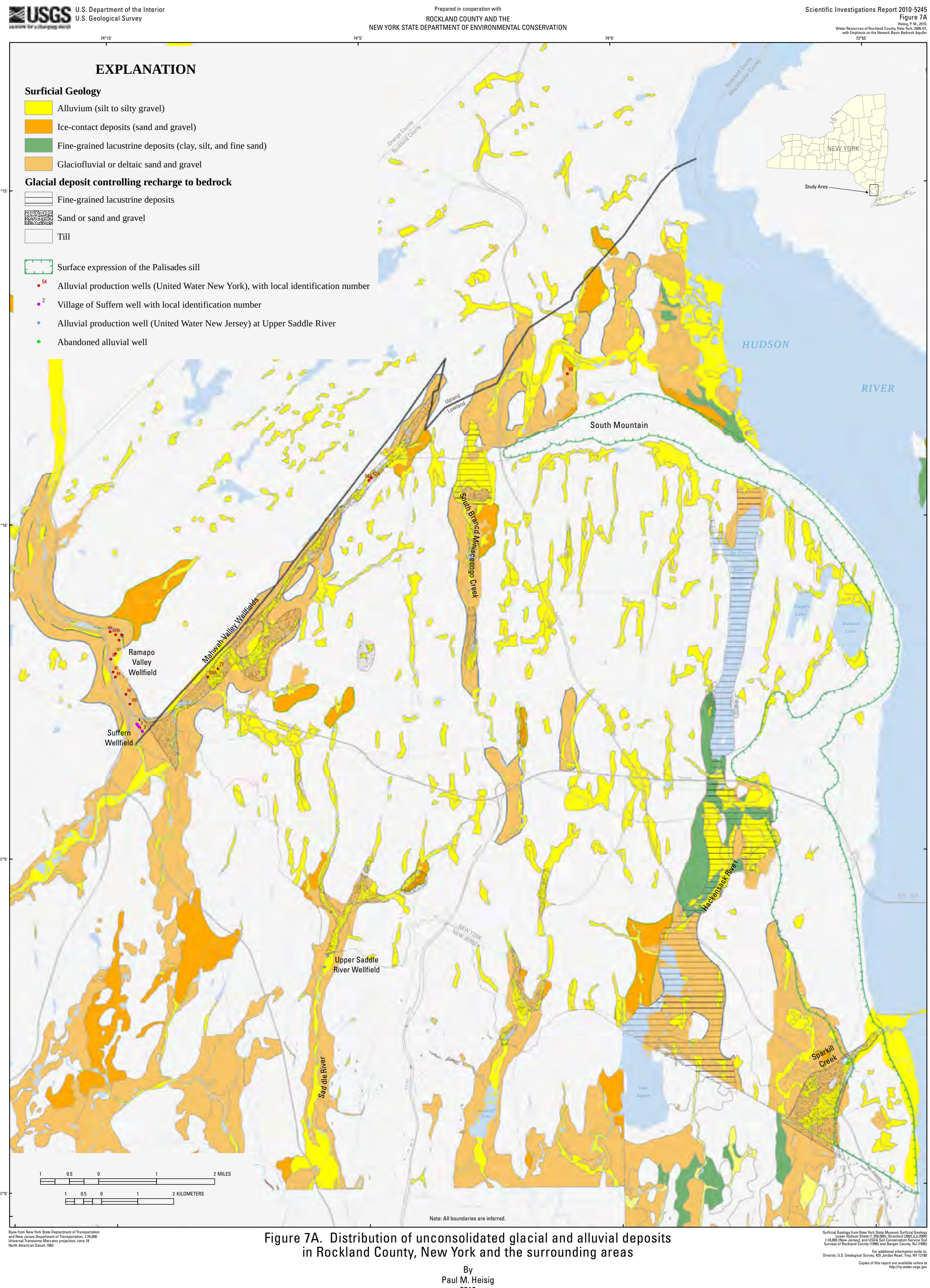


Figure 7A. Unconsolidated glacial and alluvial deposits in Rockland County, New York: *A,* distribution of unconsolidated glacial and alluvial deposits, and *B,* thickness of glacial and alluvial deposits. (Click to view full-size map at http://pubs.usgs.gov/sir/2010/5245/plates/Figure7A.pdf)

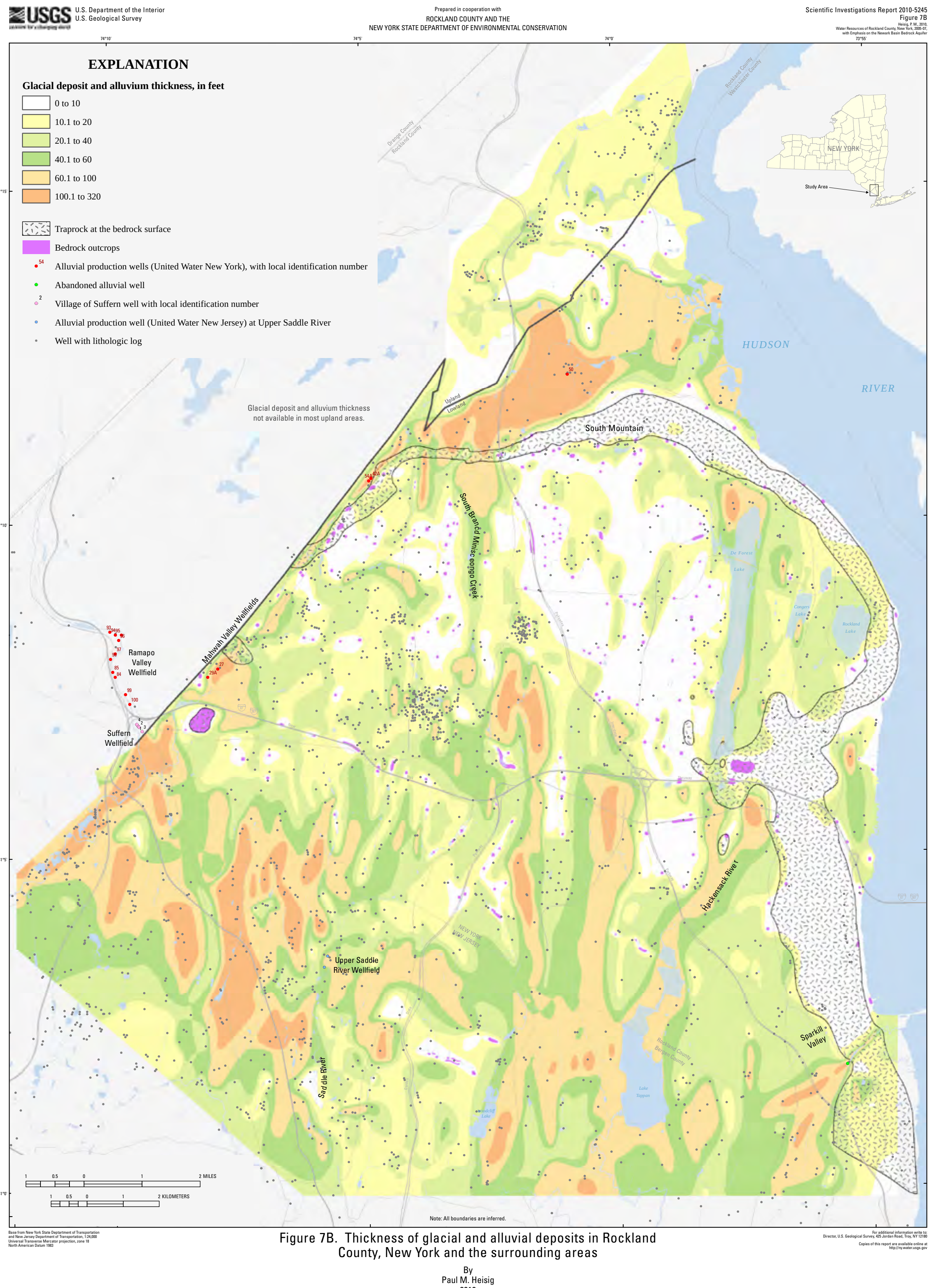


Figure 7B. Unconsolidated glacial and alluvial deposits in Rockland County, New York: *A,* distribution of unconsolidated glacial and alluvial deposits, and *B,* thickness of glacial and alluvial deposits. (Click to view full-size map at http://pubs.usgs.gov/sir/2010/5245/plates/Figure7B.pdf)—Continued from Potake Pond). In effect, the Ramapo River and alluvial aquifer are a single water resource; the well field is limited as a source of supply by low streamflows, unless stormflows can be captured and stored or other surface-water storage can be utilized.

The Newark basin aquifer in Rockland County provides about 3.90 Ggal/yr (32 percent) of UWNY public water supply (1990–2006 average; fig. 2). Over the last 50 years, water supply has shifted from mostly individual supply wells of low to moderate yield (<100 gal/min) that served domestic, institutional, commercial, and industrial water supplies (Perlmutter, 1959) to a more widely spaced network of deeper, higher-yield production wells administered by private water companies. The current number of active domestic, irrigation, and commercial wells outside the production network is about 6,000 wells, based on records of the Rockland County Health Department (D. Miller, Rockland County Health Department, written commun., 2008). Options for new production wells are limited by lower well yields in the eastern part of the aquifer, lack of available land, poor water quality, and potential impacts or liability issues with existing domestic supplies. From a hydrogeologic standpoint, additional water is available from the Newark basin aquifer. The resource, in areas unaffected by supply wells, could be drawn from a distributed network of lower-yielding supply wells, which are not likely to be economically viable for a private water company. The availability of this additional resource is evidenced by the existence of, or historical information regarding, former supplies that served small developments, bungalow colonies, summer camps, and institutions (see Perlmutter (1959) for examples).

Regardless of the water-resource potential of the aquifer, a continuing challenge is to prevent the loss of existing resources from groundwater contamination. Widespread suburban development over this fractured bedrock aquifer with many areas of thin soil make it highly susceptible to contamination. At least 13 production wells were abandoned or taken offline until site investigations were completed and treatment systems installed. Gasoline, solvents, dry-cleaning agents, chlorofluorocarbons, and other industrial chemicals have contaminated groundwater across the county (Slayback and Rothenberg, 1984; Hoven and others, 1985; reports on file at NYSDEC, New Paltz, NY).

The Lake DeForest Reservoir impounds headwater drainage from the Hackensack River in the eastern part of the county. This less-permeable part of the aquifer has few production wells. Withdrawals from Lake DeForest (1990–2006 average; fig. 2) have provided 4.50 Ggal/yr (37 percent) of public water supply provided by UWNY; withdrawals from Lake DeForest are limited to an annual average daily withdrawal of 10 Mgal/d by a Water-Supply Application (WSA) permit with NYSDEC. This reservoir water resource is also limited by its dependence on precipitation within the upper Hackensack River watershed.

A series of three surface-water impoundments on the headwater reach of Minisceongo Creek in the Highlands is currently (2008) used for public supply from May through October. This water resource formerly served as the water supply for the Letchworth Village State Mental Institution. Average daily demand during the highest demand periods is about 1.45 Mgal/d (R. Raczko, United Water New York, written commun., 2009). Peak daily use can be as high as 3 Mgal/d (D. Miller, Rockland County Department of Health, written commun., 2009).

Previous Investigations

The bedrock geology of Rockland County was summarized by Perlmutter (1959). Geology of the crystalline rocks of the Highlands area in New York was described by Gates and others (2001) and Lowe (1958), and in northern New Jersey, it was summarized by Puffer (1980). An overall description and structure of the Newark basin sedimentary rocks was documented by Kummel (1899), Savage (1967, 1968), and Ratcliffe (1988). The New York State bedrock geology map (1:250,000 Lower Hudson Sheet; Fisher and others, 1970) is based on the structure and stratigraphic delineations of Savage (1967). Refinement of the stratigraphy, including naming the Passaic Formation to replace the Lower part of the Brunswick Formation, was presented by Olsen (1980). Parker and others (1988) and Parker (1993) refined the Newark basin stratigraphy in northern New Jersey and southern Rockland County. Systematic tectonic (high-angle) fracturing and the types of water-bearing fractures in New Jersey were described by Herman (2004a, 2004b) and Morin and others (1997).

Structure of the intrusive Palisade Diabase was discussed by Lowe (1959), and its relation to the extrusive basalts at Ladentown and Union Hill was investigated by Ratcliffe (1988). Geology of the Ramapo fault and adjacent areas was also investigated by Ratcliffe (1980, 1982) and Ratcliffe and Burton (1985).

The origin of glacial deposits of southern Rockland County was described by Averill and others (1980) and Stanford and Harper (1991). Glacial deposits throughout the county are depicted on the New York State Geological Survey Lower Hudson Sheet surficial geology map (Cadwell, 1989).

The hydrogeologic framework and groundwater flow in the Newark basin aquifer south of Rockland County were conceptualized in New Jersey by Michalski (1990), Michalski and Britton (1997), and Houghton (1990) and in Pennsylvania by Sloto and Schreffler (1994). Similar findings were summarized in the Durham Rift Basin in North Carolina (Glazier and others, 2003). Groundwater flow in the gently dipping sedimentary rocks is predominantly along bedding strike and within bedding-plane partings or fractures that are separated by leaky confining units (Michalski, 1990). These water-bearing zones are typically less transmissive with depth, and productive fractures below 500–600 ft are rare. High-angle fractures are typically much less transmissive than bedding-plane fractures but can provide some leakage through confining units. Wellbores that intersect more than one water-bearing zone represent important, highly transmissive, vertical conduits for water movement between such zones (Michalski, 1990). The resulting framework of the bedrock aquifer is thus a tilted stack of thin water-bearing zones separated by units that are semiconfined or unconfined near the bedrock surface and increasingly confined with depth. Michalski (1990) described this as a "leaky multiple aquifer system."

Groundwater flow is largely within fractures or partings parallel to bedding within this framework (Senior and Goode, 1999). Groundwater flow along bedding strike commonly is indicated by aquifer responses to pumping stresses, groundwater transport of contaminants, and detailed borehole geophysical testing of wells. The most common response to pumping is an elongate cone of depression largely parallel to bedding strike; examples from New Jersey and Pennsylvania include Herpers and Barksdale (1951), Vecchioli and others (1969), Carswell (1976), Sloto and McManus (1996), and Sloto (2002). Lewis-Brown and others (2005) investigated the hydrogeologic framework and simulated groundwater flow at the Fairlawn Well Field Superfund Site in Bergen County, NJ, which is about 10 mi south of Rockland County. Detailed borehole geophysical logging and hydraulic testing using straddle-packers of numerous wells also indicated groundwater flow parallel to the strike of gently dipping beds. Feshbach-Meriny and others (2003) documented movement of a contaminant plume subparallel to bedding strike rather than in the direction of the greatest potentiometric-surface gradient. This finding indicates that potentiometric-surface maps alone cannot be used to determine regional groundwater-flow directions without knowledge of the bedding orientation of the underlying bedrock.

Water resources in Rockland County have been assessed periodically since the 1950s. The most comprehensive data compilation and descriptive account of geology and groundwater resources was a countywide study by Perlmutter (1959), which described the bedrock and glacial geology and the water-bearing properties of each type of aquifer, documented water use, and compiled data from over 500 wells and springs, including water levels, yield, and water quality. The alluvial aquifers in the Ramapo and Mahwah River valleys were described and delineated by Moore and others (1982). A countywide water-supply study by Quirk, Lawler, and Matusky Engineers (1970) documented public water supplies in Rockland County (in 1966), made projections for future water use, and outlined plans for future water-supply projects, including reservoirs. Leggette, Brashears & Graham, Inc., (1979) performed a hydrogeologic assessment of the Newark basin aquifer in Rockland County that used existing data to document water use, water quality at production wells, and water availability from the aquifer by developing water budgets for each major surface-water basin. This study estimated that groundwater withdrawals in 1978 were 60 to 70 percent of estimated average recharge rates and that the aquifer was nearing full water-supply potential. Consumptive water use was estimated at 83.5 percent, largely due to widespread sanitary sewering. The New York–New Jersey Highlands Regional Study (U.S. Department of Agriculture, Forest Service, 2002) included much of Rockland County and described water-use and water-availability aspects of water resources across the region. Changes to the hydrologic system with increasing degrees of development were outlined and simulated. Vecchioli and Miller (1973) estimated, from streamflow records, a sustained aquifer yield of 200,000 to 300,000 gal/d/mi^2 for the Brunswick Formation (now Brunswick Group) in the New Jersey part of the Ramapo River basin.

Numerous investigations of production well fields have been completed for the Spring Valley Water Company (now UWNY) since the 1950s (mostly by Leggette, Brashears & Graham, Inc.). A 1992 report that documents an aquifer test at the Spring Valley well field is of particular note because a large number of observation wells were installed and screened at discrete intervals, which provided a detailed view of aquifer response to pumping stress (Leggette, Brashears & Graham, Inc., 1992; Woodward Clyde Consultants, 1992).

General water-quality or specialized water-chemistry studies are important sources of information on the Newark basin aquifer. Numerous studies of groundwater contamination have been completed at industrial sites and gas stations in Rockland County and are on file at the NYSDEC regional office in New Paltz, NY. Tritium-helium ($^3H/^3He$) age dating of composite groundwater samples from a subset of the bedrock supply wells (Aeschbach-Hertig and others, 1998) resulted in average groundwater $^3H/^3He$ age dates between 6.1 and 23.3 years, which indicate relatively rapid groundwater circulation within the aquifer.

Two USGS studies have addressed surface water in Rockland County. The most comprehensive study, by Ayer and Pauszek (1963), collected 1 to 3 years of streamflow data from 17 continuous streamgages, 5 partial-record streamgages, and 20 miscellaneous sites. Stream water quality was measured at 22 sites, and suspended sediment was measured at 4 sites. Lumia (1980) developed rainfall-runoff models (HEC-1 Flood Hydrograph Package) for 10 stream sites in Rockland County to update flood-frequency estimates.

Precipitation amounts associated with three water-supply shortages (water emergencies) since 1995 in Rockland County were compared with long-term variations in precipitation and increases in development and water use by Lyon and others (2005). The study indicates that these recent events occurred under low precipitation conditions that were not especially severe and were much less severe than those experienced during the 1960s drought, which highlights the current limitations and vulnerability of the resource, especially given the likelihood of more severe droughts in the future.

Methods of Investigation

Borehole-geophysical logs were collected in 24 wells to investigate the hydrogeologic framework of the Newark basin aquifer (appendix 1A). A variety of probes were lowered into the wells to determine rock type, levels of natural-gamma radiation, borehole diameter, rock structure (orientation of bedding and fractures), borehole water temperature and specific conductance (a measure of the dissolved mineral content of the water), and the rate of upward or downward movement of water in the wellbore. The standard suite of borehole logs included:

- Natural-gamma logs used to identify strata with high gamma radiation. Uranium, thorium, their decay or daughter products, and potassium-40 are the primary elements that emit natural-gamma radiation in rocks (Keys, 1990). In sedimentary rocks such as those in Rockland County, uranium and thorium typically are present in clay minerals and mica minerals, whereas potassium-40 is found in potassium feldspar and mica minerals that are common constituents of arkosic sandstones. The lower Passaic and Stockton Formations contain arkosic or feldspathic sandstones. However, low levels of gamma radiation in sandstones in the western two-thirds of the Newark basin aquifer indicate that potassium-40 is not a major source of gamma radiation.
- Caliper log measures average borehole diameter with a 3-point caliper to identify fractures or zones of weak bedrock
- Optical and acoustic televiewers, which record visual and acoustic “pictures” of wellbores, can be used to identify rock type and orientation of bedding, fractures, or foliation. Optical televiewers cannot provide useful data in wellbores with turbid water, especially if the wellbores are large in diameter. Acoustic televiewer data are also limited to wellbores less than or equal to 10 in. in diameter.
- Fluid-temperature and fluid-specific-conductance logs in boreholes provide information on general water quality, identification of water-bearing fractures, and water movement within the wellbore.
- Borehole-flowmeter logs provide point measurements of water movement up or down wellbores, which allows identification of water-bearing fractures. Measurements of flow made while the well is pumping can be used to estimate the transmissivity (T) (water-bearing capability) of the fractures (Paillet, 1998, 2000, 2004).

Hydraulic properties of the Newark basin aquifer were estimated from about 60 aquifer-test datasets collected by private consultants. The majority of these tests were performed at UWNY production wells and test wells by Leggette, Brashears & Graham, Inc. (W. Prehoda, Leggette, Brashears & Graham, Inc., written commun., 2006). Values of transmisivity *(T)* were estimated from the slope of drawdown data on semi-log graphs 100 minutes into each test. Slopes typically covered the log cycle between 10 and 100 minutes, although some matches used the interval from 100 to 1,000 minutes. The slope of the drawdown trend and the pumping rate of each test were substituted into the equation (Driscoll, 1986):

T, in gallons per day per feet = 264 x (pumping rate, in gallons per minute) / (drawdown per log cycle, in feet) (1)

(*T*, in feet squared per day is obtained by dividing the gallon-per-day-per-foot value by 7.48)

Groundwater levels were measured in selected wells during four synoptic surveys: summer 2005 (91 wells), spring 2006 (106 wells), summer 2006 (112 wells), and spring 2007 (158 wells); appendix 2). Measurements were made with disinfected electric water-level tapes and a sonic water-level meter, depending on access at each wellhead. Water-level measurements with electric tapes are scaled to the nearest one-hundredth of a foot, whereas sonic water-level measurements are given to the nearest tenth of a foot. Sonic measurements were empirically found to be about 0.55 ft deeper than electric-tape measurements and rarely differed by greater than 1 ft. Water-level elevations (plus or minus 1 ft) at Rockland County wells were tied to the digital terrain model of the county, from which points were interpolated to develop a surface from which 2-ft altitude contours were delineated. New Jersey well altitudes are derived from a digital elevation model based on 10-ft contour map data. Well altitudes are about plus or minus 5 ft.

Groundwater levels were measured at active and inactive wells during four countywide surveys. Measurements at active wells were avoided during pumping cycles. Water levels typically recovered rapidly to within 1 to 2 ft of pre-pumping conditions. Groundwater-level measurements at actively pumped wells (cyclic pumping) represent the highest water level between pumping cycles. Recovering water levels in pumped wells were noted.

Groundwater-level data from about 45 UWNY production wells were obtained for each water-level-survey period (appendix 3). These measurements are derived from continuous airline readings at each well. Airline lengths may not be known accurately, can be altered, and can malfunction for a number of reasons. An effort was made to look at periods of record rather than discrete point measurements; spurious water-level records were discarded. The absolute accuracy of the depth measurements is unknown. Greater confidence can be assigned to the relative changes in water levels at any given well.

Streamflow (or stream-discharge) was measured at 12 or 13 sites during three low-flow surveys: Sept. 13–14, 2005; March 23, 2006; and July 18–19, 2006. Eleven of the sites were gaged in the early 1960s, including the Mahwah River near Suffern streamgage, which is the only long-term-record streamgage of a largely unregulated watershed in the county. One survey was during extreme low flows (99-percent flow exceedance at the Mahwah near Suffern streamgage; Sept. 13–14, 2005) and the other two during moderate- to low-flow conditions (about 70-percent exceedance for the March 23, 2006, and July 18–19, 2006, surveys).

Streamflow was estimated at 239 stream sites across the county in conjunction with the extreme low-flow survey of September 2005. Streamflow was measured at 12 sites during the survey for comparison with the visual streamflow estimates (figs. 8A, B). The average of each estimated flow range (for example, an average of 0.25 ft^3/s from a flow range of 0.2–0.3 ft^3/s) compared with the measured values indicates a median difference of -1.7 percent and maximum departures of +70 and -60 percent of the measured flows. Nearly all (92 percent) estimated flows were less than 1 ft^3/s. Most headwater sites were dry, and 42 percent of all sites were dry (zero measurement error).

Water-chemistry data used in this study were primarily major-ion analyses, pH, and specific conductance. Data included (1) 80 samples collected by USGS during this study that were analyzed at the USGS New York Water Science Center laboratory at Troy, NY; (2) more than 1,000 samples collected by UWNY from their production wells that were analyzed at the United Water New Jersey laboratory at Haworth, NJ; and (3) sample-analysis records on file at the Rockland County Department of Health (see below), and analyses of samples collected by environmental consultants at test wells or at monitoring wells at contamination sites (about 50 samples). Department of Health records include samples collected by the Department: (1) from wells that serve public supplies other than UWNY (150 samples), (2) from domestic wells at homeowner request (about 30 samples), and (3) in association with contamination investigations (about 50 samples). All of these samples were analyzed at the Westchester County Health Department Laboratory. Another dataset (444 samples) consisted of samples collected by homeowners or consultants in response to a 2005 Rockland County well-testing law that requires basic water-quality analysis of domestic well water in conjunction with real-estate transactions. These samples were analyzed by private laboratories that are required to have Environmental Laboratory Approval Program (ELAP) certification (D. Miller, Rockland County Department of Health, oral commun., 2008). The ELAP is administered by the New York State Department of Health.

Limited numbers and types of specialized water analyses were used in this study to answer specific questions. They included the following:

- Eight organic wastewater contaminant samples (USGS National Water Quality Laboratory, Denver, CO); these samples were collected to provide an initial reconnaissance of the occurrence of wastewater contamination in streams and groundwater.

- Two samples of nitrogen and oxygen isotopes of nitrate (USGS Reston Stable Isotope Laboratory, Reston, VA); these samples were collected to help identify the source of nitrate concentrations in groundwater (wastewater and (or) fertilizer).

- Four $^{3}H/^{3}He$ groundwater-age-date samples (Lamont-Doherty Earth Observatory Tritium-Helium Laboratory, Palisades, NY); these samples were collected to supplement existing composite groundwater-age dates from production wells in the county and to provide depth-specific dates from an unused well that deeply penetrates the Newark basin aquifer.

Numbering Systems for Wells and Streamgages

All wells listed in the text, maps, tables, or figures in this report are identified as Rockland County wells with the prefix “Ro-” followed by a number identifier starting at 1. These well identifiers are the same as those published in Perlmutter (1959). UWNY production wells are identified in the text by their local UWNY number (ex. UWNY 79). Well data are listed in appendixes 1–4.

All active and inactive USGS streamgages are identified with 8-digit numbers that increase sequentially downstream along the main-stem stream in each drainage basin (table 1.). Streamgages on tributary streams are assigned identification numbers that are intermediate between those of the main-stem streamgages. Streamgages are also identified by name and by proximity to the nearest village. For example, one of the active streamgages in the study area is 01387450, Mahwah River near Suffern, NY. Currently, three active streamgages measure unregulated flow from drainage areas that wholly or partially overlie the Newark basin aquifer within Rockland County. Another streamgage monitors regulated flow on the Hackensack River, whose drainage overlies much of the eastern part of the Newark basin aquifer. Sixteen streamgages in Rockland County were operated between 1959 and 1962 (Ayers and Pauszek, 1963). Daily streamflow data for all these streamgages are available on the USGS New York Water Science Center website (http://usgs.ny.gov).

Hydrogeology of the Newark Basin Aquifer System in Rockland County

The hydrogeology of the bedrock aquifer system includes (1) the framework of overlying unconsolidated glacial and alluvial deposits, the Palisades sill and associated basaltic rocks, and the Newark basin sedimentary rocks; (2) groundwater conditions, including water levels and water chemistry; and (3) surface-water conditions, including streamflow and the specific conductance of streams that flow over or onto the aquifer from surrounding areas. The framework of the system consists of the type and thickness of unconsolidated deposits, bedrock type, orientation of bedding and fractures, and hydraulic properties. These properties largely constrain how easily water can enter the system and in which direction(s) it can flow. Groundwater conditions encompass aquifer-wide measurements of water levels and

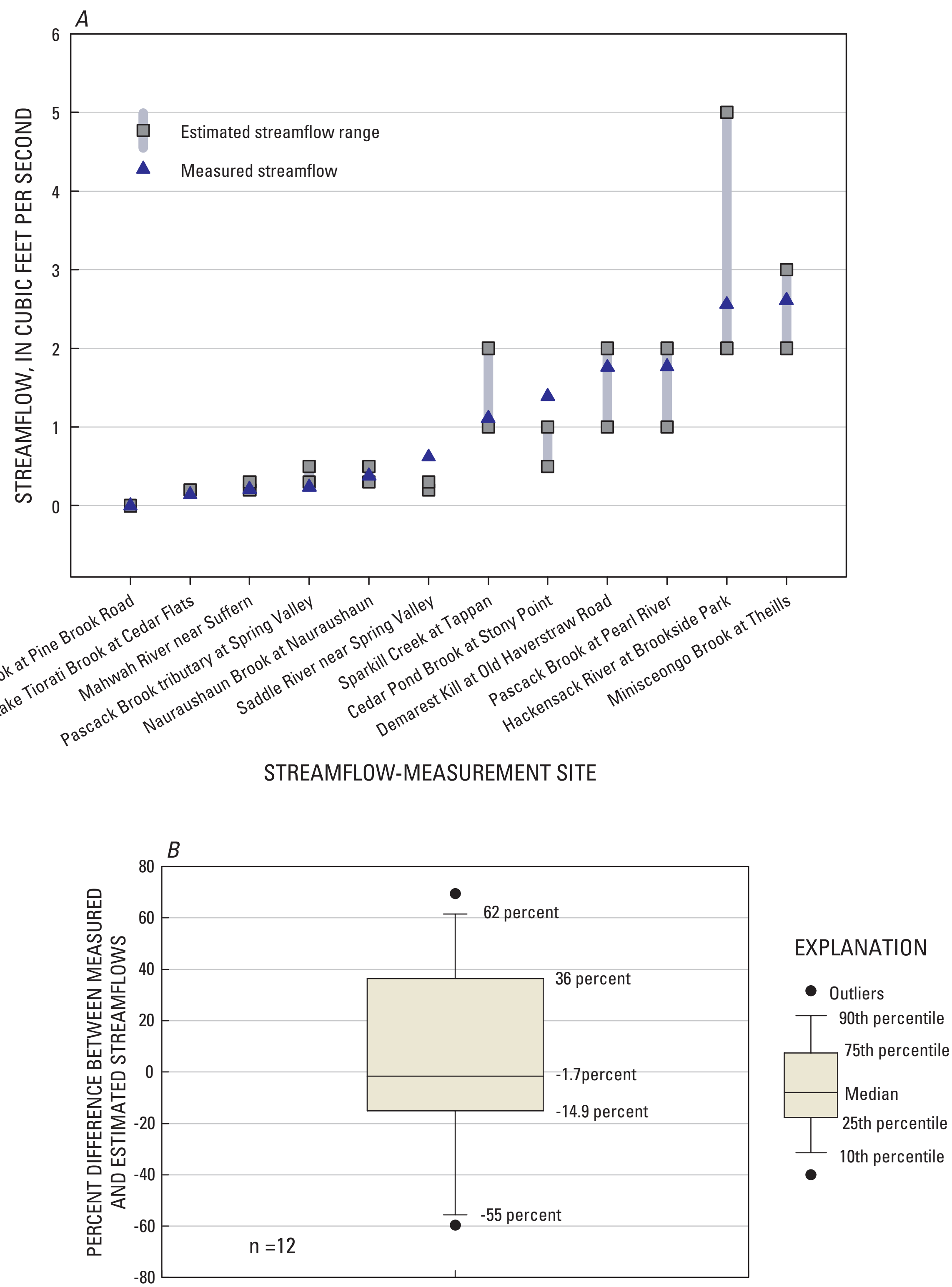


Figure 8. Comparisons of 12 estimated streamflows with measured streamflows, during the September–October 2005 stream survey, Rockland County, New York: *A,* Estimated flow range compared with measured flow at individual streams and *B,* Range of percent difference between midpoint of estimated flow range and measured flow.

water chemistry as well as long-term, seasonal, and daily groundwater-level responses to pumping. Investigation of surface-water conditions included:

1. Periodic flow measurements at previously or currently gaged sites,
2. Analysis of changes in low flow at a long-term streamgage,
3. A survey of streamflow and stream specific conductance during low-flow conditions, and
4. Evaluation of the effects of percent impervious surface on the flow regime of streams.

Hydrogeologic Framework

The areal distribution of unconsolidated deposit thickness, its composition (till, sand and gravel, lacustrine silts and clays, and alluvium), and its permeability are important in determining the likelihood of recharge to the sedimentary bedrock aquifer and whether or not the unconsolidated material itself is an aquifer. Delineation of diabase and basalt in the subsurface is important because it may influence permeability and groundwater flow in the Newark basin aquifer. Definition of the framework of the tilted (dipping) sedimentary rocks of the Newark basin aquifer constrains/defines the groundwater flow system. Subsequent interpretation of data collected from the aquifer system is dependent on a well-defined aquifer framework. The interpretation of the aquifer framework was based on existing data such as outcrop measurements, well yields, aquifer-test results, and well-yield changes with well depth, supplemented by borehole-geophysical logs collected from 22 wells and by correlations of the gamma and optical logs among pairs of nearby wells.

Unconsolidated Deposits—Thickness, Texture, and Types

Unconsolidated deposits consist of recent alluvium deposited by streams and rivers and glacial deposits deposited by glaciers or glacial meltwaters. Deposits of alluvium are thin, generally fine grained, limited to stream valleys (fig. 7), and not considered aquifers. Glacial deposits are the primary unconsolidated deposits in the county. Glacial deposits are divided into stratified sediments, which were deposited by water, and unstratified sediments (till), which were deposited from glacial ice. Stratified deposits range from fine-grained sediments (clay, silt, and fine sand) that settled out of lacustrine (lake) environments to coarse-grained sediments (sand and gravel) deposited by flowing meltwaters (glaciofluvial outwash or ice-contact deposits). Stratified deposits constitute public-supply aquifers only in the largest valleys that contain sand and gravel. Unstratified deposits are made up of till, an unsorted mixture of clay- to boulder-size sediments. Till is the most common unconsolidated deposit across Rockland County but is not a viable aquifer for public supplies. The thickness and types of glacial deposits are shown in figure 7.

Fine-grained stratified deposits confine underlying minor aquifers consisting of coarse-grained sediments. The Hackensack River valley is the primary example of this kind of setting (fig. 7). The lack of wells in this area indicates that the underlying sediments are either too fine grained, too thin, or of limited extent.

Coarse-grained stratified glacial deposits form the best aquifer material—these deposits are the most widespread and permeable in the reach of the Ramapo River valley that crosses the crystalline Highlands (fig. 7). Deposits of sand and gravel also are present in the Mahwah River and Sparkill Creek valleys but are more limited in extent (fig. 7). The drainages of south-flowing Saddle River and Pascack Brook have thin stratified deposits, but as drainage area increases to the south in New Jersey, deposits thicken to form productive alluvial aquifers (fig. 7). Typical (and maximum) thicknesses of sand and gravel in all these valleys are as follows—Ramapo River 40–60 ft (up to 140 ft at Suffern, NY), Mahwah River 40 ft (up to 60 ft) but discontinuous (Moore and others, 1982), and Sparkill Creek 40–70 ft (up to 86 ft; Perlmutter, 1959). Production wells in these aquifers derive the majority of their water by inducing flow into the aquifer from the streams or rivers.

Other areas mapped as sand and gravel are not productive because they have thin saturated thicknesses—these areas include stream valleys such as reaches of Pascack Brook, Nauraushaun Brook, and Minisceongo Creek (fig. 5). Stratified deposits on hillside or hilltop areas may be completely unsaturated. Deposits of sand and gravel in the Hackensack River valley and a reach of Minisceongo Creek are underlain by fine-grained lacustrine deposits that form a low-permeability barrier between shallow and deep deposits of sand and gravel and underlying bedrock (fig. 7).

Localized deposits of sand and gravel over bedrock in stream valleys are important hydrogeologic features, despite being limited as aquifers (fig. 7A, see explanation: controlling glacial deposit over bedrock—sand or sand and gravel). Induced flow from local streams through the sand and gravel into bedrock can be an additional source of water to bedrock production wells. Many production wells are located in stream valleys to take advantage of potential favorable hydrogeologic conditions.

Till is the most widespread glacial deposit. Thicknesses of 40 ft or less are most common (fig. 7B), but thicknesses up to 198 ft have been recorded just north of the western tip of South Mountain (Perlmutter, 1959). Other areas of thick till are in central and southern Rockland County, oriented north-south and streamlined in the lee of bedrock highs (fig. 7B).

Till thicknesses typically increase to the south in Bergen County, NJ (fig. 7B), where till is mapped as two surficial units (Stanford, 2002a, 2002b, 2004): *Rahway Till*, derived primarily from Newark basin sedimentary bedrock, is reddish brown, light reddish brown to reddish yellow and *Netcong Till*, derived primarily from Highlands crystalline bedrock, is yellow, yellowish brown to pale brown or gray brown in color. The matrix of Rahway Till is compact, nonsticky, and nonplastic to slightly plastic. The Netcong Till matrix is compact, nonplastic, and nonsticky (Stanford, 2002a, 2002b). Both till types were observed in Rockland County but were not mapped in this study. Netcong Till typically overlies Rahway Till.

Differences in till (and soil) permeability on the basis of source rock are expected but are not indicated in soil surveys from either Rockland County or Bergen County, NJ (U.S. Department of Agriculture, Soil Conservation Service, 1990, 1995). Crystalline source rocks generally yield sandy, relatively permeable tills; similar characteristics are expected from coarse-grained Newark basin sedimentary rocks. Fine-grained sedimentary rocks in the eastern part of the county are expected to yield tills with high clay content and relatively low permeability. The Rockland County Soil Survey differentiates between tills of moderate permeability and low permeability, but areas of moderate permeability generally correspond to higher altitudes and thin till and not east-west location.

Till is not important as an aquifer, but it is important in its capacity to transmit recharge to the underlying bedrock aquifer; bedrock wells in areas of thin till appear most responsive to precipitation, whereas bedrock wells in areas of thick till show little or no response to precipitation. Dense lodgement till (and weathered bedrock) reported in some areas of thick till (Malcolm Pirnie, Inc., 1993) hinders or prevents recharge to bedrock.

Traprock—the Palisades Sill and Associated Basaltic Rocks

"Traprock" is a generic term used in this report to refer to the diabase of the Palisades sill and associated basalts along the Ramapo fault, including those at Ladentown, NY, and Union Hill, at Suffern, NY (fig. 9). The arcuate distribution of traprock from the Palisades on the east, across the county at South Mountain, and then southeast along the Ramapo fault is punctuated by a northwest trending zone of sandstones and mudstone (some thermally altered) with some interbedded traprock extending from the Palisades sill to the center of the county. These characteristics disappear under the coarse-grained, high-altitude Newark basin strata in the western part of the basin and briefly reappear in a low in the bedrock surface.

Traprock in Rockland County is poor aquifer material; it serves only limited domestic use. Some wells have been drilled through the Palisades sill to tap the more permeable Newark basin sedimentary rock beneath. Physical weathering of traprock predominates near land surface; most slopes are covered with broken rock (talus). Shallow fracture development (within perhaps 50 to 100 ft of land surface) is present because of the prevalence of cooling fractures and physical weathering, but fractures are not open at depth. Steep road cuts and quarry faces in the county show little evidence of water-bearing fractures in the form of wet zones in summer or ice-buildup zones in winter.

The Palisades sill overlies part of the Newark basin aquifer and presumably prevents direct recharge from reaching the underlying strata. Steep slopes characterize the Palisades sill, and precipitation that infiltrates to shallow fractures likely drains down the hillslopes. This assumption is supported by the high density of streams on the lower slopes of the Palisades sill (west- and south-facing sides). Storage of groundwater in traprock is ephemeral because high gradients on hillsides drain shallow fractures (and streams) during dry periods. Groundwater that reaches the base of traprock hillslopes most likely flows into glacial deposits and ultimately discharges to the Hackensack River, Sparkill Creek, Minisceongo Creek, or one of their local tributaries.

The hydraulic interconnection of areas of the Newark basin aquifer across the Palisades sill appears unlikely. The continuity of sill thickness from place to place is a major uncertainty. South Mountain divides Newark basin strata north-south (fig. 9). Underlying Newark basin sedimentary bedrock is visible on the lower north slope of South Mountain at one locale, but well logs at the base of the south slope indicate traprock extending at least 600 ft below land surface, effectively cutting through the most permeable part of the aquifer. At Nyack, Newark basin sedimentary bedrock likely trends north-northeast, and local groundwater flow probably discharges to the Hudson River, the lowest regional drain (tidewater). South-southeast of Nyack, groundwater flow in the Newark basin strata may be blocked—well logs indicate Palisades sill thicknesses of 300 to greater than 645 ft (which extends below NAVD 88). Groundwater flow off the west side of the sill drains to Sparkill Creek.

The hydrogeologic effects of traprock in Newark basin sedimentary bedrock away from the main body of the Palisades sill are variable. Thermal metamorphism effects are inconsistent—some rocks (generally sandstone or conglomerate) adjacent to traprock appear unaffected, whereas others are baked, change color, and become harder (fig. 10; appendix 1; J. well Ro-647 (no discernable alteration), U. well Ro-1278 (bleached sandstones)). Shales and mudstones are commonly baked, becoming hardened and turning purplish in color. Some sandstones are bleached (leaching of iron, presumably by hydrothermal fluid circulation), or turn a purplish color, or become hardened. Wells that intersect layers of traprock within the Newark basin are generally less productive than other wells within a given area, but there are exceptions. For example, production well UWNY 21 yields a maximum of 150 gal/min, but another well in the area, Ro-1278, is reported to yield 250–300 gal/min.

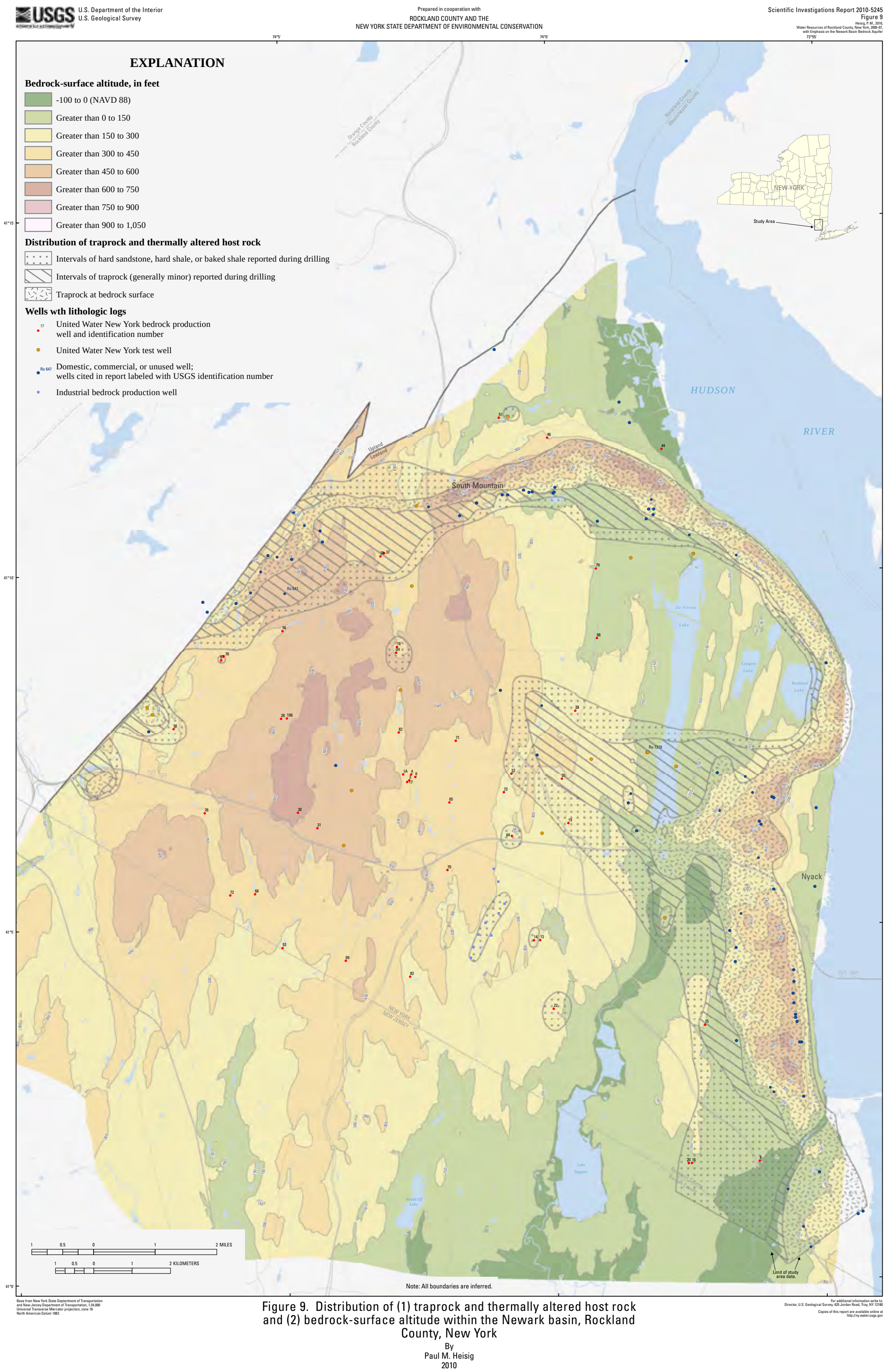


Figure 9. Distribution of (1) traprock and thermally altered host rock, and (2) bedrock-surface altitude within the Newark basin, Rockland County, New York. (Click to view full-size map at http://pubs.usgs.gov/sir/2010/5245/plates/Figure9.pdf)

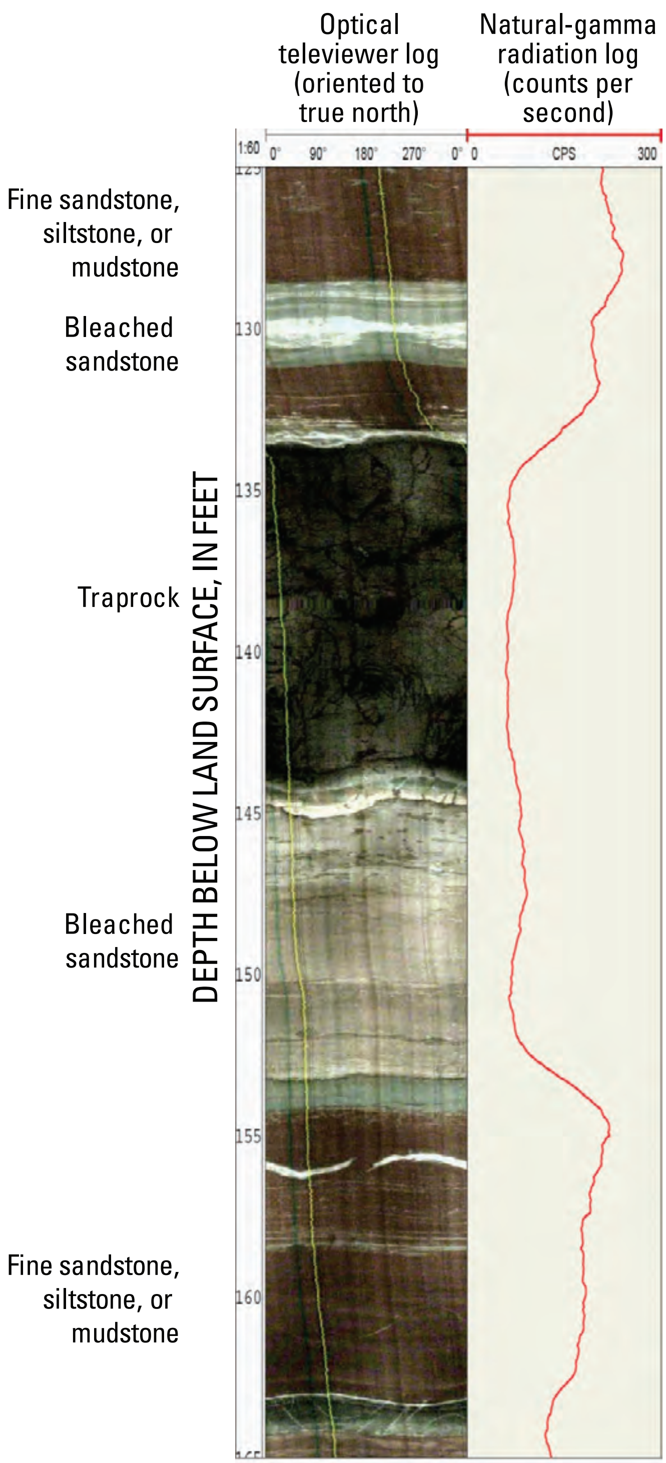


Figure 10. Optical and natural-gamma logs of well Ro-1278 (125–165 ft) showing bedding-parallel traprock intrusion and adjacent bleached sandstones, Rockland County, New York.

Hard sandstones were penetrated during drilling of several production wells; most of these wells are productive (fig. 9).

Newark Basin Aquifer

Lithologic classification of the Stockton and Passaic Formations that make up the Newark basin aquifer in Rockland County has been undertaken by Savage (1967, 1968), Olsen (1980), Parker and others (1988) and Parker (1993) (southern Rockland County and northern New Jersey), and Ratcliffe (1988). Lithologic logs from old and new (post 1968) deep exploratory or supply wells indicated some uncertainty in the definition of lithofacies boundaries between the (1) sandstone-siltstone-mudstone and sandstone-mudstone lithofacies, and the (2) pebbly sandstone and conglomeratic sandstone lithofacies of Parker and others (1988). One goal of this study was to use data from the borehole geophysical logs to update the lithologic and structural information and to also classify the Newark basin aquifer strata from a hydrogeologic perspective, as part of a regional aquifer.

Classification of the Newark Basin Aquifer into Aquifer Zones

A prime hydrogeologic consideration for classification was the permeability of the rocks, as indicated by well yields and T estimates. Permeability is not solely a function of lithology; low permeabilities in coarse-grained rocks have been noted in proximity to the Ramapo fault and to the Palisades sill and associated volcanic rocks.

Several types of borehole logs were used to classify lithology across the aquifer. Optical televiewer borehole logs were helpful in differentiating the pebbly sandstone and conglomeratic sandstone facies. Comparison of natural-gamma logs from 24 wells indicated increases in the intensity and changes in the pattern of gamma radiation in wellbores across the aquifer (fig. 11). These changes presumably reflect the increase in mica and clay content from west to east, as described by Parker and others (1988). The gamma logs provide an objective means of categorizing general changes in sediment texture. Low gamma radiation from mica-poor arkosic sandstones indicates that potassium-40 in potassium feldspars is not an important source of gamma radiation.

Transmissivity estimates across the aquifer generally parallel the textural changes indicated in well logs and the gamma logs; T values typically decrease as sediment size decreases and are low near the Ramapo fault and where diabase or basalt are present (fig. 11).The decrease in T values with smaller sediment size is related to water-bearing fracture development rather than the primary permeability of the rock. Differences in grain size among adjoining beds (fine grained adjacent to coarse grained) appear to favor development of water-bearing fractures. Localized areas of high T values are present in most lithologies and generally in proportion to the most common T values of the surrounding area. Favorable areas for high T values include low areas in the

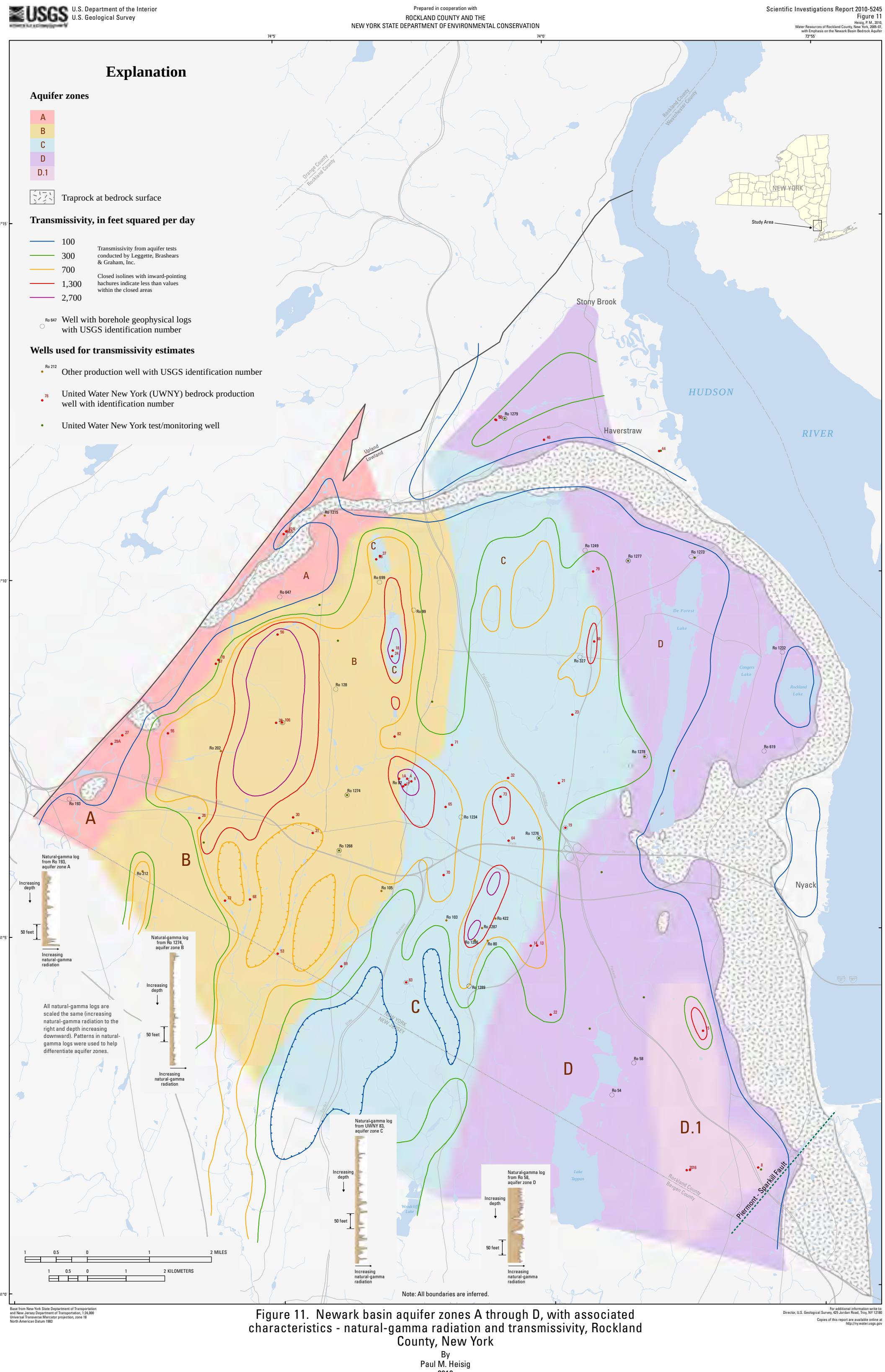


Figure 11. Newark basin aquifer zones A through D, with associated characteristics—natural-gamma radiation and transmissivity, Rockland County, New York. (Click to view full-size map at http://pubs.usgs.gov/sir/2010/5245/plates/Figure11.pdf)

local topography and areas with low bedrock dip angles and increasing land-surface altitudes in the updip direction.

Four aquifer zones, A through D, were defined on the basis of lithology, gamma-log patterns and intensities, aquifer T, well yields, proximity to the Ramapo fault, and proximity to the Palisades sill and associated rocks (table 2. ; fig. 11).

Aquifer zone A is along the western edge of the aquifer, where the regional structure and water-bearing properties of Newark basin rocks have been disrupted by the Ramapo fault and by emplacement of basaltic rocks associated with the Palisades sill. The lithology is conglomeratic sandstone and fanglomerate in the uppermost strata. Well Ro-647 depicts this part of the zone and includes two intervals of traprock (part of the Ladentown basalt; fig. 11; appendix 1A, log K). At least 300 ft of sandstone and shale underlie 130 ft of conglomeratic sandstone at a UWNY well (Grandview 67) just east of (outside of) aquifer zone A. The bedrock dip in this area is reversed (to the east) as a result of faulting. Farther south, sandstone and pebbly sandstone were the coarsest lithologies observed at a well logged in Suffern, NY (Ro-193; fig. 11; appendix 1A, log F). The gamma log from this well indicated low gamma radiation in the upper 340 ft, with minor peaks at intervals of about 25 ft. Below 340 ft, gamma-radiation peaks doubled in intensity. Well yields in aquifer zone A were relatively low and did not exceed 70 gal/min. Transmissivity values in aquifer zone A were generally less than 100 ft^2/d.

Aquifer zone B corresponds most closely to the conglomerate and conglomeratic sandstone lithofacies of Savage (1968) and Parker and others (1988), respectively. The zone extends eastward into the pebbly sandstone lithofacies delineated by Savage (1968) and Parker and others (1988). This zone also corresponds to the highest altitudes of Newark basin strata in Rockland County. Gamma logs from aquifer zone B have a low gamma-radiation base line and low peaks that are less than double the base-line count at intervals that range from 10 to about 100 ft. Well yields in this zone are among the highest in the county; test-well and supply-well yields range between 150 and 800 gal/min. Transmissivity values calculated from tests at deep wells are commonly between 700 and 1,300 ft^2/d (fig. 11). Borehole logs from this zone are depicted in appendix 1A, logs D, E, L, P, R, and W.

Aquifer zone C, in the central part of the county, is characterized by “spikey” gamma-log patterns in most wellbores, representing a base line of “clean” sandstone units with low gamma-radiation levels interbedded with finer-grained units with high peak gamma-radiation levels (fig. 11). This aquifer zone corresponds most closely to the gravelly sandstone lithofacies of Savage (1968) and the pebbly sandstone facies of Parker and others (1988). The thickness of fine-grained units ranges from a fraction of a foot to about 10 ft. Frequency and thickness of the fine-grained units increase eastward and transition into aquifer zone D. Yields of deep wells in aquifer zone C range from 65 to 600 gal/min, and T values are commonly between 300 and 700 ft^2/d (fig. 11; appendix 1A, logs C, G, H, I, N, S, and X).

Fine-grained units with high natural-gamma radiation in aquifer zone C are common locations of water-bearing zones, especially within the upper 200 to 300 ft of bedrock (appendix 1A, log X). These units appear to be fissile, can contain dissolvable cements (calcite, gypsum most likely) and adjacent bleached sandstone, and are subject to disintegration and erosion in wellbores and in outcrops (fig. 12). Exposure in wellbores and increased rates of groundwater flow increase dissolution of cements and erosion of these units; caliper logs of old wellbores (appendix 1A, logs D, E, H, O) show more erosion at water-bearing fractures and within the wellbores in general than do caliper logs of relatively new wellbores (appendix 1A, logs L, Q, U, W).

Aquifer zone D is characterized by high base-line gamma-radiation levels from mica and clay minerals in the finer-grained rocks and mica in arkosic sandstones; some low-gamma zones appear to be non-micaceous sandstones, some appear to be leached or bleached in association with the emplacement of the Palisades sill (fig. 11; appendix 1A, logs A, B, J, M, O, Q, T, and U). Parts of this zone have been thermally altered by intrusion of traprock (fig. 9). This aquifer zone represents the siltstone and arkose lithofacies of Savage (1968) and the Stockton Formation and Passaic Formation lithofacies 1 (siltstone, mudstone, and sandstone) of Parker and others (1988).

Aquifer zone D is divided into two areas—the main area D and subarea (D.1) in the extreme southeast corner of the aquifer zone (fig. 11). Area D covers most of the aquifer-zone area and is characterized by well yields of not more than 150 gal/min and T values between 100 and 300 ft^2/d. Aquifer zone D.1 is characterized by maximum well yields between 200 and 350 gal/min and T values generally between 100 and 2,000 ft^2/d. Three UWNY well fields draw from the D.1 subarea. Locally higher proportions of sandstone than siltstone probably account for the relatively high well yields. Subarea D.1 is mostly north of the Piermont-Sparkill fault and was mapped as Passaic Formation (Brunswick Formation at that time) by Savage (1968) and as Stockton Formation by Parker and others (1988) and Ratcliffe (1988). The contact between the Passaic and Stockton Formations is transitional and not conclusively defined by local well logs.

Lack of wells for borehole geophysical logging limited or prevented classification of the aquifer in the Nyack, Haverstraw, and Stony Point areas (fig. 11). The Nyack area is mostly used for domestic supply, whereas a few production wells in the Haverstraw and Stony Point areas have yields of about 200 gal/min. Most of these areas are likely part of aquifer zone D. One wellbore (Ro-1279; appendix 1A, log V), however, has about 250 ft of relatively light-colored sandstones that may be part of the Stockton Formation rather than the lower Passaic Formation.

Fracture Occurrence in Wellbores

Optical and acoustic televiewer logs from 23 wells (appendix 1A) were used to identify and measure the

Table 2. Characteristics of aquifer zones A–D, Newark basin aquifer, Rockland County, New York.

[ft, feet; gal/min, gallons per minute; <, less than]

Geophysical properties and associated lithology			Hydrologic properties		
Aquifer zone	Pattern of natural-gamma radiation	Lithology	Well-yield range among wells greater than or equal to 250 ft deep (gal/min)	Most common range of aquifer transmissivity from figure 11 (ft^2/d)	Maximum aquifer transmissivity (ft^2/d)
A	Low base-line levels, with regular, low peaks that are less than double the base line in upper 200 ft. Larger peaks below 200 ft	Mostly interbedded conglomerate, pebbly sandstone, and sandstone; interbedded pebbly sandstone and sandstone in the extreme south (at Suffern, NY)	20–70	<100	760
B	Low base-line levels, with regular, low peaks that are less than double the base line.	Mostly interbedded conglomerate, pebbly sandstone, and sandstone	125–700	700–1,300	13,370
C	Low base-line levels, with regular, high peaks that are typically more than double the base line. Boundaries are transitional, with increasing percentages of high peaks toward the eastern boundary	Pebbly sandstone and sandstone interbedded with thin (10 ft or less) fine-grained micaceous or clayey layers at intervals of about 5 to 20 ft. Two small outlying areas at two United Water New York wellfields (18, 24 and 37, 38) in aquifer zone B.	65–600	300–700	4,600
D	High base-line levels, with low peaks every 5 to 10 ft; few low-gamma zones of “clean” sandstone, about 10 ft thick. Low-gamma zones increase in thickness and frequency toward the west.	Sandstone (arkosic, micaceous), siltstone, mudstone, and shale	25–150	100–300	1,060
D.1	no data	Sandstone and shale (or mudstone)	200–350	100–300	3,800

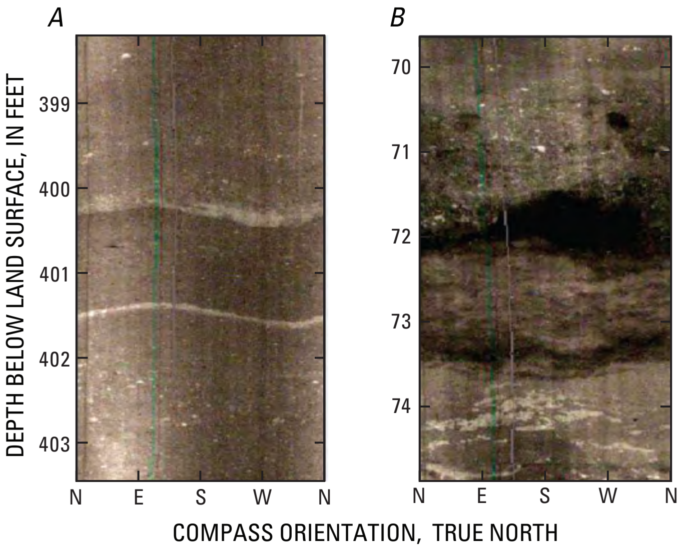


Figure 12. Comparison of *A,* deep unweathered and *B,* shallow weathered fine-grained, high natural-gamma-radiation zones showing disintegration and erosion of shallow zone and the associated water-bearing fractures at well Ro-1289.

occurrence and frequency of high- (greater than 30 degrees) and low-angle fractures in bedrock wells (appendix 1B). The dataset is uncorrected for the under-representation of high-angle fracture frequency in vertical wells. However, the general distribution of high-angle fracture occurrence among wellbores is valid. Water-bearing fractures within the total population of fractures were identified by changes in the temperature and (or) specific conductance of water in the wellbores or by measurement of changes in upward or downward flow within wellbores. This dataset provided information on the occurrence of water-bearing fractures and did not indicate the productivity of individual fractures. The number of each type of fracture and their water-bearing subsets, by aquifer zone, are depicted in fig. 13.

Characteristics of the occurrence of fractures and water-bearing fractures from figure 13 are described as follows:

- Low-angle fractures (less than 30 degrees) (mostly bedding partings) are the dominant fracture type in every aquifer zone, with the exception of a single well (Ro-1276).
- Low-angle fractures (less than 30 degrees) are the dominant water-bearing fracture type in every aquifer zone.
- Coarse-grained aquifer zone B differs from the other aquifer zones in the dominance of low-angle fractures, which accounted for 91 percent of all fractures and 96 percent of water-bearing fractures. Low-angle fractures in the other three aquifer zones accounted for 68 to 78 percent of total identified fractures. The percentages of water-bearing fractures with low dip angles in aquifer zones A, C, and D were 82, 87, and 91 percent, respectively.
- High-angle fractures are most common in areas adjacent to faulting, such as the Ramapo fault (aquifer zone A), and in areas adjacent to the Palisades sill and associated volcanic rocks (aquifer zone D). A high count of high-angle fractures and a large, cavernous interval at well Ro-1276 suggest faulting in that area (appendix 1).

Fracture Yield with Depth: Contributing Factors and Contributing Areas to Pumping Wells

Data on well yield with depth from 27 production wells were used to define the occurrence of the productive water-bearing fractures and the thickness of the most active parts of the groundwater flow system. Decreases in the yields of water-bearing fractures with depth are commonly reported in bedrock (for example, Harlow and Le Cain, 1991). Yields were typically measured at irregular intervals as the wells were drilled. Yield data were therefore apportioned into 50-ft intervals to standardize the data (fig. 14).

Well yield-depth data were divided among the four aquifer zones. The thickness and depth of the most-productive interval of bedrock varied across the aquifer zones, increasing in both aspects with coarsening of sediments and increases in altitude. Most yield was from the upper 200 ft of bedrock in wells in the far eastern part of the county (aquifer zone D), whereas substantial yields in the west (aquifer zone B) were from as deep as 350–400 ft. Aquifer zone C was intermediate; most yield was from the upper 300 ft. Yields from three wells in aquifer zone A were highest in the upper 100 ft, but moderate percentages of total yield extended to 300–400 ft.

A number of hydrogeologic factors can affect the yield of fractures with depth: sediment texture, depth of weathering, depth to water below land surface, seasonal and drought-related variations, aquifer storage associated with fractures, and lithostatic pressure. Coarse-grained sedimentary bedrock units tend to be brittle, which favors open fractures at greater depths than in fine-grained units such as shale or mudstone. Fine-grained units behave more plastically with depth, which tends to close or reduce fracture openings. Areas with deeply weathered bedrock can be expected to have less permeability in shallow fractures as bedrock competence is degraded. Differentiation between rock and overlying till is difficult in such areas. Shallow bedrock fractures may be dry and thus have no yield in areas with greater depths to water (40 ft or greater) year-round, as in parts of aquifer zone B, or in other areas during dry summer seasons or longer-term droughts.

If a fracture or fracture zone is permeable, an additional consideration is the amount of the aquifer storage connected with the fracture. This can be an important factor in both fracture yield with depth and overall well yield. Most productive water-bearing fractures are parallel or sub-parallel to dipping bedding, so the extent and permeability of the fracture plane along strike and updip define the aquifer storage associated with a fracture. The greater the amount of storage available in the fracture based on the saturated, updip width of the fracture, the greater the availability of water. This

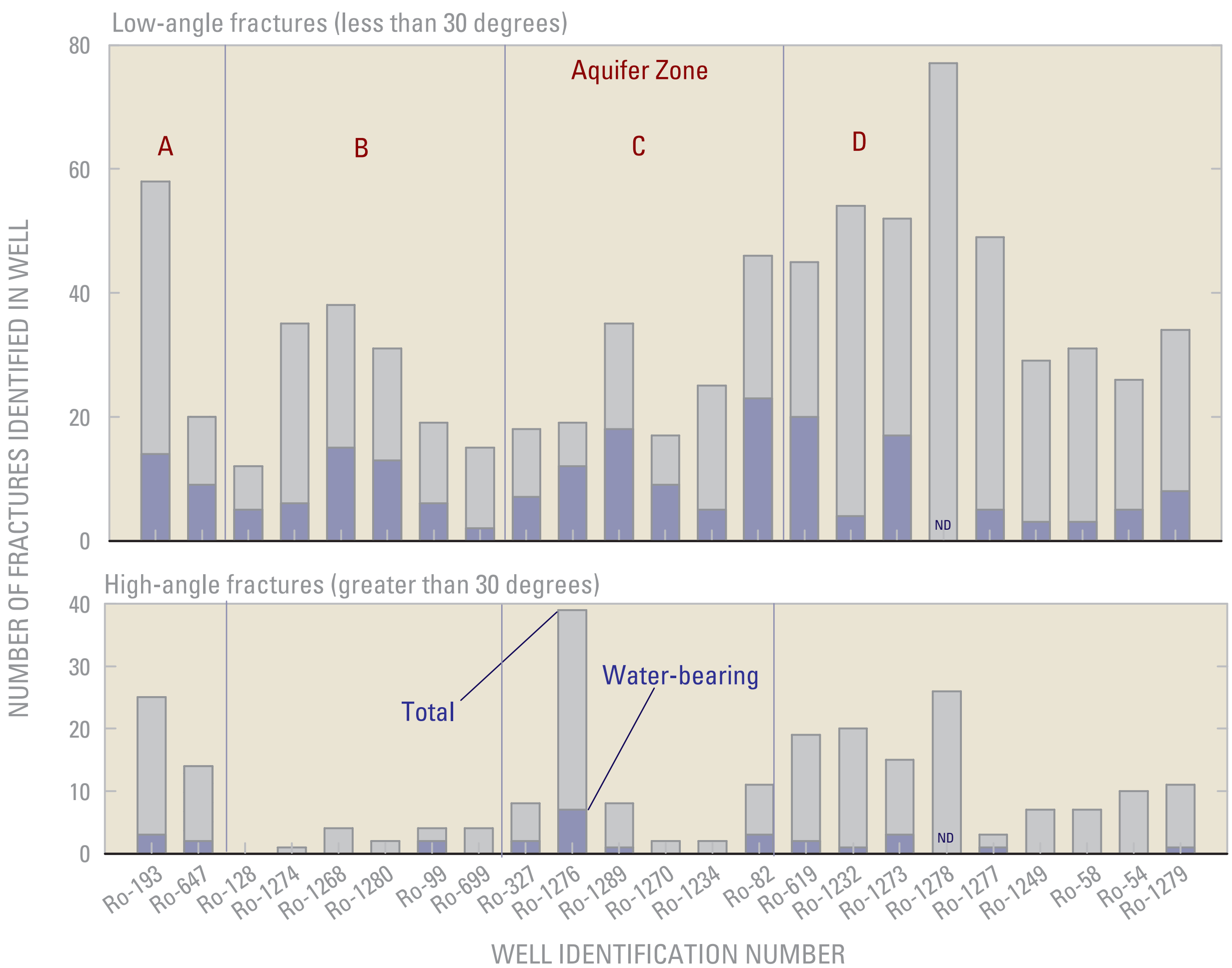


Figure 13. Fracture occurrence in wellbores, Rockland County, New York. (ND, no data)

reasoning suggests that in dipping bedrock, given fractures of the same permeability, a deep fracture would have more storage than a shallow fracture. If topography increases in the updip direction, updip storage is potentially increased, and a higher head (water level) would be observed in the deeper fracture. The lower the dip of the bedding, the wider the updip saturated area of the fracture (fig. 15). Thus, within a given aquifer zone with all other factors being equal, the best yield potential is in areas with relatively low bedding dip and more specifically from fractures intersected at depth (200–300 ft), but not so deep that fractures are less permeable. The most productive zones among aquifer zones A through D are different and generally are indicated by the highest percentages of yield among the depth intervals in fig. 14. This information indicates how contributing areas to pumping wells can be expected to reflect local bedrock structure. In all cases, elliptical areas are aligned with the strike of bedding. Water levels are affected less in the downdip direction as fractures become less permeable with depth. The ellipse is broad (closer to circular) in areas of low dip and narrower and more elongated in areas of higher dip. Such responses were observed around the Viola (UWNY 28, 106) and New Hempstead (UWNY 18, 24) well fields and are described in a following section entitled “Groundwater Levels Affected by Groundwater Withdrawals.”

Bedrock Structure

Assuming that groundwater flow mostly parallels the strike of strata in the Newark basin aquifer, definition of the strike and dip angle of the sedimentary bedrock (and fractures) is critical for constraining regional groundwater flow directions. Previous bedrock mapping of strike and dip measurements at outcrops (Kummel, 1899; Savage, 1967; N. Ratcliffe, written commun., 2005) were integrated with new datasets (fig. 16A, B) including the following:

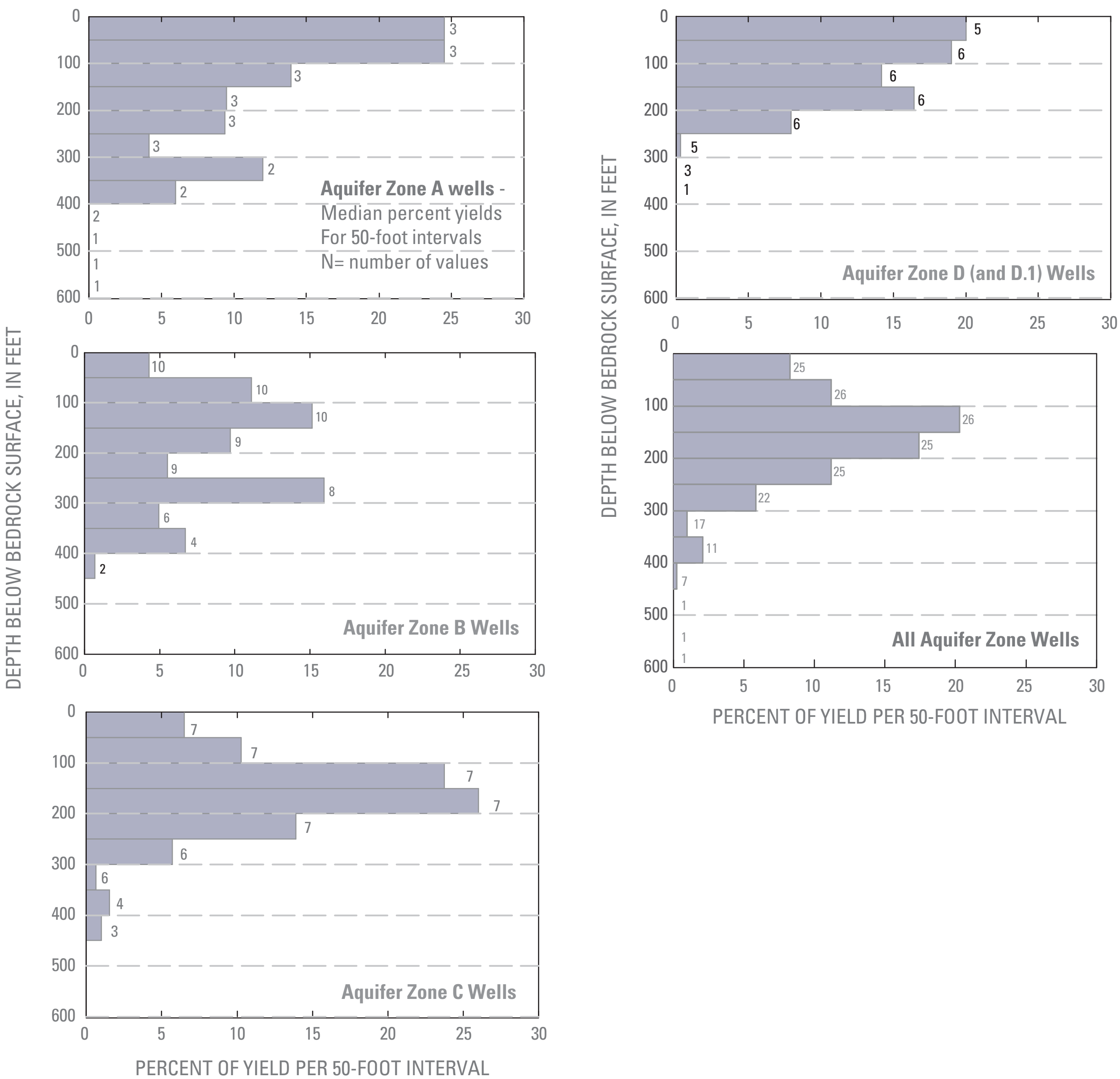


Figure 14. Well yield with depth, by 50-foot intervals, from wells in aquifer zones A–D, Newark basin aquifer, Rockland County, New York.

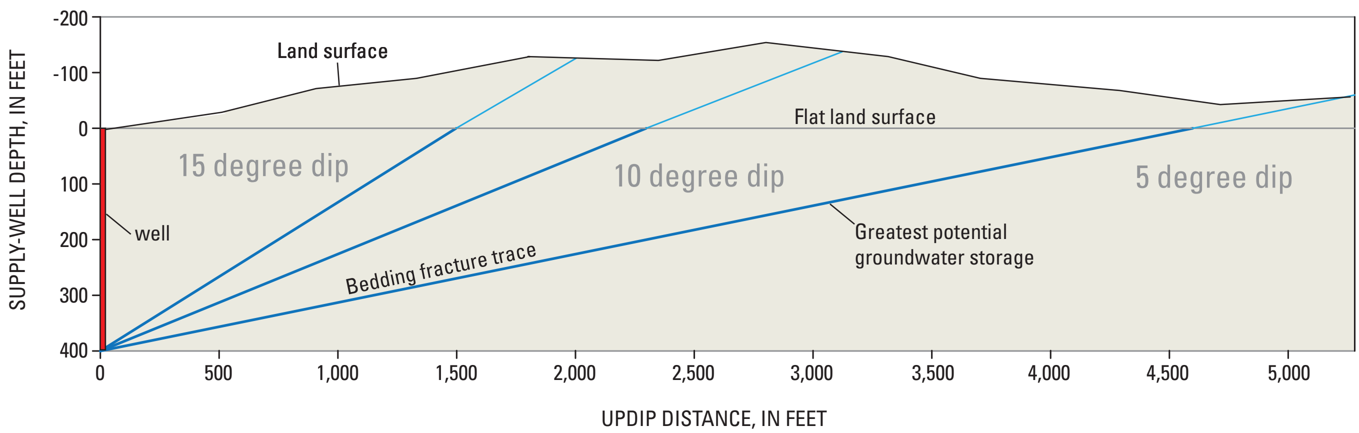


Figure 15. Schematic section showing the effect of dip angle on potential updip groundwater storage area for water-bearing fracture zones parallel to bedding in the Newark basin aquifer, Rockland County, New York.

1. Strike and dip measurements from optical and acoustic televiewer borehole logs from 18 wells with between 78 and 444 ft of open borehole (appendix 1A).
2. Strike and dip measurements at selected outcrops
3. Correlation of optical and natural-gamma logs among two pair of nearby wells (Ro-54 and Ro-58; Ro-1268 and Ro-1274; fig. 16A).
4. Identification of hydraulic interconnections among wells from aquifer-test data and from continuous water-level monitoring (fig. 16A).
5. Identification of linear features, such as stream orientation/alignments in areas of thin glacial deposits that differ from the north-south glacially streamlined landscape (fig. 16A).
6. Groundwater-level maps, which indicate areas in which groundwater levels change gradually or abruptly. Gradual changes in groundwater levels are generally consistent with flow along bedding strike. Abrupt changes in groundwater levels away from well fields indicate some kind of barrier to groundwater flow. These areas likely indicate changes in groundwater level across to the strike of bedding rather than with it.
7. Chloride distribution across the aquifer but especially in areas where high concentrations have entered the aquifer and are being transported by the regional groundwater flow system (fig. 16B).
8. A band of bedrock with low carbonate content (less than 2 percent) generally striking northeast in the east-central part of the aquifer (fig. 16B), as measured by Savage (1967). This area of the aquifer historically has had low values of groundwater pH, alkalinity, and hardness. Low pH values in this area are documented in the groundwater chemistry section of the report.

Interpretation of the strike and dip data alone resulted in identification of numerous areas with similar bedding orientation (fig. 16A). The dip of the bedding is uniformly northwest or west except in places along the Ramapo fault and between the South Mountain and the Theills fault (fig. 16A). Dip ranges from 5 to 17 degrees (fig. 16A). Some of the discontinuities in strike and dip may be associated with faulting or folding, including the possibility of movement along fine-grained bedding planes, antithetic to the Ramapo fault. Faulting in addition to previously mapped faults (Ramapo, Theills, Sparkill, and at least one at Long Clove along the Palisades sill) is likely present; Ratcliffe (1988) has inferred the presence of additional faults within the Newark basin aquifer (fig. 16A). Numerous lineaments also were identified during this study, some of which are included in fig. 16A. Changes in bedding orientation with depth were noted in two wellbores (Ro-1268, Ro-1274), and changes in bedding orientation with altitude/topography occur among outcrops (fig. 17, appendix 1B). Calcite veins, also commonly associated with faulting, were noted in some well logs. The hydrogeologic importance of faults or fracture zones within the Newark basin aquifer, as groundwater-flow conduits or barriers, was not determined.

The strike of bedding across the aquifer generally parallels the boundary lines of aquifer zones A–D (fig. 17, fig. 11) and the lithologic units of Savage (1967) as depicted on the New York State Geologic Map (Fisher and others, 1970) (fig. 6). Previous depictions of bedrock strike lines in Rockland County (Ratcliffe, 1988) and in New Jersey (Olsen and others, 1996; Michalski and Britton, 1997; Parker, 1993) are typically more continuous than those depicted in figure 16.

Three sections of the Newark basin aquifer in Rockland County are illustrated in figure 18; the sections are nearly perpendicular to bedding strike and depict the dip of bedding from outcrop and borehole geophysical data. The sections illustrate the compartmentalized nature of the aquifer—if groundwater flow is mostly along strike, then groundwater flow in the bedrock is mostly into or out of the page, and pumping wells can only affect a limited east-west cross-sectional area.

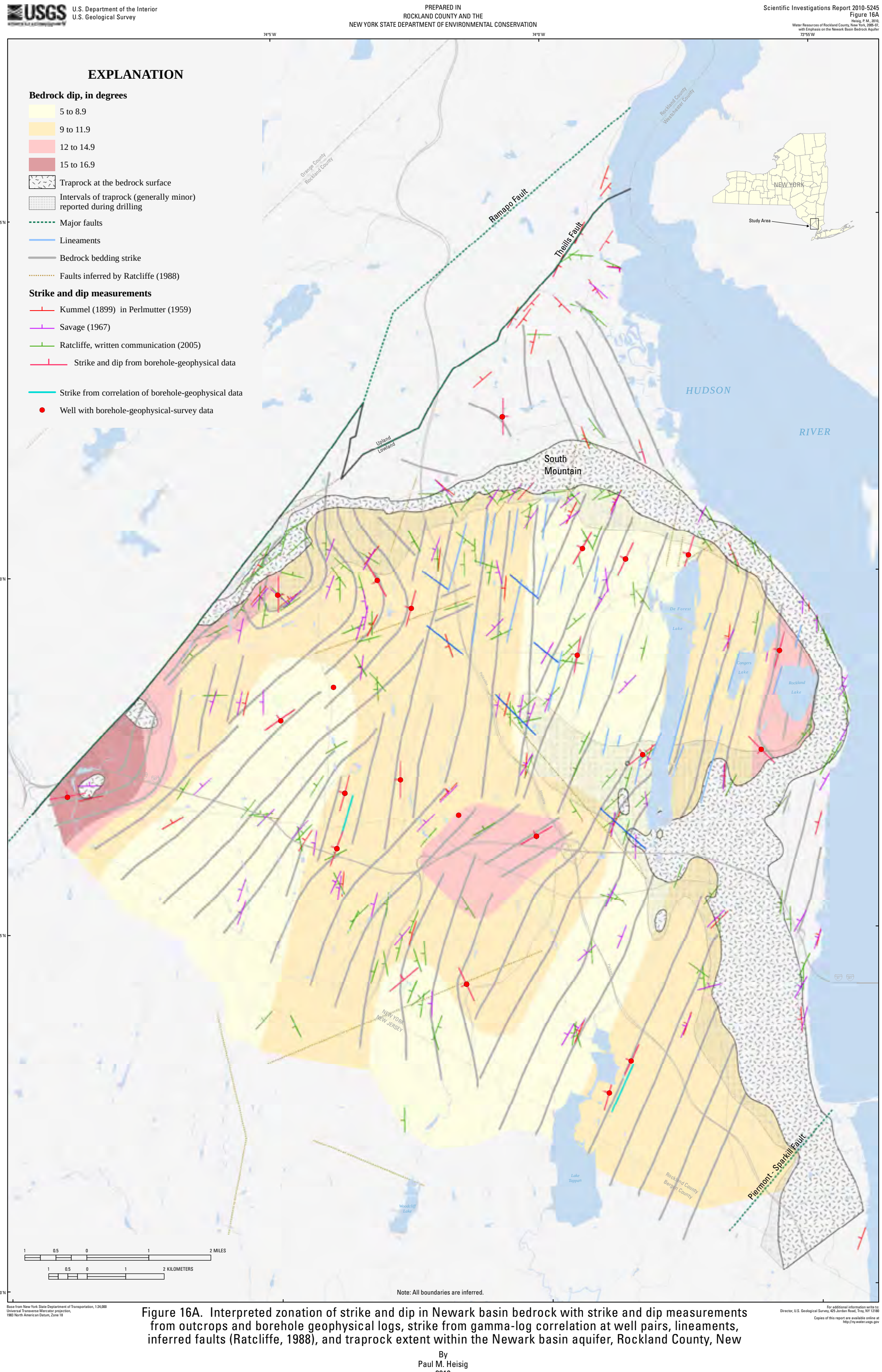


Figure 16A. Interpreted zonation of strike and dip in Newark basin bedrock, with *A.* strike and dip measurements from outcrops and borehole geophysical logs, strike from gamma-log correlation at well pairs, lineaments, inferred faults (Ratcliffe, 1988), and traprock extent within the Newark basin aquifer, *B.* hydrogeologic data used in support of interpretation, Rockland County, New York. (Click to view full-size map at http://pubs.usgs.gov/sir/2010/5245/plates/Figure16.pdf)

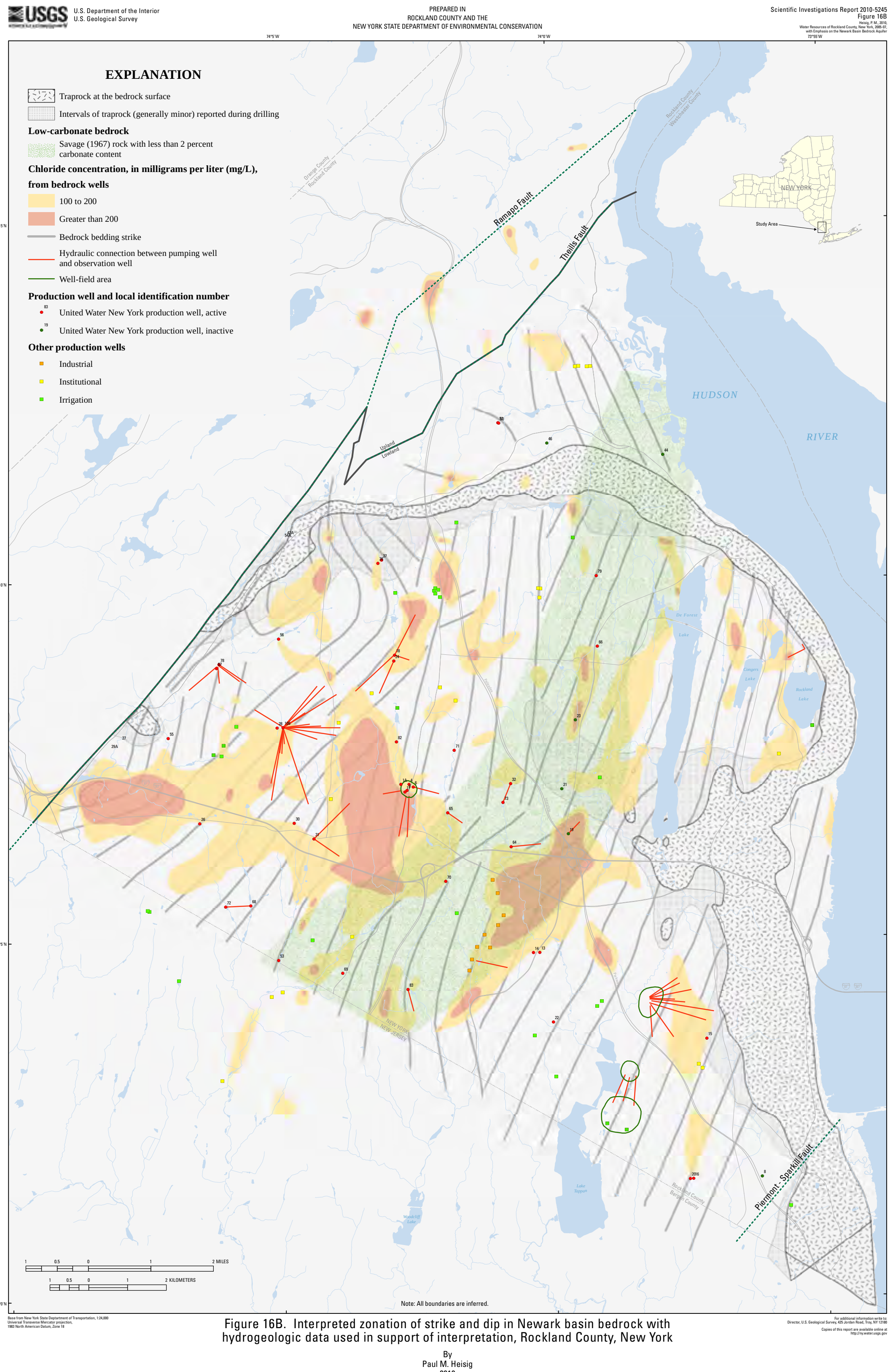


Figure 16B. Interpreted zonation of strike and dip in Newark basin bedrock, with *A.* strike and dip measurements from outcrops and borehole geophysical logs, strike from gamma-log correlation at well pairs, lineaments, inferred faults (Ratcliffe, 1988), and traprock extent within the Newark basin aquifer, *B.* hydrogeologic data used in support of interpretation, Rockland County, New York. (Click to view full-size map at http://pubs.usgs.gov/sir/2010/5245/plates/Figure16.pdf)—Continued

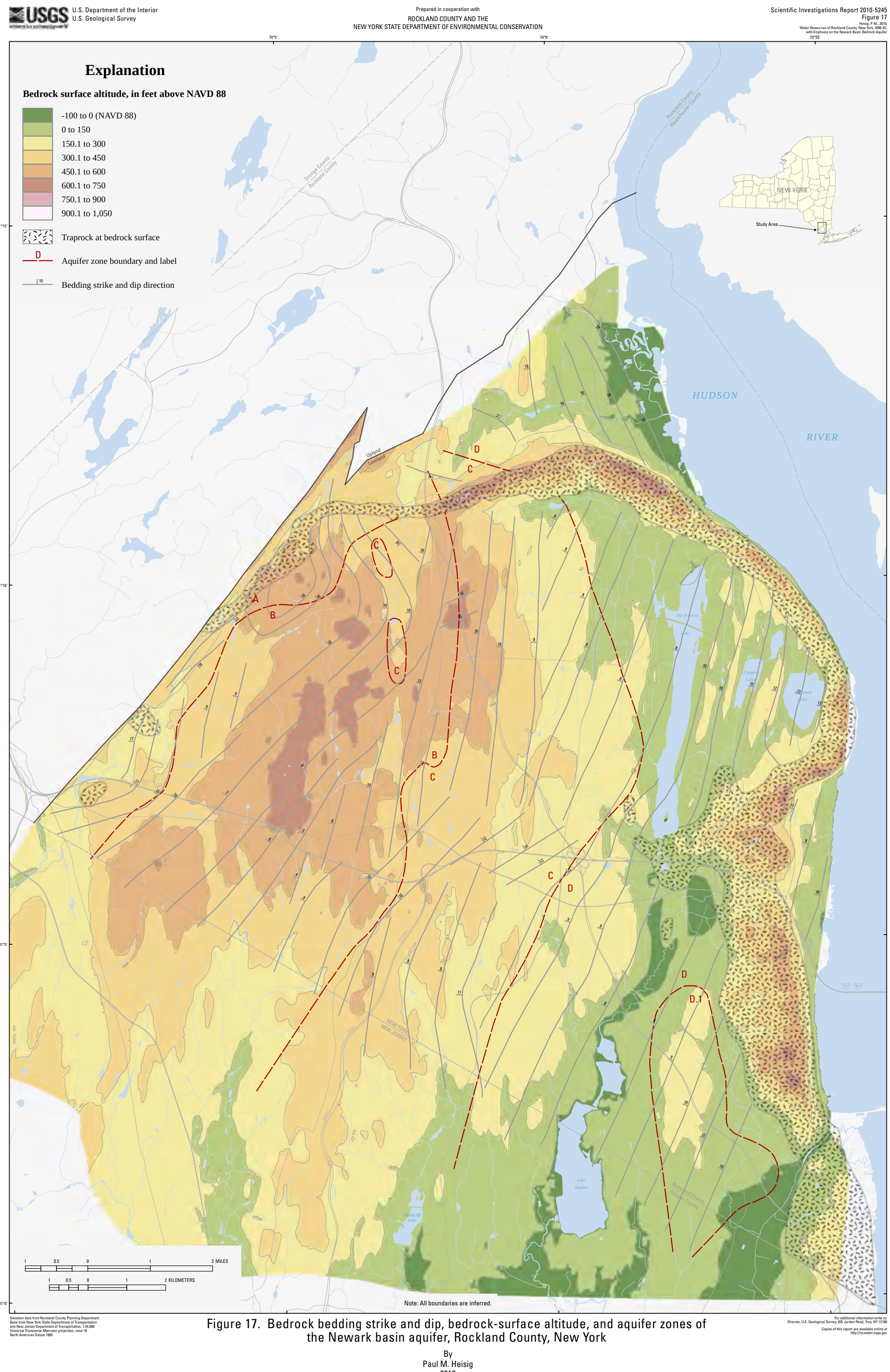


Figure 17. Bedrock bedding strike and dip, bedrock-surface altitude, and aquifer zones of the Newark basin aquifer, Rockland County, New York. (Click to view full-size map at http://pubs.usgs.gov/sir/2010/5245/plates/Figure17.pdf)

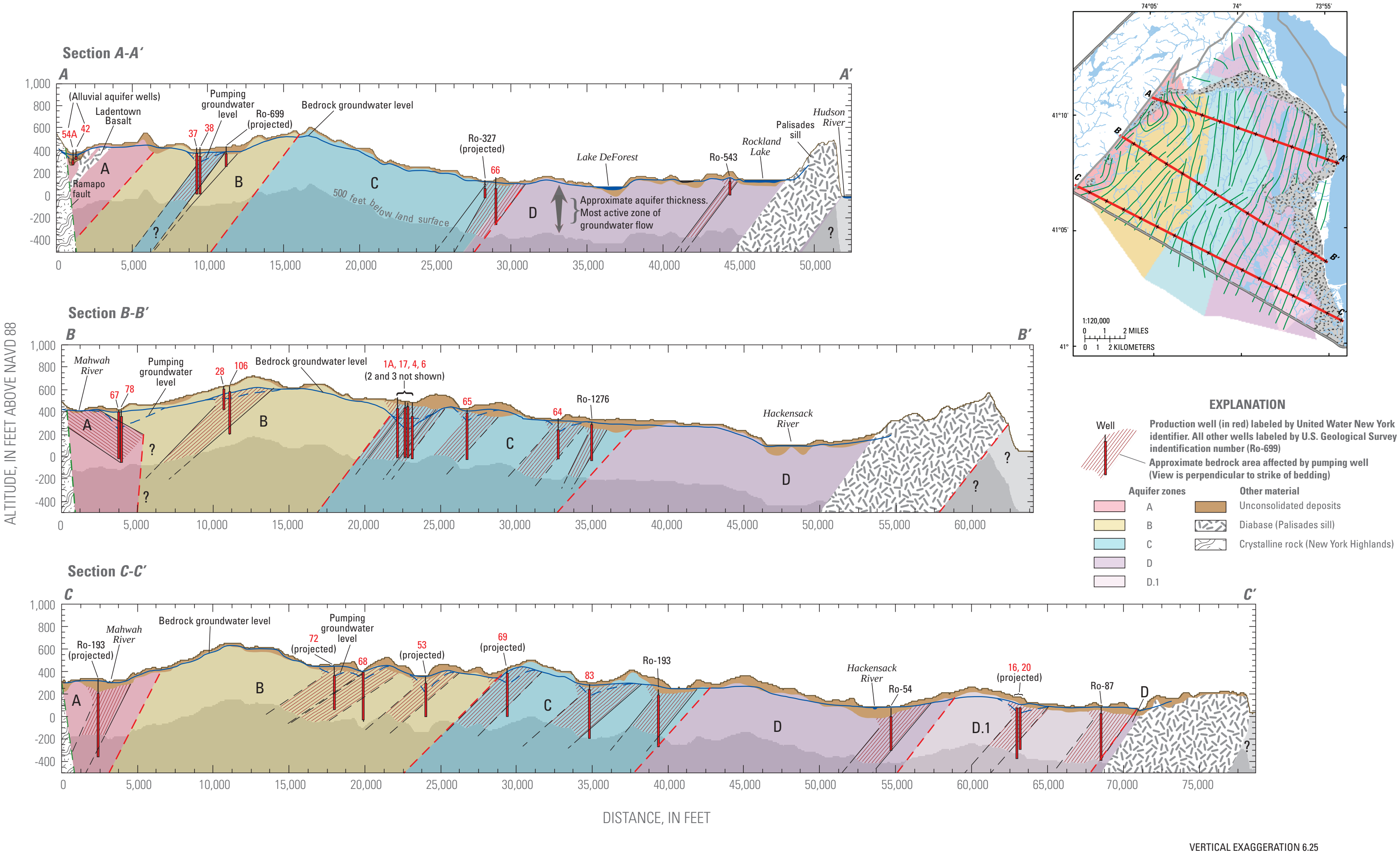


Figure 18. Hydrogeologic sections *A, B,* and *C,* of the Newark basin aquifer, Rockland County, New York. (Click to view full-size map at http://pubs.usgs.gov/sir/2010/5245/plates/Figure18.pdf)

Wellbore Interconnection of Otherwise Isolated Fractures

When bedrock wells are drilled, the framework of the local groundwater flow system is changed if the wellbore intersects two or more water-bearing fractures. The wellbore is a highly permeable vertical conduit in the aquifer that interconnects fractures that, prior to well installation, may have been hydraulically isolated from one another. The net result is that groundwater flow is (or can be) greatly accelerated (on a relative scale) by these borehole "short circuits." Head (pressure) differences between fractures cause upward or downward flow zones to develop within the wellbore as water flows from fractures with high head to fractures with low head. Flow in wellbores is typically upward if the well is located in a groundwater discharge area—a topographically low area drained by streams, lakes, or wetlands. Wellbore flows are generally downward if the well is located in a recharge area, which includes all other areas of the local topography. Upward flows (at flowing wells) were much greater than downward flows under nonstressed aquifer conditions. Wellbore flows were highest (and downward) in wells affected by groundwater pumping, with the exception of one nonstressed flowing well.

Flow logs were collected at 18 wells in Rockland County; three subsequent measurements were made at three of the wells to assess the variability of flow rates over time. Flow rates ranged from non-detectable to at least 17 gal/min, which was the maximum direct measurement possible with the flowmeter.

Flow rates in Rockland County were influenced by several factors in addition to those mentioned above: proximity to pumping wells, degree of confinement, and T value within the aquifer zone. High pumping rates in nearby production wells did not result in high vertical flow rates in wellbores. Vertical flow rates were less than 1 gal/min at well Ro-1280, which is about 20 ft from UWNY production well 106. Low vertical flow rates are attributed to a nearly even vertical head distribution among fractures near the withdrawal point. As a result, horizontal flow across the wellbore at water-bearing fractures is the dominant flow. The component of lateral flow could not be measured with the heatpulse and electromagnetic flowmeters used in this study. Lateral flow is indicated by occasional "spikes" (positive or negative) in temperature or specific-conductance fluid logs at fractures and by downhole videos that show horizontal movement at fractures (particle movement or the movement of flagging that was suspended below the video camera). Likewise, little or no flow was measured at well Ro-1234 in a highly confined area affected by well UWNY 65, which is about 1,600 ft away. Head differences among fractures were again small, and horizontal flow under confined conditions was likely the dominant flow component.

The highest wellbore flows were observed in aquifer zones B and C (appendix 1A, logs D, E, I, R, S), which have the highest T values (fig. 11), yields with depth (fig. 14), topographic relief, and groundwater-withdrawal rates. Low flow rates were common in aquifer zone D for the opposite reasons.

Wellbore flow varied over time in response to groundwater level (head) at three wells that were repeatedly measured (Ro-128, Ro-1274, and Ro-1276). Higher water levels generally corresponded to higher flow rates in the wellbores (fig. 19; appendix 1C). A water level in a bedrock well that intersects more than one water-bearing fracture represents a composite water level (a transmissivity weighted average head of the heads from each water-bearing fracture).

In all three wells, the flow was downward each time, as groundwater from shallow fractures recharged deeper fractures at least partly in response to groundwater withdrawals from local well fields. Flow rates changed by 1.5, 6, and 11 gal/min over time. The magnitude of downward flows appears to be largely in response to the water levels or heads in the shallow water-bearing fractures, which respond most directly to recharge. The heads in deeper fractures, if affected by pumping wells, can be variable because some wells are used all year, whereas others are used seasonally.

The repeat measurements of borehole flow confirm that shallow fractures provide less water to borehole flow as groundwater levels decline in the summer. In one instance, the shallow-fracture contribution declined as the water level approached the fracture; when the water level dropped below the fracture, much lower flow cascaded from the fracture to the water surface. This scenario indicates a decline in shallow water available to replenish deeper fractures as summer progresses. This can translate into decreased yields at production wells when the demand for water is greatest. The loss of aquifer storage from shallow intervals can result in increased drawdown rates in the aquifer—shallow fractures can account for a disproportionate amount of aquifer storage (and yield). High percentages of well yield from shallow depths in aquifer zone D (fig. 14) make this zone particularly susceptible to decreased well yield as summer progresses. In fact, decreased yields have been reported over the course of the summer season at golf-course irrigation wells (Ro-693 and Ro-694) and at wells that formerly served the Rockland Psychiatric Hospital (for example, Ro-54 and Ro-58). These data indicate that well-yield tests, conducted at times of year other than mid -to late summer are likely to overestimate well yields during late summer. Yields determined from well testing during dry summer periods can help ensure long-term viability at production wells, barring additional aquifer withdrawals in the same area.

Another ramification of the borehole flow data in Rockland County is that the drilling of at least 6,000 wells has altered the groundwater flow system. Groundwater flow has been accelerated, particularly in areas with high densities of wells. The presence of additional wells in areas pumped by production wells likely represents enhancement of aquifer yield at the production well because the aquifer is now more permeable; this facilitates additional, mostly shallow, groundwater flow towards production wells. The net effect is an expansion of the contributing areas to production wells

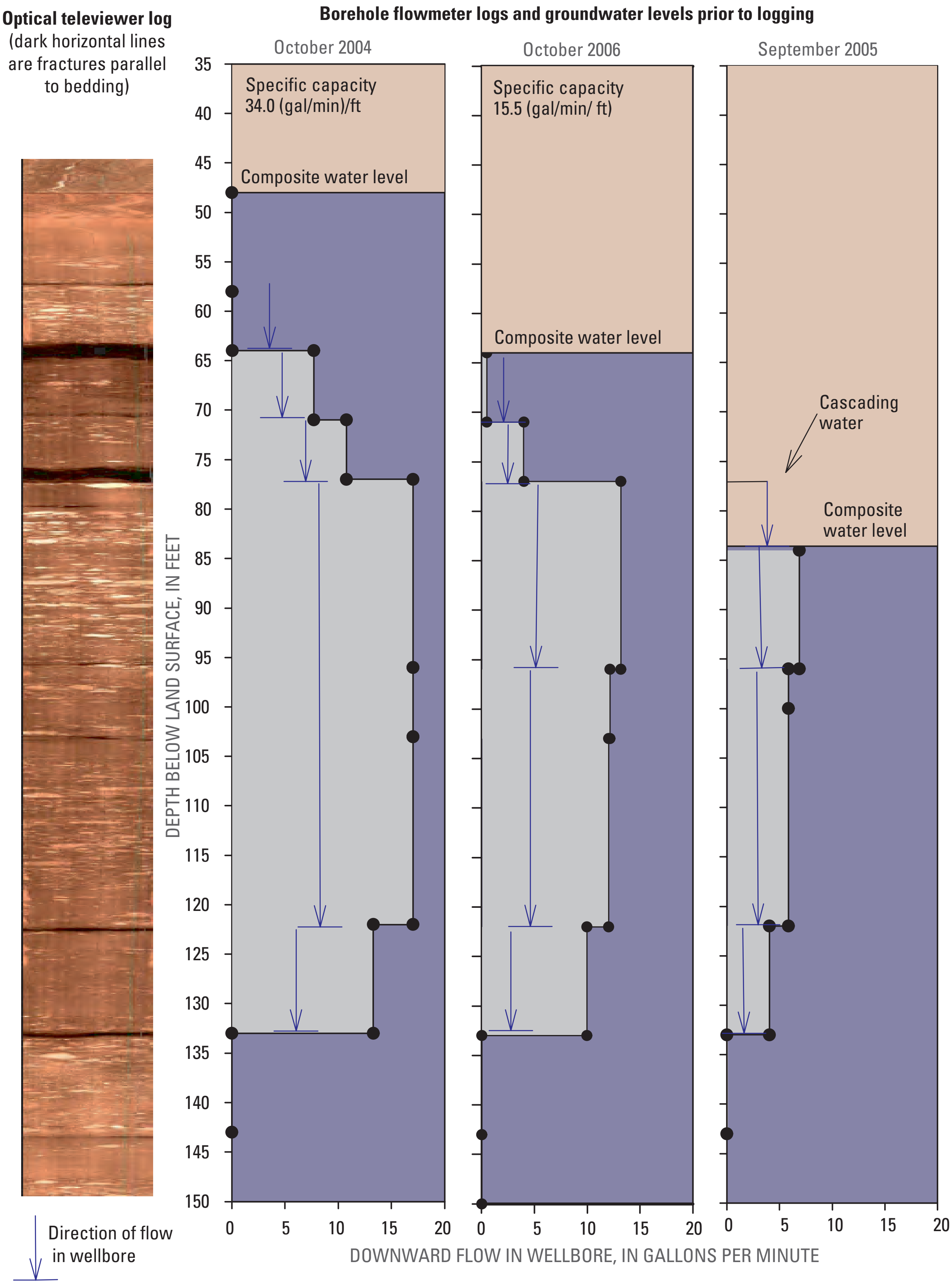


Figure 19. Multiple wellbore flow logs of well Ro-128 under different groundwater-level conditions. Downward flow to deeper fractures (affected by regional pumping stresses) decreases as shallow fractures are dewatered.

but also increased susceptibility to contamination because of enhanced connection to shallow groundwater.

Groundwater Conditions

Groundwater conditions were evaluated with water-level and water-chemistry data. These datasets, along with the aquifer-framework data presented earlier, form the basis for the conceptual model of the Newark basin aquifer.

Groundwater Levels

Groundwater-level conditions in the aquifer were assessed through groundwater-level measurements at nearly 250 observation wells and UWNY water-level and pumping-rate data from 45 production wells (fig. 20). Eighteen observation wells were continuously monitored for periods of a few weeks to nearly 3 years in natural (relatively unstressed) and stressed areas of the aquifer (fig. 20). An additional eight wells in the Newark basin were monitored by UWNY (fig. 20). Historic groundwater-level data were compiled, and a generalized water-level map was developed. A water-level network of between 91 and 158 wells was developed from existing wells and measured four times during the study. Water-level (potentiometric-surface) maps were constructed from two of the groundwater-level surveys. The regional groundwater flow system was delineated from interpretation of potentiometric-surface data overlaid on the bedding-strike map of the Newark basin aquifer (fig. 17).

Most observation wells are between 100 and 250 ft deep, and the water levels represent a composite of the head values from water-bearing fractures, weighted by their respective transmissivities. The water levels are considered a reasonable approximation of average conditions in the most active upper part of the groundwater flow system. Water levels are most likely to be biased low in high-altitude recharge areas and biased high in low-altitude discharge areas in response to natural groundwater gradients.

Degree of Aquifer Confinement

The Newark basin aquifer ranges widely in its degree of confinement. Shallow bedrock is generally unconfined unless overlain by poorly permeable till. The bedrock aquifer is anisotropic because the primary water-bearing fractures are either parallel or subparallel to bedding (see borehole geophysical logs in appendix 1). This degree of anisotropy imparts vertical and horizontal restriction of groundwater movement (fig. 21) and all but the shallowest water-bearing fractures are considered confined (artesian). However, many bedrock wells are responsive to precipitation, which indicates local confinement (connection with the atmosphere). Wells sufficiently downslope and downdip from the recharge area of their water-bearing fractures (where the fracture intersects the bedrock surface; fig. 15) will flow at land surface because they are locally confined, but they also respond to precipitation. Confinement of bedrock fractures from the atmosphere generally increases with depth and where the glacial till is thick. A deep well does not ensure a high degree of confinement. For example, wells Ro-1249 and Ro-1272 are 130 and 400 ft deep, respectively, but their water-level hydrographs are similar, which indicates that shallow fractures or deeper fractures with hydraulic connection with updip shallow fractures are the dominant water-bearing fractures in the deeper well. The deeper well also does not respond appreciably to changes in barometric pressure—this indicates only local confinement of the aquifer.

Barometric efficiency, the percentage of (atmospheric) barometric-pressure change observed in water levels at a well, is indicative of the degree of aquifer confinement from the atmosphere at the well. High barometric efficiencies correspond to a high degree of confinement. Barometric efficiencies of about less than 20 to 97 percent were calculated for Rockland County wells (table 3). High degrees of confinement are typically associated with sediments of low permeability overlying and, at least locally, isolating the aquifer from the atmosphere. High barometric efficiencies were noted at some bedrock wells with poorly permeable thick till, but other wells had high barometric efficiencies with thin, relatively permeable till and an interval of unsaturated bedrock within the wellbore. The bedrock strata above the principle water-bearing fractures serve as the confining layer in these wells. For example, the till at the Viola well field (UWNY 28 and UWNY 106) is thin and permeable, but barometric efficiencies at both wells are high (about 75 to 95 percent). Local confinement by overlying bedrock is indicated by natural (unstressed) artesian flow of about 80 gal/min when the original well (UWNY 28) was first drilled and the lack of major water-bearing zones in the upper 140 ft of the new well (UWNY 106). Another well (Ro-99) with high barometric efficiency (93 percent) is only about 168 ft deep. Confinement at this well is highlighted by water-level declines of tens of feet in response to groundwater withdrawals at a well field about 0.7 mi away, discussed in a following section entitled "Groundwater Levels Affected by Groundwater Withdrawals." Barometric efficiencies at 14 of the 25 wells were greater than or equal to 50 percent (table 3.). High barometric efficiencies are generally more common in aquifer zones B and C than in zones A and D. This finding may reflect more extensive permeable fractures at depth in the coarse-grained strata of aquifer zones B and C (fig. 14).

Continuous Monitoring at Selected Wells

Groundwater levels were monitored on an hourly basis at 18 wells for intervals of weeks to nearly 3 years. Water-level data were used to characterize natural and stressed groundwater conditions, including responses to precipitation, degree of aquifer confinement, hydraulic interconnection of wells, and local effects of groundwater withdrawals on the aquifer.

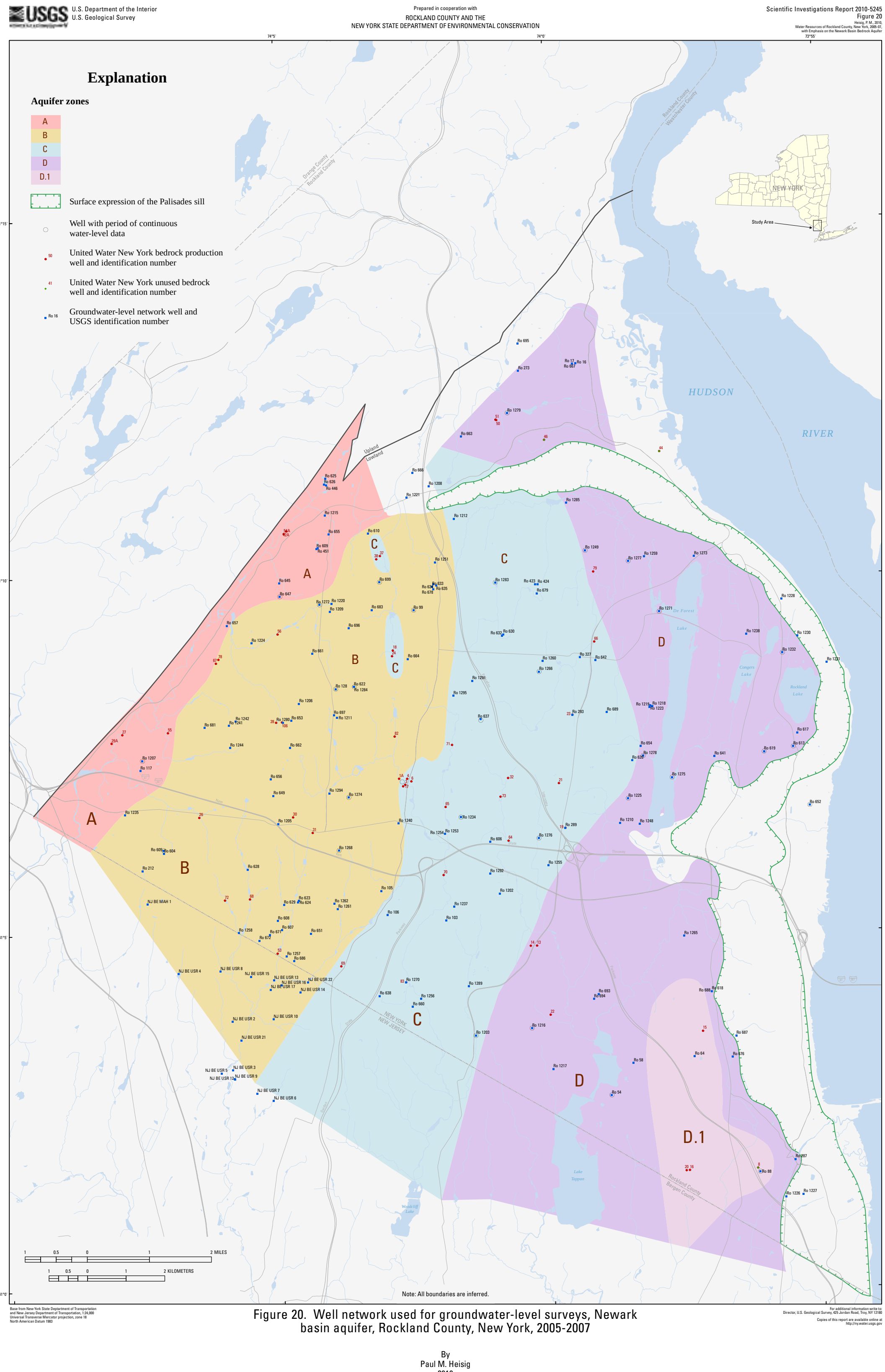


Figure 20. Well network used for groundwater-level surveys, Rockland County, New York, 2005–07. (Click to view full-size map at http://pubs.usgs.gov/sir/2010/5245/plates/Figure20.pdf)

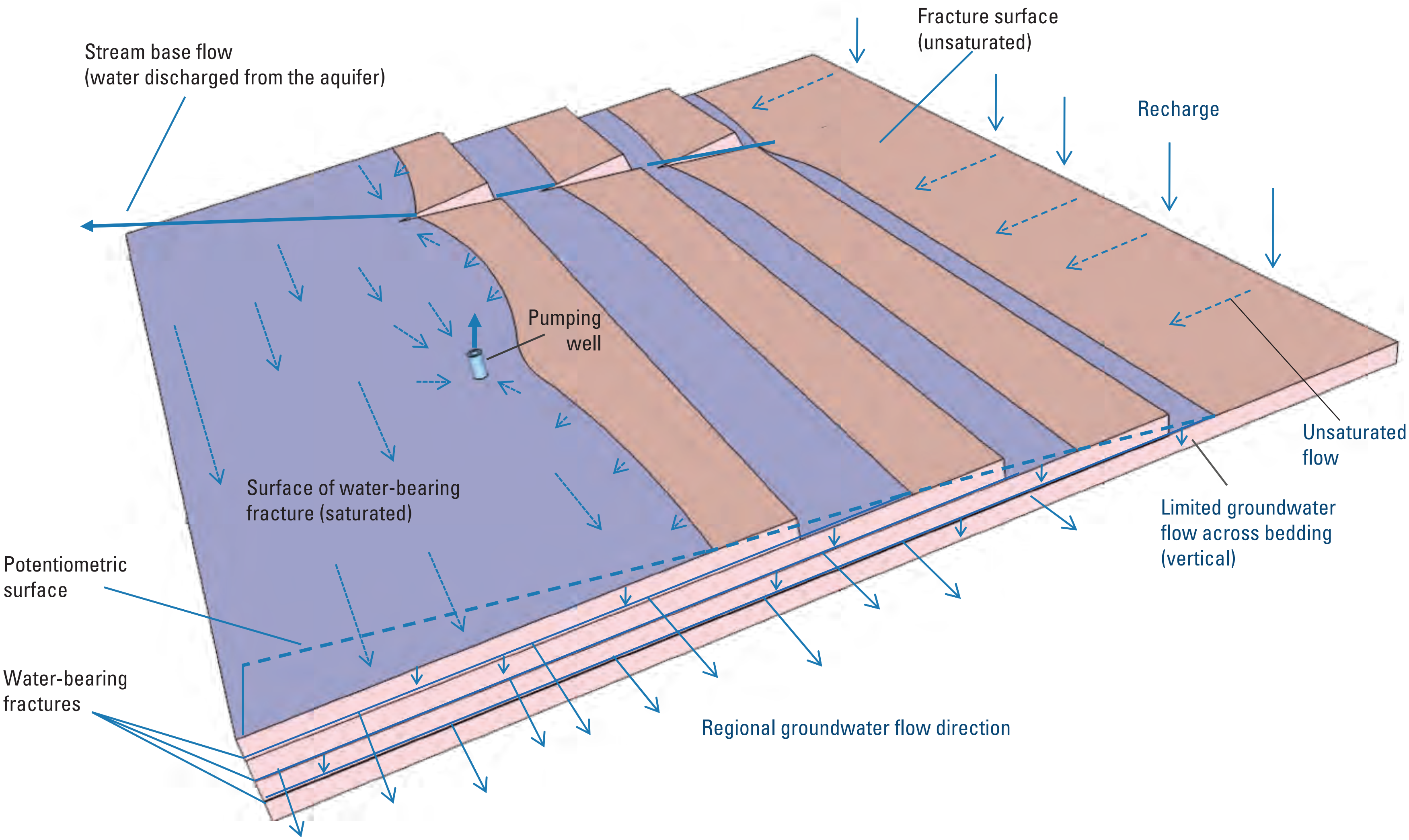


Figure 21. Schematic illustration of groundwater flow in dipping sedimentary beds.

Table 3. Barometric efficiencies calculated from groundwater levels in Rockland County, New York.

[ft, feet; ~, approximate; ND, not known; <, less than]

Well identification number	Barometric efficiency, (percent)	Well depth (ft)	Well casing length, in (ft)	Aquifer zone
Ro–54	< 20	402	91	D
Ro–76	60	300	47	C
Ro–99	93	168	32	B
Ro–103	~70	302	~60	C
Ro–128	86	150	50	B
Ro–327	50	186	74	C
Ro–605	35	51	~15	B
Ro–647	47	295	9	A
Ro–699	~< 20	185	30	B
Ro–1207	~33	113	ND	A
Ro–1232	28	156	21	D
Ro–1234	89	280	140	C
Ro–1249	31	109	31	D
Ro–1271	27	450	ND	D
Ro–1272	~< 20	407	18	B
Ro–1276	80	367	36	C
Ro–1277	18	402	49	D
Ro–1278	~50	400	55	D
UWNY 13	70	325	108	D
UWNY 19	62	477	50	C
UWNY 28	95	215	~20	B
UWNY 46	97	320	32	D
UWNY 66	~60	401	79	C
UWNY 70	< 20	450	37	B
UWNY 106	~75	440	50	B

Natural Groundwater-Level Fluctuations

Natural groundwater-level fluctuations in the Newark basin aquifer were measured at five wells in a variety of hydrogeologic settings (fig. 22). These hydrographs were minimally affected by pumping stresses. Well Ro-1277 appears to show the effects of groundwater withdrawals at nearby domestic wells. Glacial-deposit thickness and character at the wells varied from less than 10 ft of till to 80 ft of sand and fine-grained lacustrine deposits. Depths to water ranged from land surface to 30 ft below land surface (fig. 22). The largest responses to precipitation at the wells ranged from 13 ft to a fraction of a foot.

The shape and height of groundwater-hydrograph peaks in response to precipitation are indicative of the location of the well within the groundwater flow system (Risser and others, 2005) and the thickness and type of glacial deposit. Most areas apart from surface waters and wetlands can accept recharge to some degree. Sharp, relatively high hydrograph peaks (rapid rise and fall, well Ro-647) indicate an upland location with little (at least locally) upgradient area and thin or permeable till. Rapid water-level response but relatively low peaks with gradual declines represent downgradient locations in the flow system (near groundwater discharge areas) with thin glacial deposits and large upgradient groundwater flow-system areas (well Ro-1277). Water-level responses to precipitation become progressively more muted with decreases in till permeability or increases in till thickness (wells Ro-1249 and Ro-54).

Usually, groundwater-hydrograph peaks are highest in upgradient areas of the flow system because the water table is within bedrock that has a low specific yield (water-storage capacity) relative to the glacial deposits; therefore, responses to recharge inputs can be at least several times higher than in areas where the water table is within the glacial deposits. Peaks decline rapidly because there is little upgradient flow-system area that must drain past the well. In downgradient areas, low peaks with gradual declines are attributed to (1) the water table within glacial deposits, which have a higher specific yield than bedrock, (2) increases in groundwater velocity near discharge areas (Risser and others, 2005), and (3) a substantial upgradient flow-system area that contributes prolonged groundwater flow past the well towards discharge areas such as streams.

Well Ro-605 is about 30 ft below the top of a till-covered bedrock hill, with a till thickness of 10.5 ft at the well (fig. 22). This location appeared to be favorable for measurement of natural water-level fluctuations. However, water levels responded poorly to precipitation when they were below 10 ft but were responsive to large rainfall events when water levels were above 10 ft. Apparently, water levels fluctuate between till and bedrock, which seems to affect water-level responses to precipitation. The well log indicated a sandy till with some silt and coarser material, with gravel just above the bedrock. Bedrock consists of poorly cemented conglomerate and very coarse sandstone. The hydrogeology indicates that water levels in the till are responsive to precipitation because specific yield should be lower than in the gravel or poorly cemented conglomerate below. If water levels are low (below 10 ft), high specific yield and permeability at the top of bedrock and high hillside gradients at this location are likely to divert incoming recharge downdip and downslope, resulting in little water-level response in the hydrograph. Limited permeability and storage in bedrock were indicated when the well was pumped to obtain a water-quality sample; the water level did not fully recover until a major precipitation event occurred more than a week later.

The most subdued groundwater-level responses to precipitation occur in confined bedrock settings where direct recharge is delayed and attenuated or does not occur at all;

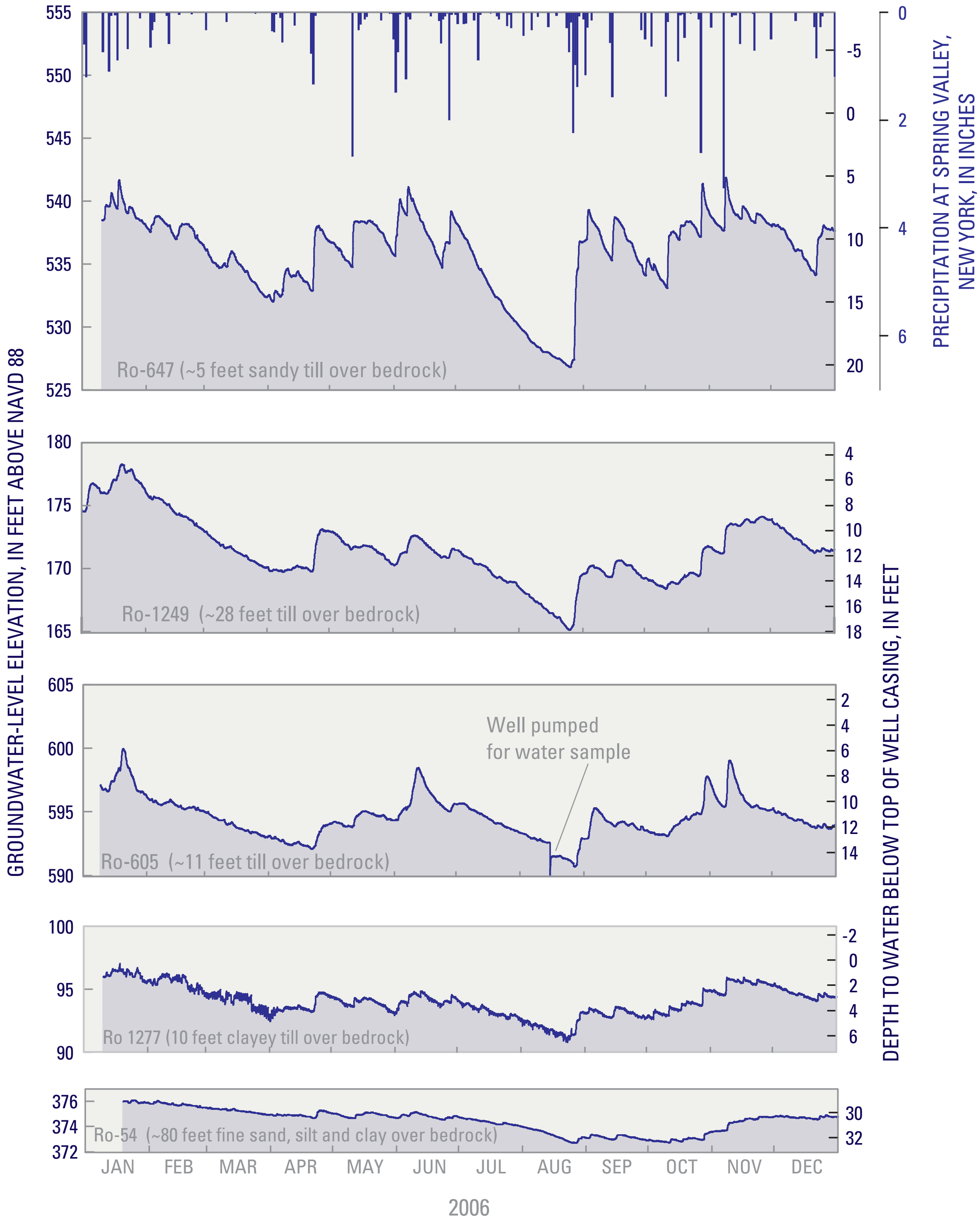


Figure 22. Natural groundwater-level hydrographs from Newark basin aquifer wells in areas with minimal pumpage, Rockland County, New York, 2006. Locations shown on figure 20.

water levels may increase either from translation of pressure from outlying recharge areas that are in hydraulic connection with the well or from increases in overlying pressure from the water table above. Well Ro-54 is in this type of setting—annual groundwater-level fluctuations were responsive in time but were small. The annual fluctuation was only about 3 ft in 2006 (fig. 22).

Groundwater Levels Affected by Groundwater Withdrawals

The majority of continuous groundwater-level records collected during the study showed the effects of groundwater withdrawals. Water-level fluctuations from nearby domestic-well withdrawals were common but were about 1 ft or less. Water-level fluctuations associated with withdrawals from production wells (water supply and irrigation) ranged from a fraction of a foot to 65 ft at distances as great as 1 mi (fig. 23A, B). Identification of the hydraulic interconnection of production wells with observation wells or other production wells provides local information on the structure of, and degree of confinement in, the bedrock aquifer. Areas affected by withdrawals from production wells are shown in figure 23B relative to interpreted bedrock structure and groundwater divides.

Well Ro-1234 is in an area of the aquifer confined by about 130 ft of till and, as a result, does not appear to receive any direct recharge (fig. 23A). The hydrograph shows no water-level changes in response to precipitation (compared with natural/unstressed groundwater fluctuations in figure 22). All water-level changes at this well appear as responses to changes in pumping at well UWNY 65, which is about 0.3 mi west and downdip along the bedding (fig. 23B). In fact, high rates of pumping at this production well in the summer of 2005 resulted in air-entrainment problems—pumping was greatly curtailed, and water levels at well Ro-1234 recovered 20 ft over the following 7 months until withdrawals increased again. The slow recovery of the water level is indicative of limited recharge because of the degree of confinement. Little borehole flow was measured at this well. Lack of flow in a well that is stressed by a nearby production well indicates that the head is similar throughout the wellbore and that most flow is horizontal because little water is available from the overlying till.

Well Ro-1276 is confined by thinner glacial deposits than well Ro-1234 but still shows little response to precipitation. Water-level fluctuations, up to about 10 ft, are largely in response to withdrawals from well UWNY 64 (fig. 23A, B).

The hydrographs from wells Ro-99 and Ro-128 are most strongly affected by production-well withdrawals, with maximum seasonal fluctuations of 50 to at least 65 ft, but are also the greatest distances (0.7 and 1.0 mi, respectively) from the production wells that are affecting them (fig. 23A, B). Water levels in well Ro-99 are affected by withdrawals at the New Hempstead well field (wells UWNY 18 and 24), and water levels in well Ro-128 are affected by the Viola well field (wells UWNY 28 and 106). These well fields are among the most productive in the aquifer, with normal production rates of 600 to 800 gal/min and peak summer rates of 800 to about 1,800 gal/min.

Both observation wells (Ro-99 and Ro-128) are locally in connection with shallow groundwater, as indicated by seasonal responses to precipitation and substantial borehole flow rates in response to pumping wells (fig. 19). Till thickness in both areas is generally thin. Confinement is therefore largely from the bedrock strata overlying water-bearing fractures. The dip and strike of the bedrock strata determine the shape of the areas affected by groundwater withdrawals (fig. 15, fig. 18, fig. 23B)—higher dips result in narrower (and potentially longer) areas, and lower dips result in wider areas. Bedding strike determines the orientation of the greatest distance affected (unless bedrock dip is low and updip areas are large because of higher topography). Dips at well Ro-99 (10 degrees) are higher than at well Ro-128 (8 degrees, with dips of 6 degrees nearby, to the south). The shape of the areas affected by well-field withdrawals helps constrain the bedrock structure. Seasonal declines were most extreme at well Ro-99; this well went completely dry at some point during two of three summer seasons.

The hydrograph of well Ro-1232, at Rockland Lake State Park, illustrates the seasonal effects of pumping for irrigation of a golf course. Nightly irrigation cycles draw water levels down by a fraction of a foot during the summer. Drawdowns are relatively small given the proximity (0.3 mi) of the withdrawals because this system draws water from two sources simultaneously—from the bedrock aquifer and from a pipe connection to an adjacent pond.

Water Levels at Production Wells

Concerns over the long-term viability of the Newark basin aquifer center on whether or not withdrawals at production wells have been, or are, sustainable at current withdrawal rates in both the long term (years) and the short term (seasonally). Water-level and pumping-rate data from production wells were obtained from UWNY to provide a current “snapshot” of aquifer conditions and to identify potential resource limitations during future drought conditions.

Long-Term Water-Level Fluctuations

Downward water-level trends or downward pumping-rate trends with stable water levels of 1.5 to 6 years duration were identified at six bedrock wells and all four sand and gravel wells that tap the Mahwah River alluvial aquifer during 1989–2002 (table 4). Data from production wells were not

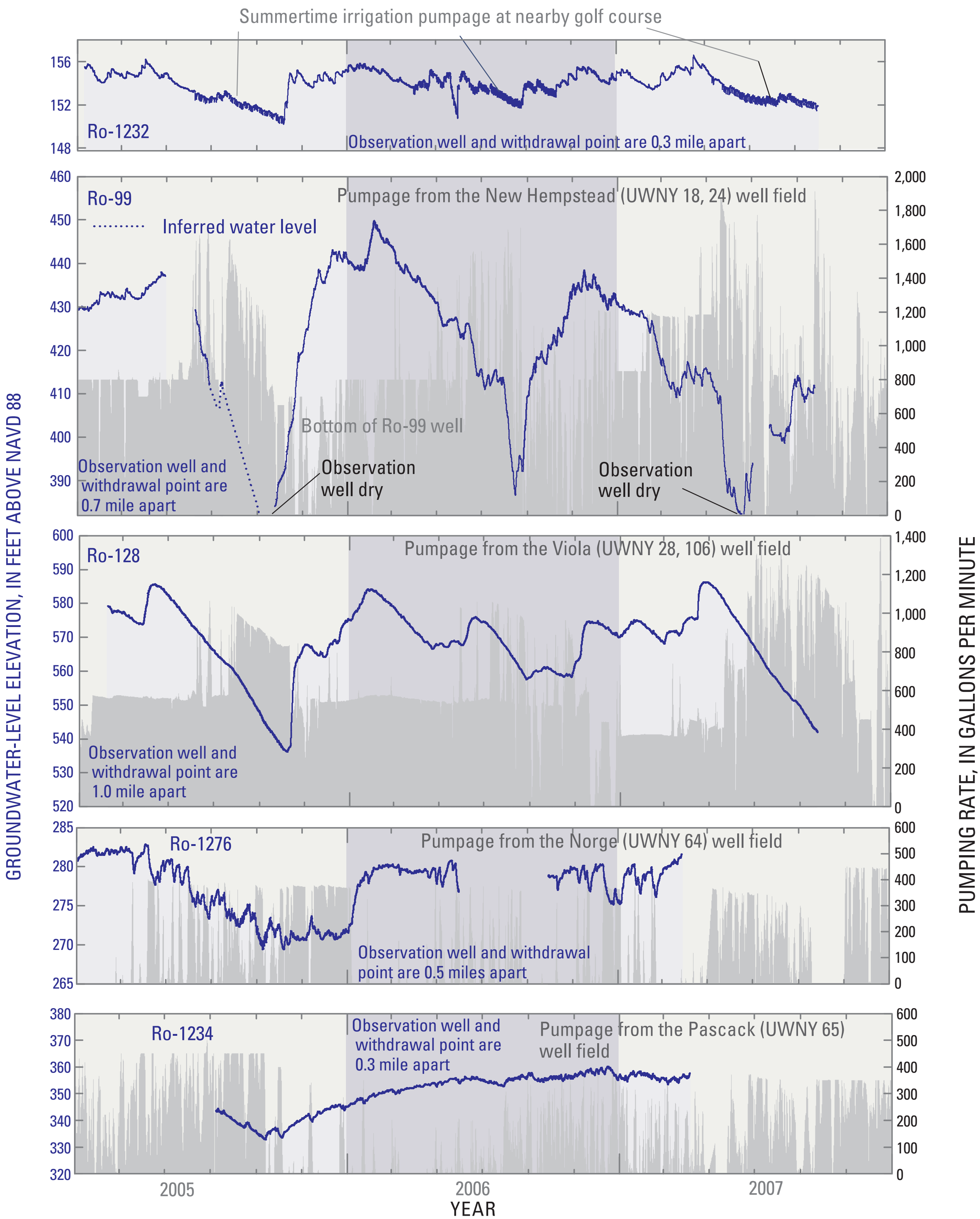
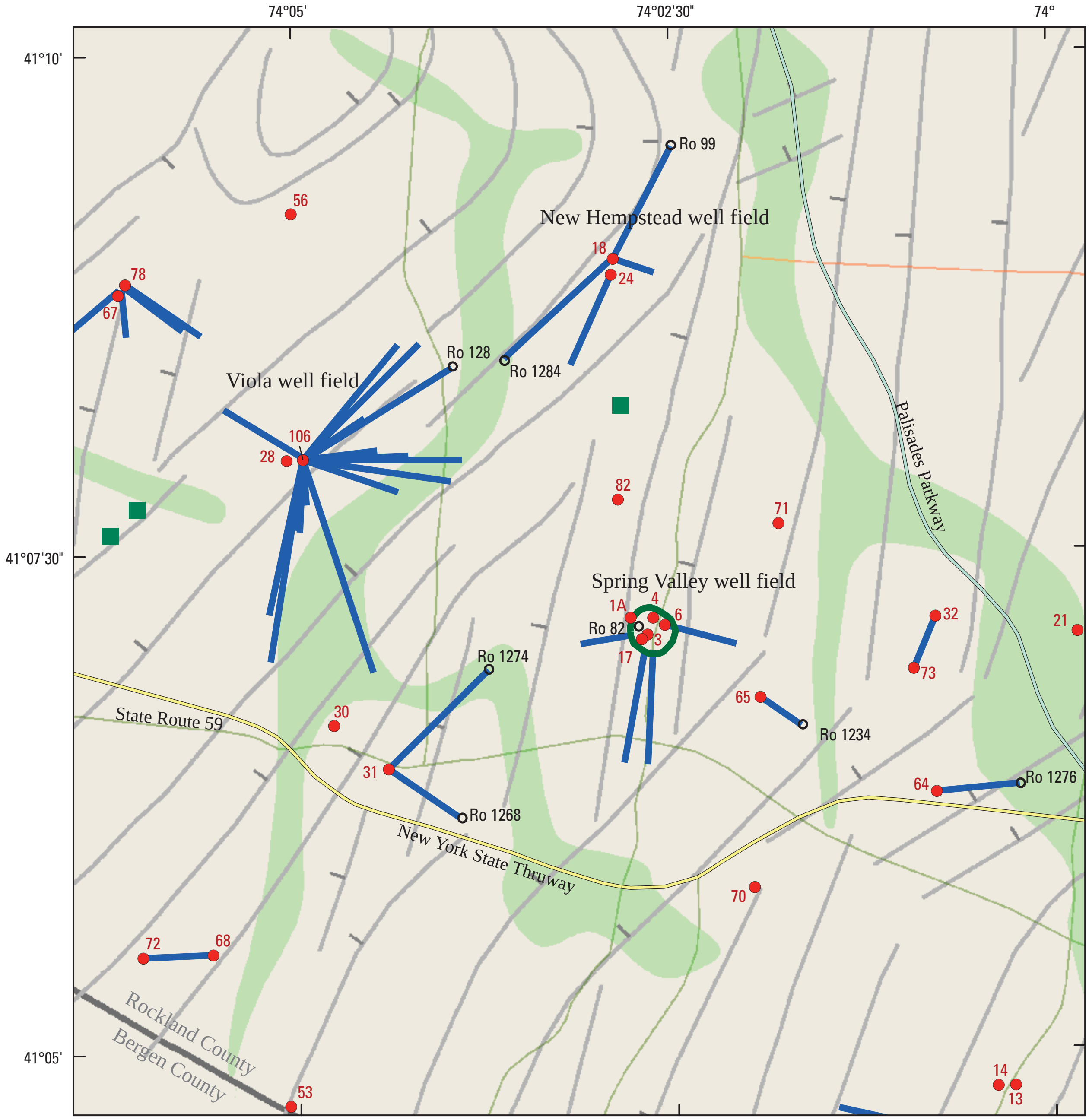


Figure 23A. Groundwater-levels in areas affected by pumping wells, Rockland County, New York, 2006: *A,* hydrographs from selected Newark basin aquifer wells, *B,* map view of hydraulic connections between pumping wells and measured wells over the conceptual model of bedrock strike and dip and groundwater divides. Data are from this study and from aquifer testing by Leggette, Brashears & Graham (W. Prehoda, Leggette, Brashears, & Graham, Inc., written commun., 2005.)



Base from New York State Department of Transportation, 1:24,000,
Universal Transverse Mercator projection, Zone 18
North American Datum 1983

EXPLANATION

Groundwater divide area—groundwater flows away from divide areas, generally parallel to bedding strike

Bedrock bedding strike lines—ticks denote dip direction

Well field area

Hydraulic connection between pumping well and other wells—measured change in groundwater level in response to pumping at production well

New York State Thruway

Palisades Parkway

State roads

County roads

United Water New York bedrock production well—with local identifier

Irrigation well

Observation well—with U.S. Geological Survey identifier

Figure 23B. Groundwater-levels in areas affected by pumping wells, Rockland County, New York, 2006: *A,* hydrographs from selected Newark basin aquifer wells, *B,* map view of hydraulic connections between pumping wells and measured wells over the conceptual model of bedrock strike and dip and groundwater divides. Data are from this study and from aquifer testing by Leggette, Brashears & Graham (W. Prehoda, Leggette, Brashears, & Graham, Inc., written commun., 2005.)—Continued

Table 4. Long-term (year-to-year) declines in production well water-levels and (or) pumping rates at United Water New York wells, 1989–2002.

[ft, feet; gal/min, gallons per minute]

Well identification number	Aquifer	Time interval	Initial submergence (water level, in ft above bottom of airline)	Final submergence (water level, in ft above bottom of airline)	Initial pumping rate (gal/min)	Final pumping rate (gal/min)	Submergence change (water-level change, in ft above bottom of airline)	Pumping rate change (gal/min)	Follow-up conditions in 2006, unless noted otherwise
				Newark Basin Aquifer					
UWNY 79	Bedrock	12/1/97–12/1/01	51.8	12.0	152	109	39.8	43	Pumping rate about 110 gal/min; submergence during pumping was between 50 and 10 ft
UWNY 711	Bedrock	7/1/99–1/1/02	54.4	35.8	176	161	18.6	15	As 2005 summer pumping rate decreased from 275 to 210 gal/min, submergence decreased from 60 to 11 ft
UWNY 821	Bedrock	7/1/89–10/1/93	106.9	89.0	285	249	17.9	36	As 2005 summer pumping rate became more continuous at 245 gal/min, submergence decreased from 155 to 114 ft
UWNY 16	Bedrock	4/1/96–1/1/02	117.9	49.9	196	194	68.0	2	Pumping rate between 210 and 258 gal/min; submergence during pumping was between 84 and 37 ft
UWNY 22	Bedrock	1/1/00–1/1/02	94.1	84.9	151	122	9.2	29	Pumping rate at 75 gal/min; submergence was stable at about 138 ft
UWNY 30	Bedrock	6/1/00–10/1/02	65.0	34.7	235	221	30.3	14	Pumping rate about 240 gal/min; submergence during pumping was between 77 and 67 ft
UWNY 51	Bedrock	12/1/98–12/1/02	2.7	0.2	245	218	2.5	27	Pumping rate about 190 gal/min; submergence during pumping was between 32 and 3 ft
				Alluvial Aquifers					
UWNY 29A	Sand and gravel	6/1/96–1/1/02	14.8	5.3	1,150	676	9.5	474	Pumping rate about 900 gal/min; submergence during pumping was between 19 and 3 ft
UWNY 27	Sand and gravel	1/1/96–10/1/02	21.8	2.1	1,163	743	19.7	420	Pumping rate about 900 gal/min; submergence during pumping was between 30 and 9 ft
UWNY 42A	Sand and gravel	1/1/97–1/1/02	6.3	2.5	302	173	3.8	129	Total well-field pumping rate in summer about 280 gal/min; submergence during pumping was between 16 and 2 ft
UWNY 54A	Sand and gravel	4/1/96–1/1/02	31.6	10.4	324	201	21.2	123	Total well-field pumping rate in summer about 280 gal/min; submergence during pumping was between 15 and 0 ft

[1]Questionable airline function.

available prior to 1989. Monthly average submergence[2] and pumping-rate data were reviewed; spurious submergence data precluded evaluation of certain time intervals. The trends listed in table 4 are likely related to periods of non-sustainable pumping rates or deterioration of well performance. Well performance includes pump wear and function, clogging of well screens with encrustation or fine sediment, and clogging of fracture openings or the bottom of the well with eroded sediment. Perlmutter (1959) included Spring Valley Water Company data from the UWNY 15 well (identified as Ro-92 in that report) that indicated substantial improvement of well performance following well redevelopment, which can include surging, pumping, and chemical treatment. A follow-up on pumping rates and water levels in 2006 indicates that pumping rates have been reduced at four out of seven bedrock wells, which suggests earlier rates were not sustainable. The remaining bedrock wells were pumped at the same rate as earlier or at rates 20 to 60 gal/min higher, which suggests either well and (or) pump constraints or differences in aquifer storage. For example, 2001 was a dry year relative to 2006, so more aquifer storage in 2006 may have allowed for somewhat higher pumping rates.

All four sand and gravel wells that tap the Mahwah River alluvial aquifer (UWNY 27, 29A, 42A and 54A) showed water-level declines during 1997–2002. These wells ultimately induce water from the Mahwah River into the aquifer—their yields are likely lower during low-flow periods in the Mahwah River and higher during high-flow periods. As mentioned above, 2001 was a relatively dry year, whereas 2006 was a relatively wet year. Thus, flow in the Mahwah River is a factor that affects well yields, as is clogging or encrustation of the well screen.

Seasonal Water-Level Fluctuations

Seasonal declines in the groundwater levels at production wells are the greatest limitation of water resources from the Newark basin aquifer and the Mahwah River alluvial aquifer in Rockland County. Groundwater levels and the productivity of both aquifers decline during the growing season and especially during dry, hot summer periods as water demands increase and aquifer recharge and storage decrease. Low groundwater levels at the end of the summer (or at times during the summer) have historically recovered as demand decreases and recharge increases during fall, winter, and spring to maintain year-to-year groundwater-level stability during the 1989–2005 period. Climatic conditions during this period, however, were about average. There have been dry summer periods during this time, but no periods that approach the duration of the mid-1960s drought (Lyon and others, 2005).

The following sections describe (a) 2005 water levels and pumping rates at UWNY production wells; (b)annual pupmpage rate and water-level scenarios at UWNY production wells; (c) groundwater-level decline rates at selected production wells during the growing season, and; (d) extrapolation of growing-season rates of water-level decline .

A. 2005 Water Levels and Pumping Rates at UWNY Production Wells

An overview of daily UWNY production-well pumping rates and water levels in 2005 is depicted in figure 24. The figure shows the degree to which wells are used (some are pumped only seasonally) and how much the wells locally stress the aquifer and for what duration. Pumping rates are reported in gallons per minute, and pumping rates from well fields with more than one well are presented as total well-field pumping rate. All pumping rate graphs use the same scale so that withdrawal rates can be easily compared among the well fields. Water levels are reported as submergence, in feet above the airline. Low submergence values are of concern in all production wells but are of greater concern in bedrock wells than in sand and gravel wells because there is less storage of water in bedrock than in sand and gravel. Water levels close to the bottom of the airline in wells merit regular monitoring.

The submergence water level is measured relative to the level of the pump in a production well. If the pump is not near the bottom of the well, the question arises: Can the pump (and airline) be lowered and thus prolong the time before water levels approach the pump and become a concern? This may be a reasonable approach at some wells but not at others. The concern is that the most productive water-bearing fractures are within the upper 250 to 300 ft of bedrock (fig. 14) and drawdown approaching or exceeding that depth range may cause loss of well yield as the water level in the well decreases below important water-bearing fractures. Water from those fractures starts to cascade to the low water level and provides less water to the well than from fractures that are below the water level. Lower overall well yield will result, and the drawdown rate may increase unless the pumping rate is decreased. Lowering pump levels in aquifer zones B and C might meet with greater success than in aquifer zones A and D because wells in aquifer zones B and C tend to derive a larger percentage of their yield from deeper fractures (fig. 14).

Another consideration that can limit high withdrawal rates is air entrainment that can occur when water levels in production wells are not near the bottom of the airline (noted in fig. 24). Withdrawals from production wells lower the water levels at other wells within their drawdown area; if the

[2] Submergence is a measure of the amount of water, in feet, above the bottom of an airline (a local datum) in a production well. The airline is a plastic tube that is suspended down the well, typically 0 to 10 ft above the pump. Air is bubbled out the bottom of the airline to determine water pressure at that point, which is converted to feet of water above the bottom of the airline. A low submergence value warns the operator that water levels are approaching the pump, and a high submergence value indicates that water levels are sufficiently high above the pump. Low submergence in some wells may result in entrained air entering the water-distribution system and damaging the pump. Reliability of airline measurements is a concern at a number of wells; pinhole leaks in an airline can give false readings of water pressure.

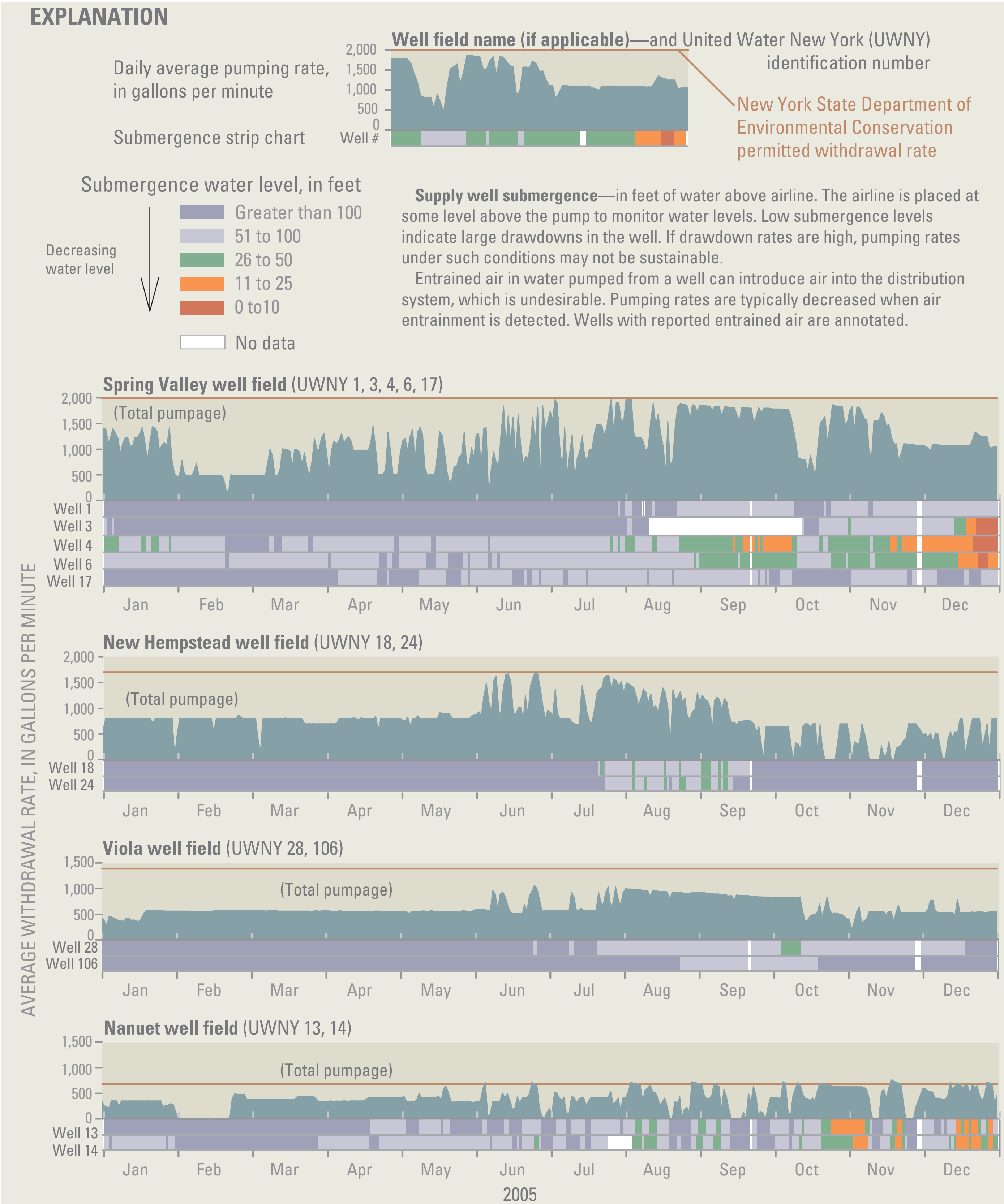


Figure 24. 2005 pumping rates and water levels above airlines at all United Water New York production wells, from daily averages, Rockland County, New York.

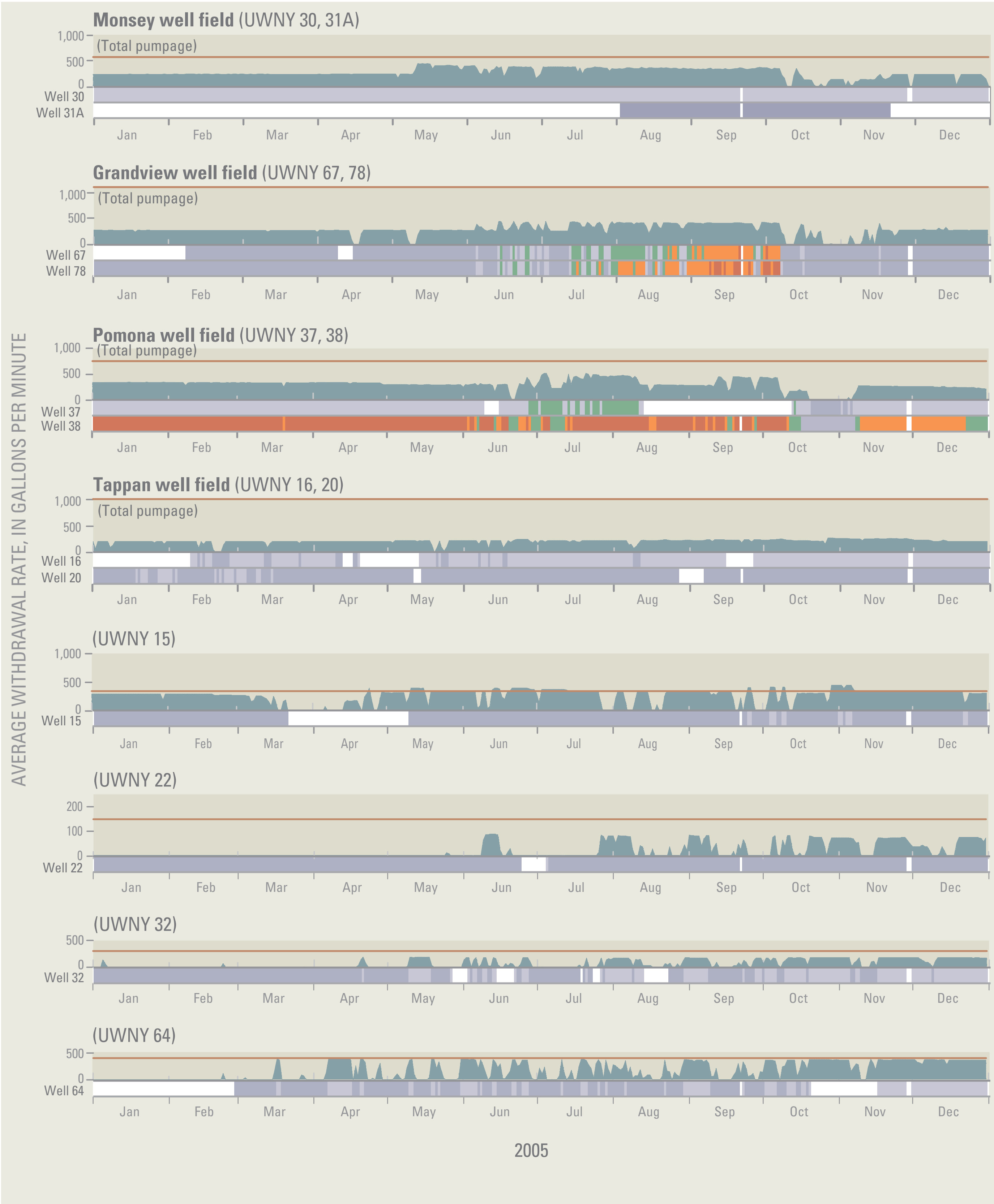


Figure 24. 2005 pumping rates and water levels above airlines at all United Water New York production wells, from daily averages, Rockland County, New York.—Continued

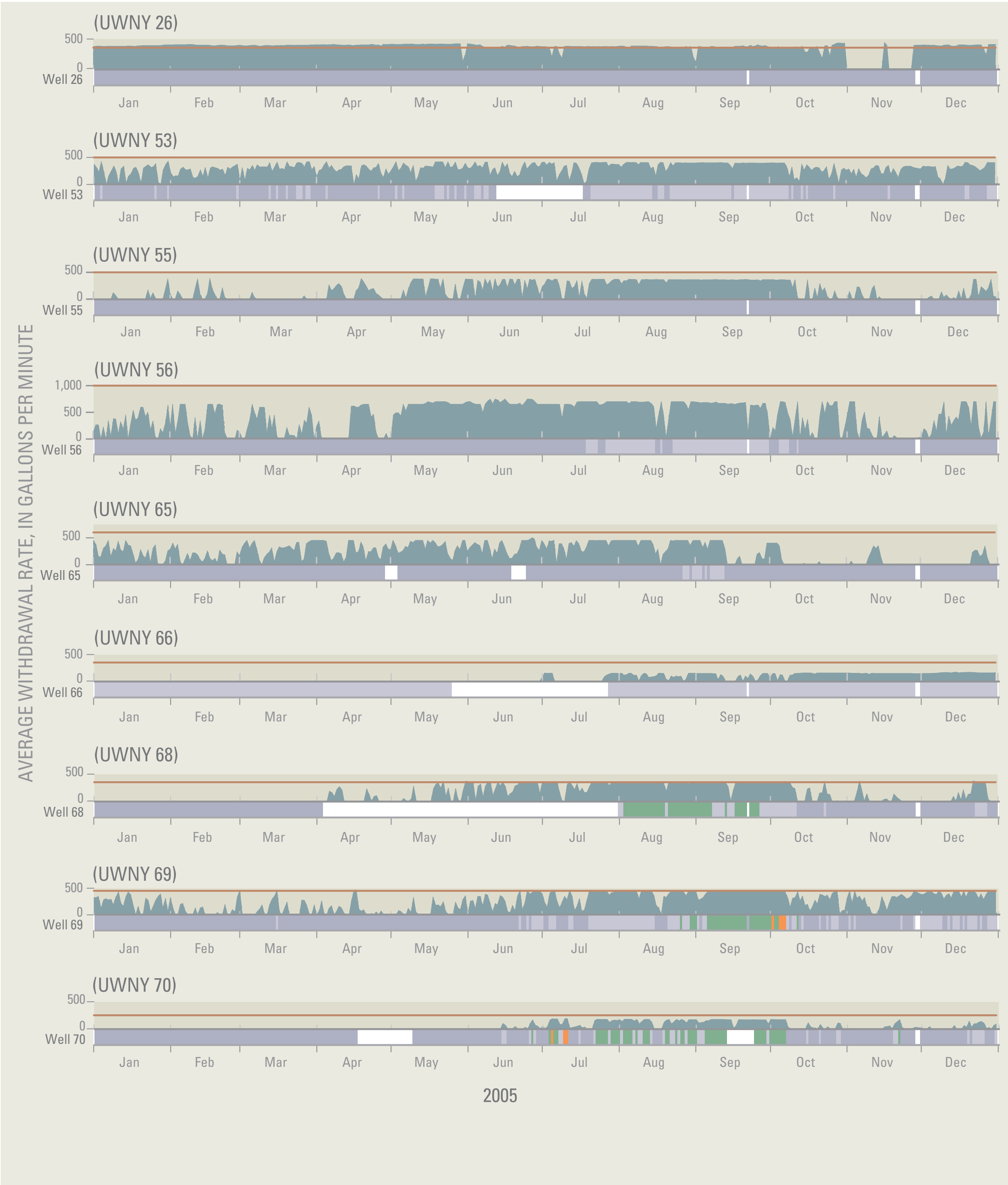


Figure 24. 2005 pumping rates and water levels above airlines at all United Water New York production wells, from daily averages, Rockland County, New York.—Continued

Figure 24. 2005 pumping rates and water levels above airlines at all United Water New York production wells, from daily averages, Rockland County, New York.—Continued

stress is large enough, water levels in outlying wells (or the production well) can be drawn down below shallow water-bearing fractures, causing water to cascade downward from shallow fractures to the water surface. This aerated water is then drawn toward the production well and can cause air problems in the distribution system. A clear well was installed at the Viola well field to allow entrained air to escape prior to entering the distribution system (W. Prehoda, Leggette, Brashears & Graham, Inc., oral commun., 2006).

The high water demand from supply wells in Rockland County during the summer months is illustrated in figure 24. Outdoor use, such as irrigation of lawns, drives the increase in demand. Most of the major well fields (Spring Valley, Viola, and New Hempstead) show increased withdrawals during this period. Many other well fields are primarily used during the summer months and only sporadically used at other times of year. Another subset of wells is pumped nearly continuously throughout the year, with no increase during the summer months.

Declines in submergence generally are greatest in summer as pumping increases and recharge to the aquifer decreases. Submergence values during the non-growing season indicate low rates of decline or stable water levels. Increased recharge during this period results in more aquifer storage (greater saturated aquifer thickness), which translates to less stress on the aquifer by the same pumping rates that cause declines in summer. Some supply wells that are pumped sporadically during the year show summertime declines that are within 25 ft of the bottom of the airline when pumped continuously (UWNY 13, 14, 67, 78, 79, 69, 68, among others) (fig. 24)—this indicates the pumping rates are not sustainable on a continuous basis.

Withdrawal rates at all UWNY production wells are permitted by the NYSDEC on the basis of aquifer testing at each well. Permitted rates are included for reference purposes in figure 24.

B. Annual Pumping-Rate and Water-Level Scenarios at UWNY Production Wells

Annual water-level trends at UWNY production wells can be reduced to one of four generalized scenarios during the growing season (fig. 25). First, an aspect common to all scenarios is that pumping rates that cause water-level declines during the growing season result in less decline or even stable water levels in the non-growing season. Water levels are more stable during the non-growing season because the aquifer receives regular recharge, as evidenced by maintenance of high groundwater levels (fig. 22). This observation is important from the standpoint of well-yield testing—tests run during the non-growing season provide a “best case” of aquifer yield that does not necessarily reflect the potential decreases in yield as aquifer storage decreases during the growing season.

The first, and most common, growing-season scenario consists of increased summertime pumping, with subsequent water-level declines that do not approach the bottom of the airline by the end of the summer (fig. 25A); pumping rates can be maintained throughout the high-demand period. However, if dry conditions persist into the fall, curtailed withdrawals may be necessary at a subset of these wells because of low water levels. Examples include UWNY 55, 68, and 65.

The second scenario (fig. 25B) includes wells pumped nearly continuously throughout the year at single sustainable rates. These wells show only minor declines in water level, although the water levels may be near the bottom of the airline. Examples include UWNY 26, 37, 38 (at 300 gal/min), 42A, and 54A (sand and gravel wells).

The third scenario (fig. 25C) includes well fields with two or more wells in which one well runs nearly continuously throughout the year and the second well is used during peak demand periods in the summer. At the beginning of the growing season, the first well experiences drawdowns similar to those in the first scenario, with a rate of decline that would not be of concern by the end of the summer. Initiation of withdrawals at the second well causes a rapid drop in water levels that slows after a few days to a new rate of decline that is faster than the one-well decline rate and clearly not sustainable for the remainder of the summer. In most instances, well yields are reduced steadily during this period to reduce the rate of decline. The aquifer is locally stressed, and local wells may experience water-level declines of 50–60 ft. Examples of this scenario include the following well fields: New Hempstead (UWNY 18, 24), Viola (UWNY 28, 106), and Spring Valley (UWNY 1A, 3, 4, 6, 17).

The fourth scenario (fig. 25D) includes wells that are pumped continuously but experience steady declines during the high-demand season that bring water levels to the bottom of the airline before the end of the season. The pumping rate is progressively decreased for the remainder of the season to maintain water levels above the bottom of the airline. Declines during the high-demand season are caused by decreases in aquifer storage and decreases in streamflow in alluvial aquifers. Examples, respectively, include UWNY 79 and both UWNY 27 and 29A.

C. Rates of Water-Level Decline at Production Wells

Hydrographs of submergence water levels from individual supply wells provide a quantitative picture of local aquifer responses to growing-season withdrawals. As pumping is initiated at a production well, water levels drop quickly, but after several days, water-level declines either stabilize or slow to a relatively constant (linear) rate (fig. 26). If water levels stabilize or decline at low rates comparable to natural declines during the growing season (about 5 ft/mo in bedrock at well Ro-647, see fig. 22), the pumping rate is considered sustainable. If water levels decline at higher than natural rates during the growing season, the pumping at that rate steadily decreases aquifer storage and is not ultimately sustainable, although it is often reasonable for the duration of the growing season. Water levels in most supply wells decline

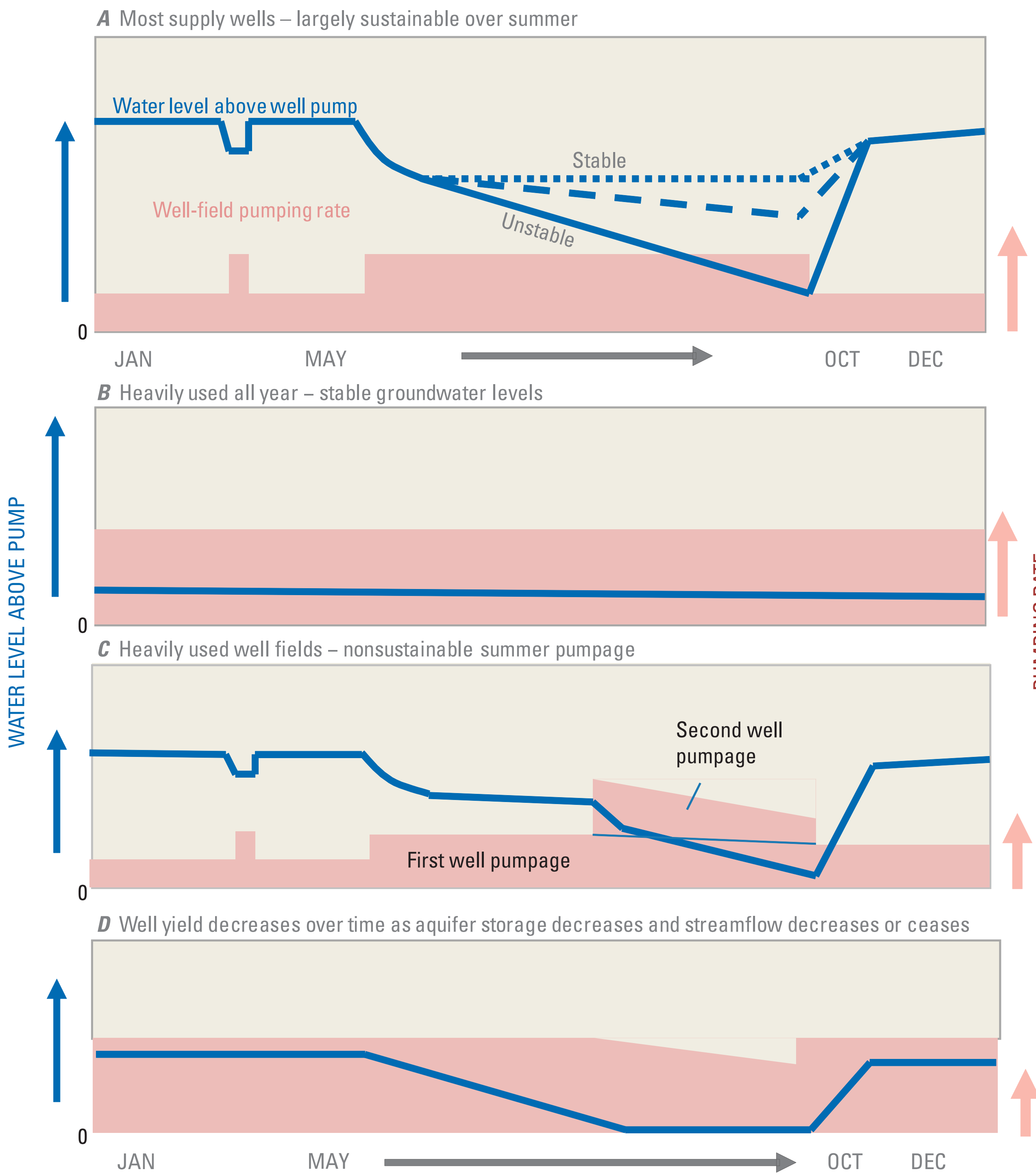


Figure 25. Generalized annual trends of withdrawals and water-level responses observed at United Water New York production wells, 2005, Rockland County, New York.

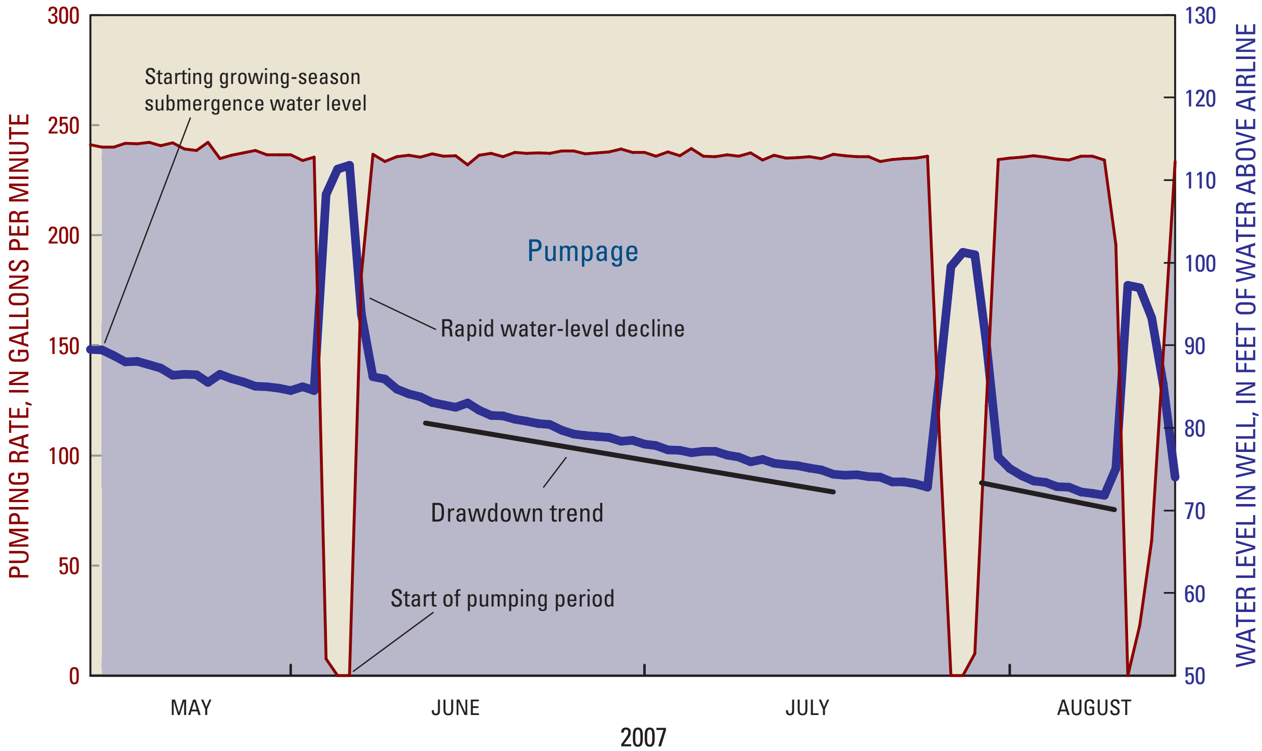


Figure 26. Example hydrograph from a production well that illustrates selection of a seasonal drawdown rate.

at rates greater than natural during the growing season. Rates of water-level decline at production wells were determined during 2005–07 from submergence water-level data and plotted on figure 27 along with associated pumping rates. A rate of water-level decline of about 5 ft/mo (shaded area) was also included to indicate an approximate maximum natural decline rate for the growing season. Rates of water-level decline ranged from 0 to 69 ft/mo. Most supply wells exceed the natural rate, and certainly, the higher rates (greater than 20 ft/mo) highlight wells of concern. The sustainability issue is: Can supply wells accommodate their drawdown rates for the duration of the growing season, assuming that recharge during the non-growing season will replenish aquifer storage? The answer to this question at each well depends on the rate of water-level decline, the starting water level at the beginning of the growing season, how much is pumped during the growing season, and the depth of the pump in each well.

D. Extrapolation of Growing-Season Rates of Water-Level Decline

Water-level declines in production wells over the course of the growing season (high water-use period—May 15 to October 15) were estimated from the decline rates in figure 27. Rates of water-level decline were projected to estimate the overall declines that might be expected over the 153-day period defined above. Available rates of water-level decline for different pumping rates at wells/well fields were included. Decline rates at individual wells in well fields with more than one well were referenced to the total pumping rate at the well field. Starting water levels (submergences) at each well were determined from representative low water levels after several days of pumping (fig. 26) during May (data from 2005 to 2007).

Water levels are reported as feet of water above the airline (submergence) in the supply wells. When water levels approach the bottom of the airline (zero water level), pumping rates typically need to be progressively reduced in order to maintain a stable groundwater level.

Daily drawdown rates at each well were applied to the 153-d period to determine the decline for continuous pumping conditions. These estimates are not conservative in that they assume continuous pumping but are conservative in that they assume no increase in drawdown rate as water levels decline. Dewatering of shallow water-bearing fractures and entrained air may reduce the amount of water available to production wells and increase decline rates. Increasing decline rates are indicated at some supply wells by decreases in pumping rates to maintain stable decline rates or stable water levels (fig. 24; UWNY 79, Spring Valley well field). Increasing decline rates and decreasing shallow groundwater availability at observation wells were indicated by reduced downward flow in wellbores (fig. 19), the onset of cascading water from shallow fractures (wells Ro-128 and Ro-1284), and total loss of water at one well (Ro-99, fig. 23).

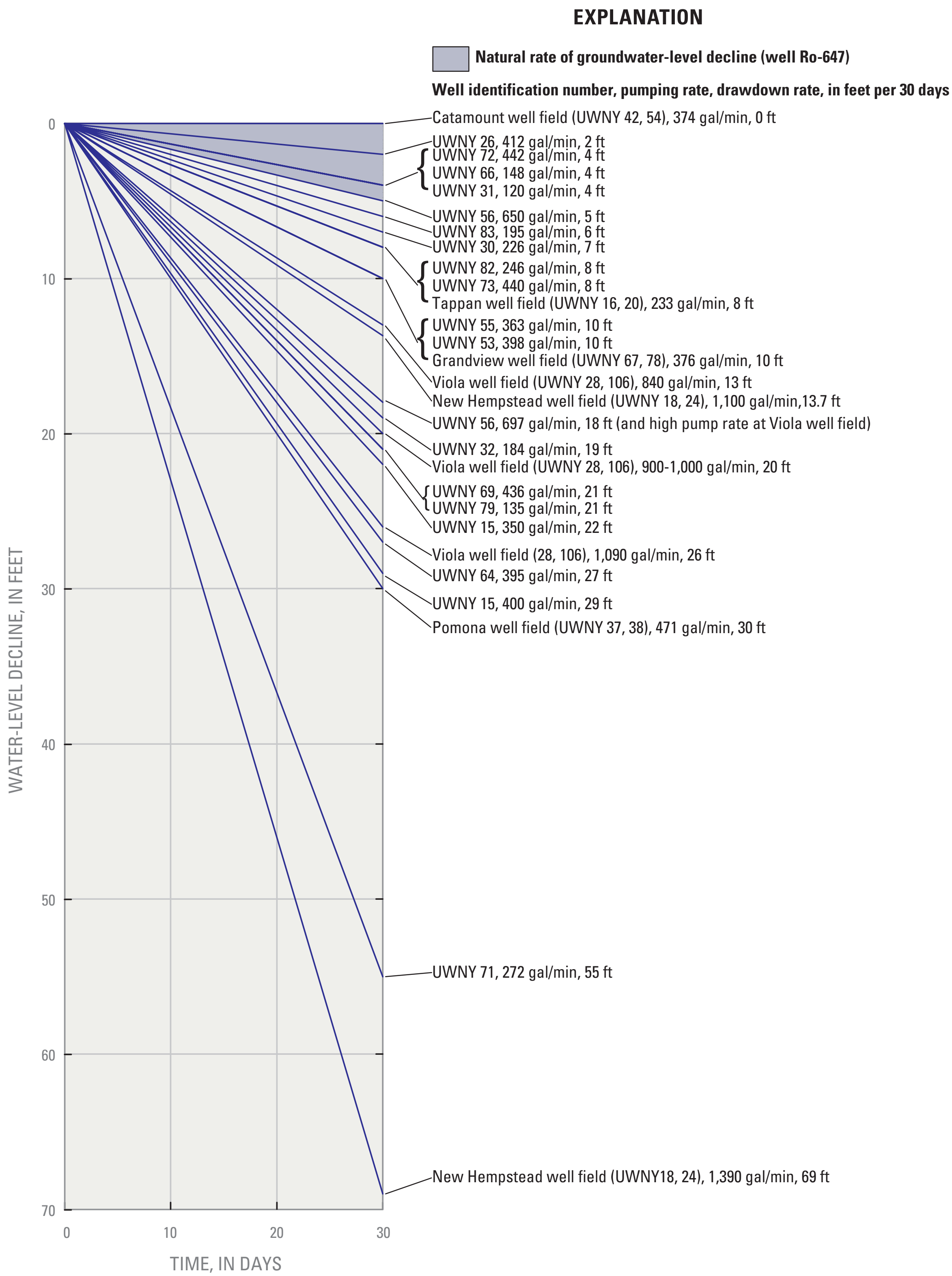


Figure 27. Growing-season drawdown rates at selected United Water New York production wells.

The accompanying graphs of groundwater-level declines (fig. 28) reflect constant drawdown rates at all bedrock wells, which provide a basis for comparing and identifying wells that might be of concern over a prolonged dry period, with the realization that conditions could be either better with less than continuous pumping or worse with dewatering of shallow water-bearing fractures or the entrainment of air. The pumping rate at sand and gravel well Ramapo 27 was altered during the 153-day period to parallel observed pumping-rate changes.

The plots in figure 28 show a range of projected water-level responses, but the majority of wells maintain water levels above their respective airlines through the 153-day period of interest. Twelve well fields ended the period with water levels between 0 and 50 ft above the bottom of the airlines. Another eight well fields ended the period with water levels greater than 50 ft above the bottom of the airlines. However, the high-demand pumping rates at nine well fields with more than one summertime rate were largely not sustainable over the 153-day period; only one well field (Spring Valley) reached the end of the period. Lower pumping rates at these same well fields were sustainable, except at the two sand and gravel well fields (UWNY 27, 29A). These two well fields tap the Mahwah River alluvial aquifer, and as river flow decreases, less water is available to the wells. Four well fields with single pumping rates reached the bottom of their airlines prior to (UWNY 79, 21) and at the end of the season (UWNY 69, 13, and 14). All these well fields except UWNY 69 are in, or adjacent to, aquifer zone D, which has the lowest T and the thinnest, shallowest interval of productive fractures of all the aquifer zones.

Aquifer-Wide Water Levels

Water-level data across the Newark basin aquifer are critical to understanding groundwater occurrence and circulation within the hydrogeologic framework. Historic water-level data that span decades are presented as a composite map. Recent (2005–07) water-level data from four synoptic surveys are also compiled in table form and maps (two surveys). Comparison between historic and recent water-level data indicates general declines in the higher-altitude areas of the aquifer.

For consistency, the water-level maps herein are called “potentiometric-surface” maps, which describe water levels in confined aquifers. The degree of confinement in the Newark basin aquifer is highly variable, depending on glacial-deposit thickness and depth and connectivity of fractures. Below about 100 to 150 ft, groundwater in bedrock fractures is locally confined and withdrawals can result in transmission of pressure changes over large distances. If a fracture is permeable in the updip direction and glacial deposits are thin, water level in the fracture can respond to precipitation as if it was an unconfined aquifer. In general, shallow groundwater in bedrock fractures is considered unconfined (under water-table conditions), unless the glacial deposits act as a confining unit.

The potentiometric-surface maps provide a general indication of water levels in the bedrock aquifer. Water levels depicted represent composite groundwater levels from wells completed within 150 to 250 ft of land surface. Because much of the aquifer can accept recharge, which imparts higher heads in the glacial deposits and shallow bedrock, shallow monitoring wells drilled at the same sites as the network wells would likely have consistently higher water levels. The interconnection of deep fractures of lower head with shallow fractures of higher head in network bedrock wells imparts a downward flow in the wellbore (in recharge areas) that results in a composite head that may be much lower than that in the shallow fractures. Decreased head in deep fractures may be further decreased by groundwater withdrawals from production wells.

Historic Composite Potentiometric Surface

Historic groundwater-level data from a single time period were not available, so data were compiled from the 1920s to late 1950s from Perlmutter (1959). Most bedrock wells from that time were shallower than 150 to 200 ft, unless they were supply or commercial/ industrial wells. Additional water-level data were obtained from well-completion reports of water-company test and supply wells drilled in the 1960–70s. The water levels were considered usable if they were from unstressed areas of the aquifer. The shape of the potentiometric surface (fig. 29) generally paralleled the topography. High water levels exceeded altitudes of 600 ft in the highest western aquifer zone B, and low water levels were below altitudes of 50 ft in the southeast at the Hackensack River valley near the New Jersey border.

Springs are related to groundwater levels in the aquifer because they represent points of groundwater discharge that contribute to stream base flow. Springs were a common feature prior to development in Rockland County and were a common water source for domestic use until the early 1900s (Perlmutter, 1959). Spring Valley was named for a “large spring in the Valley Pond” (Penfold, 1944, p. 5). Changes brought about by development (at a minimum) have reduced the number of springs in Spring Valley and dried up a long-standing spring on the border of Wesley Hills and Montebello (T. France, county resident, oral commun., 2006). Dry weather loss of streamflow is documented in the report section entitled “Stream Survey, September–October 2005.”

Recent (2005–07) Seasonal Potentiometric Surfaces

Four groundwater-level surveys of wells in the Newark basin aquifer were undertaken during late summer (late August and September) 2005 and 2006 and early spring (late March and April) 2006 and 2007. Data from the late summer 2005 and early spring 2007 surveys were used to document the potentiometric surface and seasonal water-level changes. Late summer 2005 was the driest period during the study. The early spring 2007 survey provided the most detailed depiction because it was the final iteration of the network and because

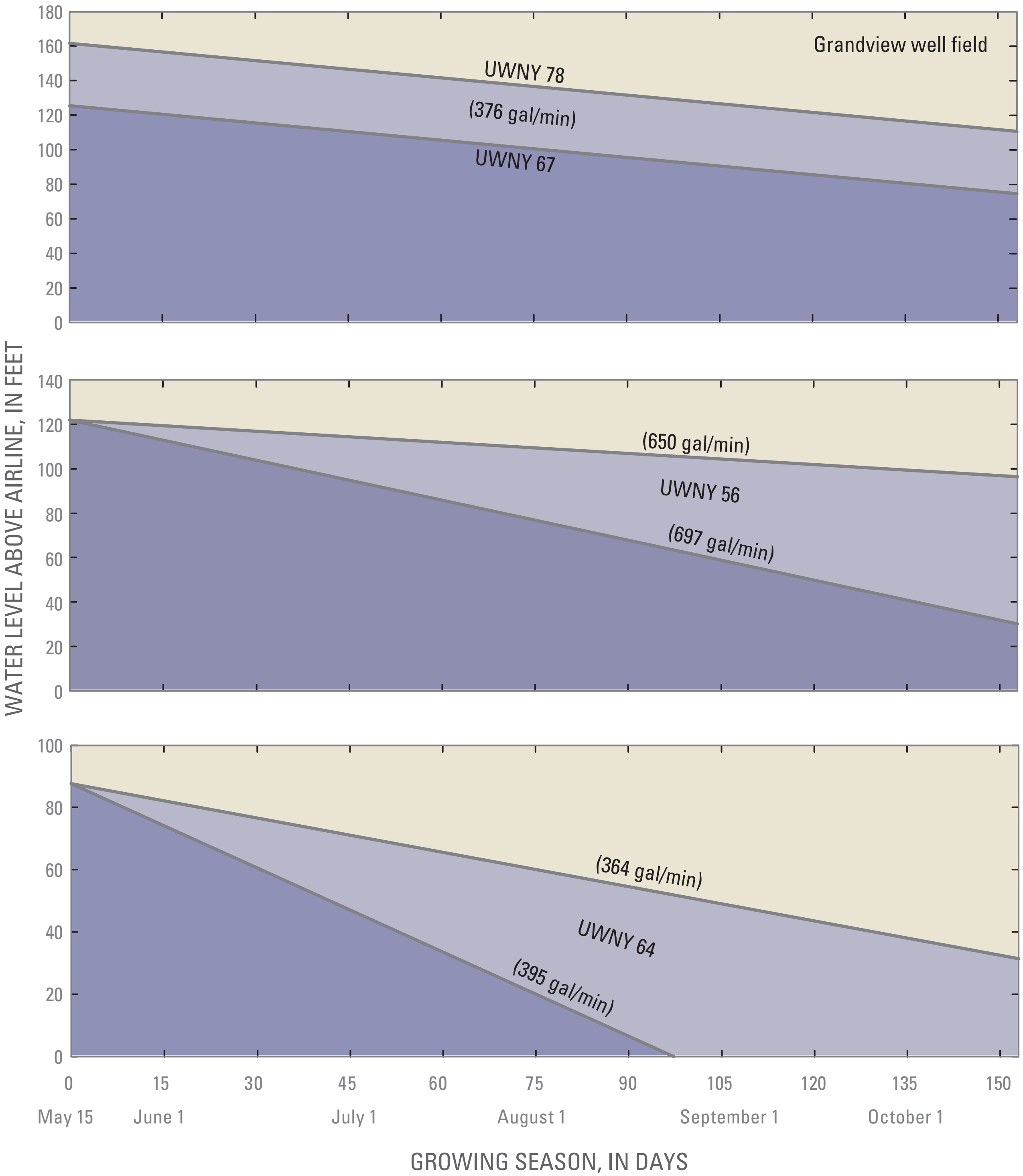


Figure 28. Projected growing-season drawdowns at selected United Water New York production wells, Rockland County, New York.

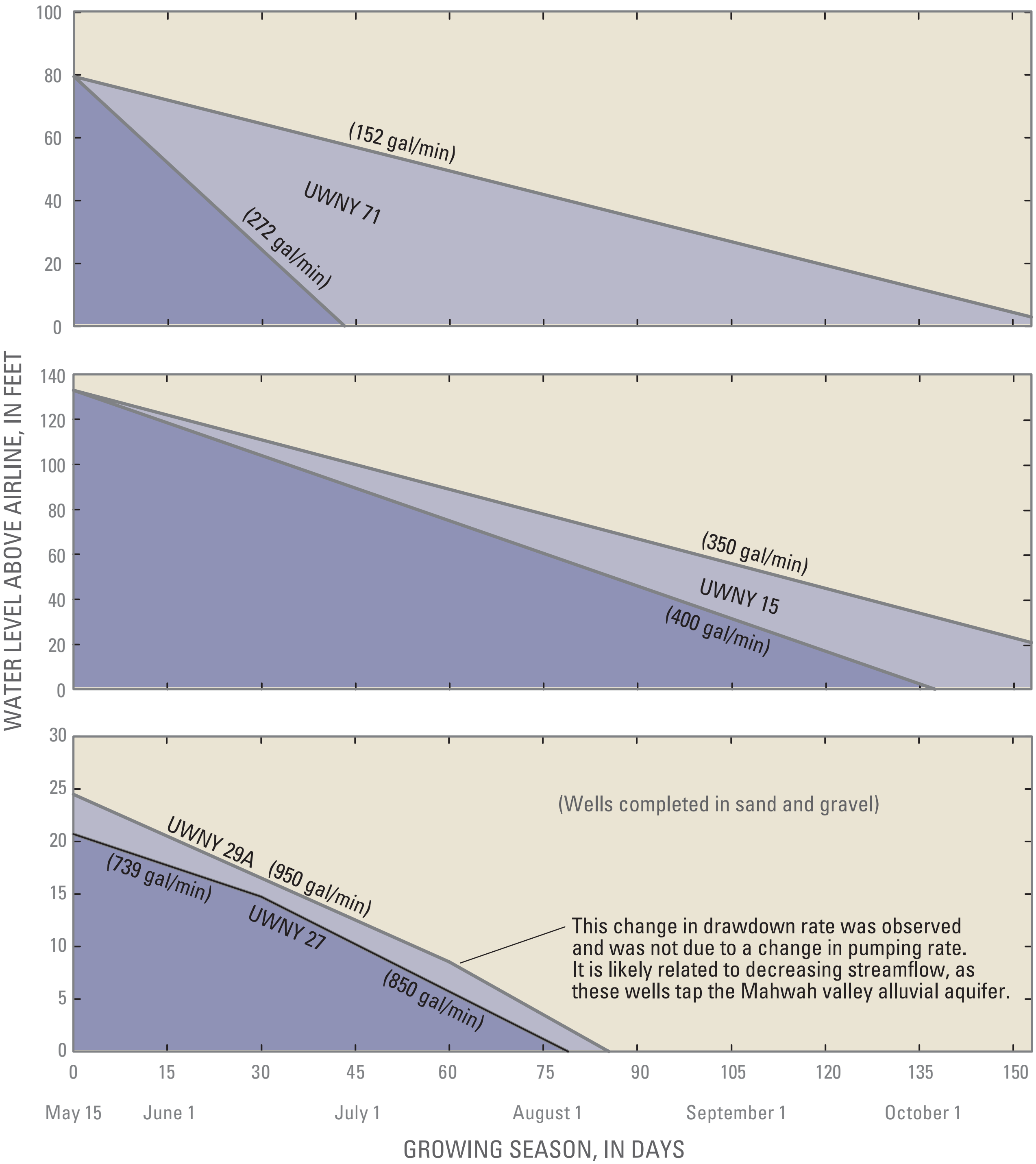


Figure 28. Projected growing-season drawdowns at selected United Water New York production wells, Rockland County, New York.—Continued

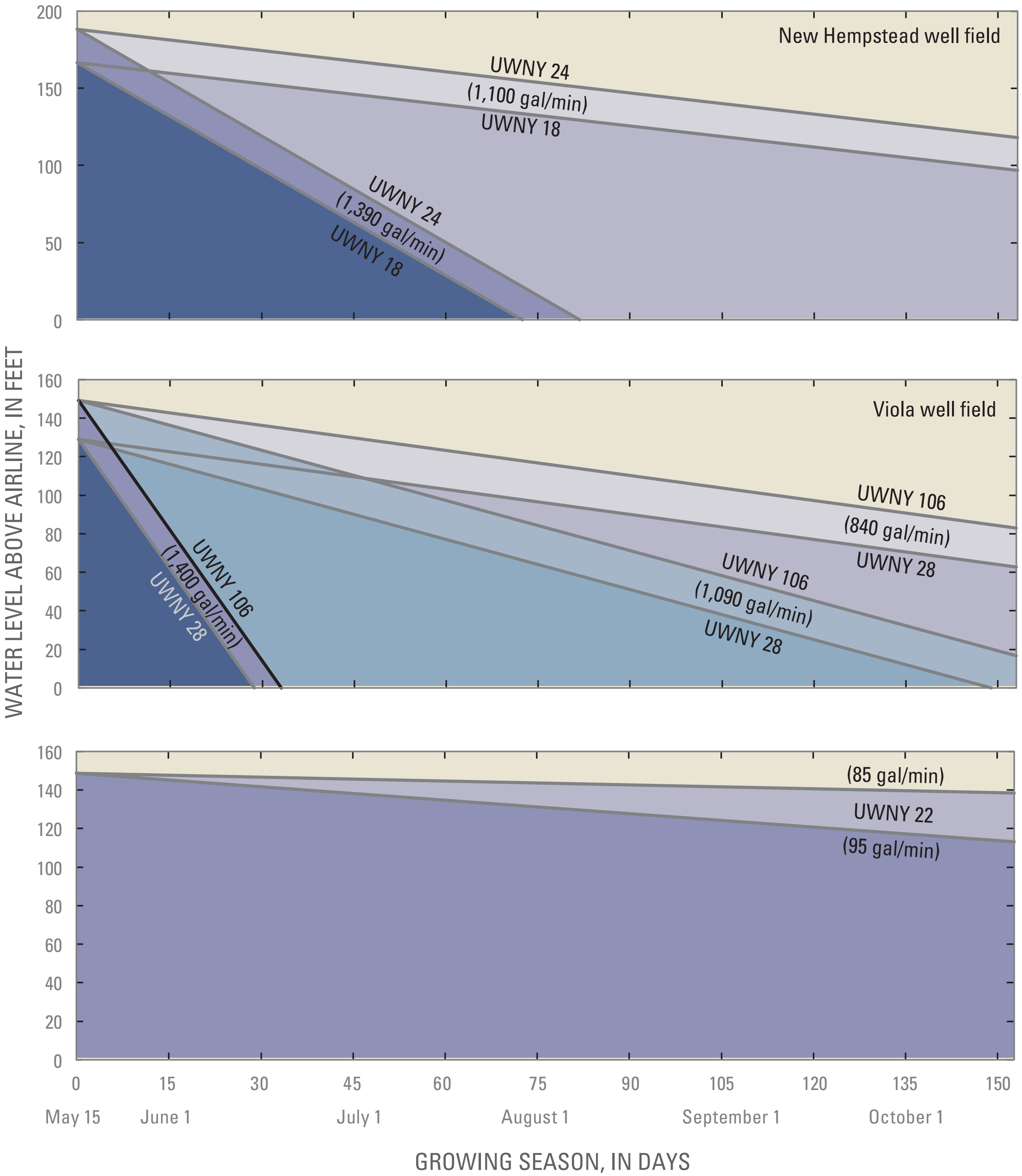


Figure 28. Projected growing-season drawdowns at selected United Water New York production wells, Rockland County, New York.—Continued

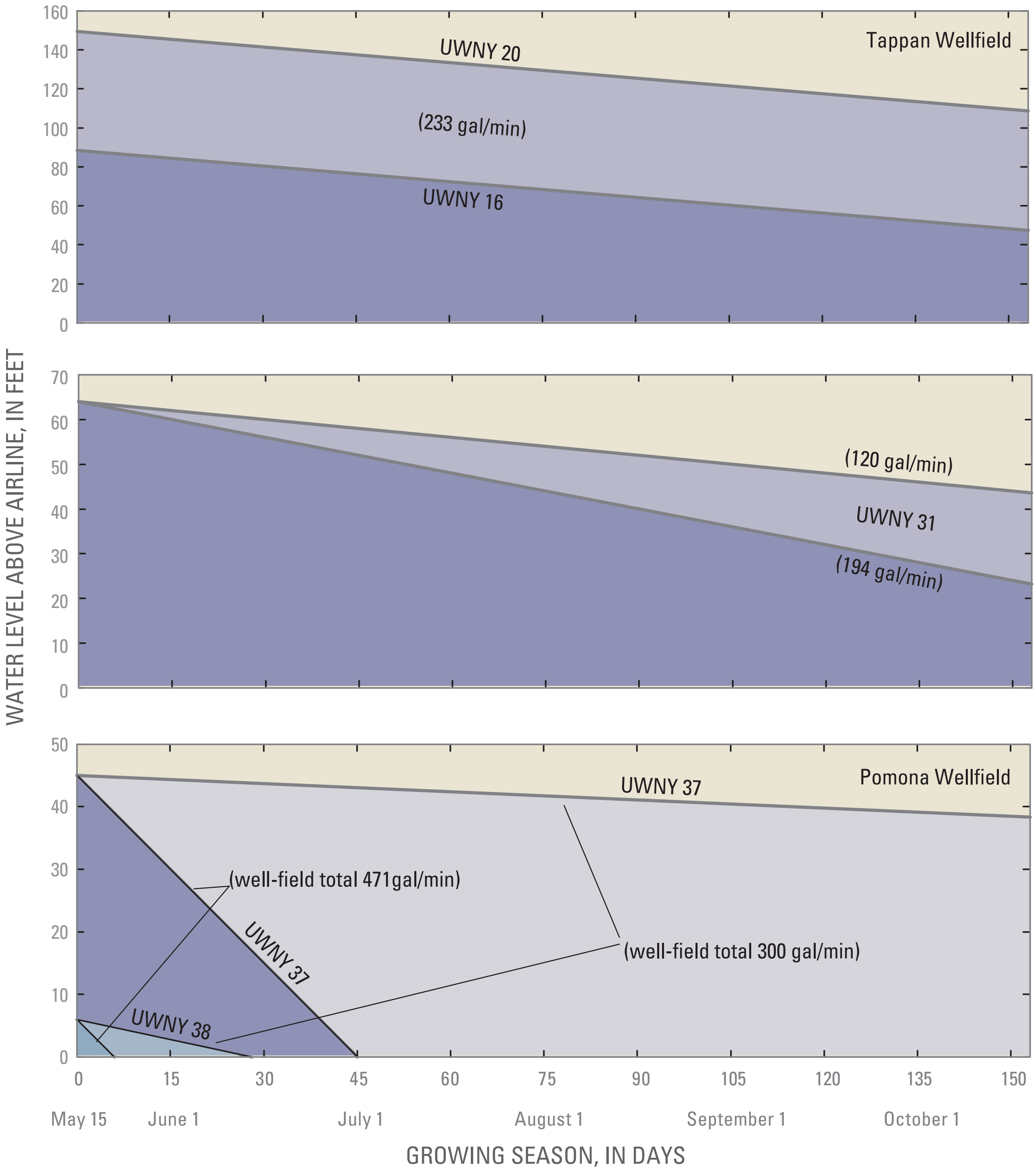


Figure 28. Projected growing-season drawdowns at selected United Water New York production wells, Rockland County, New York.—Continued

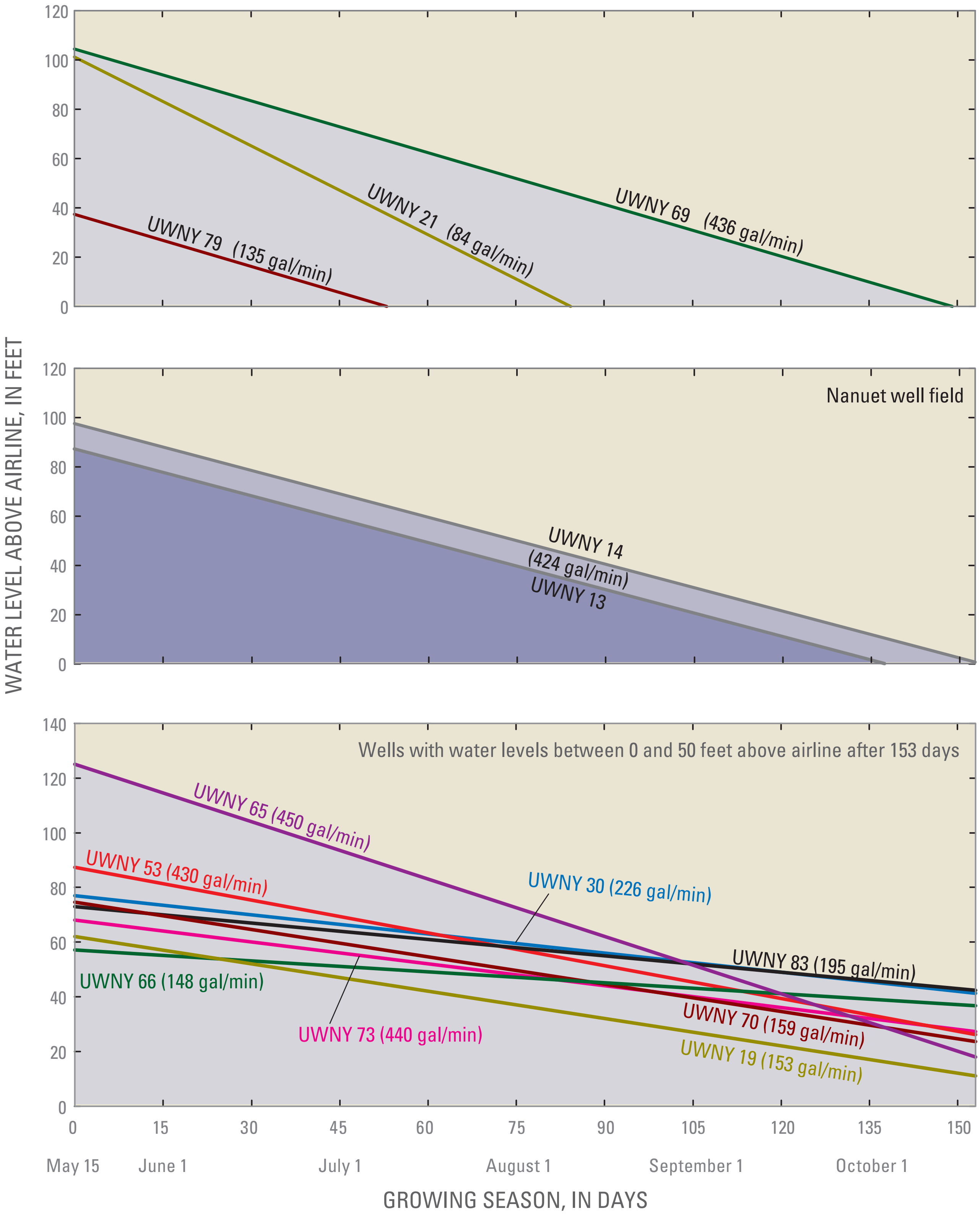


Figure 28. Projected growing-season drawdowns at selected United Water New York production wells, Rockland County, New York.—Continued

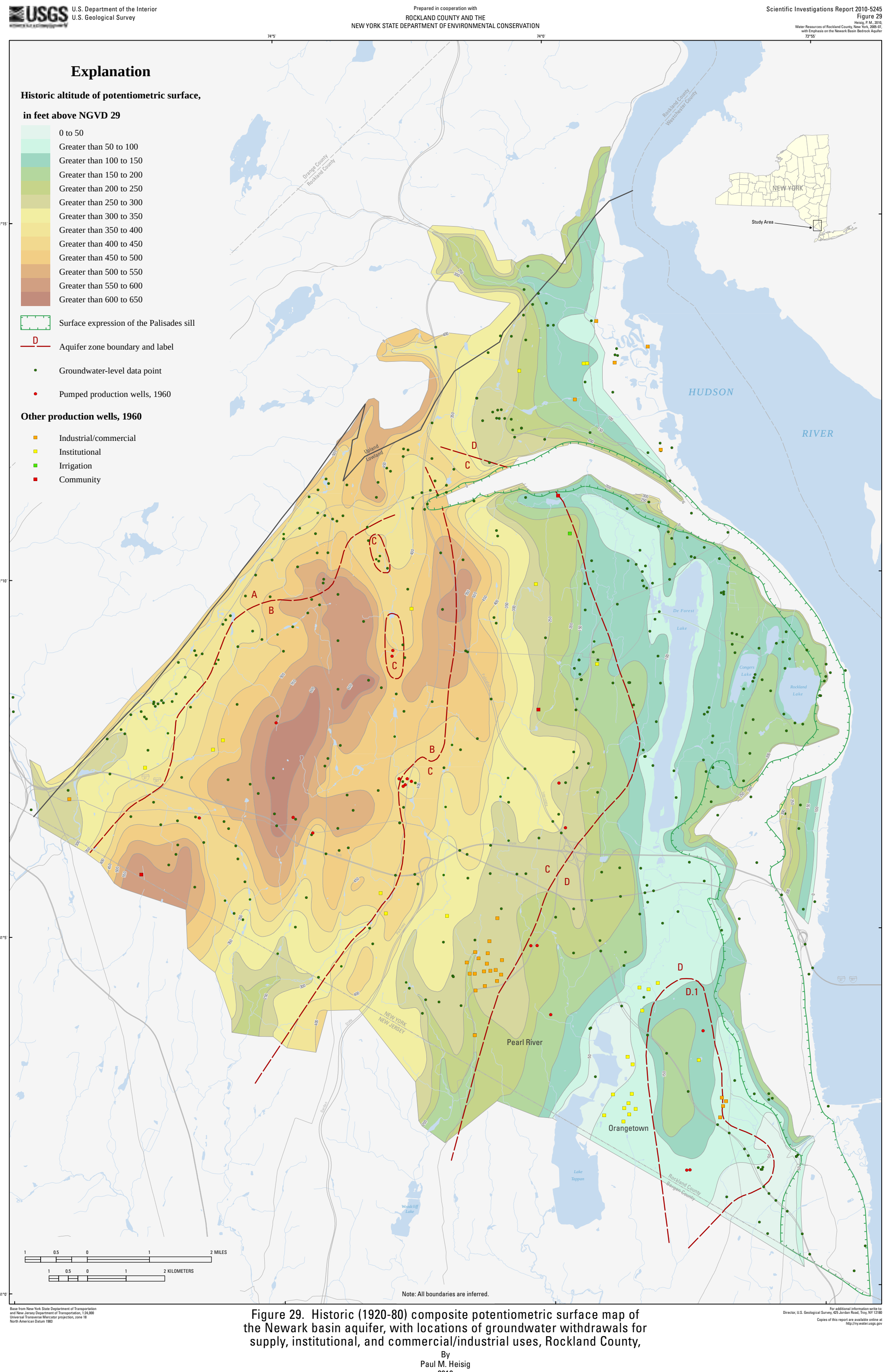


Figure 29. Historic (1920–80) composite potentiometric-surface map of the Newark basin aquifer, with locations of groundwater withdrawals for supply, institutional, and commercial/industrial uses, Rockland County, New York. (Click to view full-size map at http://pubs.usgs.gov/sir/2010/5245/plates/Figure29.pdf)

it included the largest number of wells (158). Production-well water levels from non-pumping periods also were included as available.

The recent water-level surveys provide the most concise depictions of the potentiometric surface because of the short survey periods and the large number of control points. The spring 2007 potentiometric surface also generally follows topography (fig. 30). Data on depth to water below land surface (fig. 31) indicate that water levels are deepest in the high-elevation areas of the aquifer (aquifer zones B and C) and at the high-yield well fields within that area (New Hempstead (UWNY 18, 24), Spring Valley (UWNY 1A, 3, 4, 6, 17), and Viola (UWNY 28, 106)).

Large seasonal fluctuations in groundwater levels appear to occur in areas with the greatest depths to water and the most productive well fields. Seasonal changes in groundwater levels between late summer 2005 and early spring 2007 were greatest, by far, in aquifer zone B, followed by aquifer zone C (fig. 31). Water levels fluctuated by 10 to more than 20 ft across much of aquifer zone B. A limited area of aquifer zone C exceeded 10 ft, and the water-level fluctuation in only one well exceeded 20 ft. Water levels typically fluctuated less than 10 ft in aquifer zones A and D, with a few exceptions (fig. 31). Most exceptions in aquifer zone D were from locations that are irrigated during the growing season. Well yield is known to decrease during the growing season because the most productive water-bearing fractures are shallow and thus are more prone to lose yield or go dry as water levels decline. Production-well data were not included in this dataset because the emphasis was on the aquifer in general rather than points of extraction.

Changes in the Potentiometric Surface

Comparison of historic and recent groundwater levels indicates general areas of lower water levels mostly in aquifer areas B and C, similar to the areas of greatest seasonal water-level change (fig. 31). The magnitude of change is variable but generally similar to that of the seasonal changes shown in figure 31. Lower water levels in some areas reflect essentially continuous pumping at some well fields, so that non-stressed water levels cannot be assessed (New Hempstead (UWNY 18, 24), Viola (UWNY 28, 106), Spring Valley (UWNY 1A, 3, 4, 6, 17), and Pomona (UWNY 37, 38) and an industrial well field at Pearl River). Areas of higher present-day (2007) groundwater levels (aquifer zone D) are indicated where pumping for institutional supply has been discontinued (Rockland State Psychiatric Center; the area around wells Ro-54 and Ro-58; fig. 20). Other areas historically tapped for commercial/industrial uses, which have been discontinued, have also likely experienced groundwater-level recovery, but data are lacking. Examples in southeastern Rockland County include the Orangeburg Manufacturing Company in Orangeburg (aquifer zones D and D.1) and the original industrial hillside well field that served the former Lederle Laboratories in Pearl River (aquifer zone C).

Water-level declines, particularly in aquifer area B, reflect an adjustment of the water budget in response to human activities. Groundwater withdrawn for public supply is largely lost from the local groundwater system because sanitary sewers route wastewater across the county to wastewater-treatment plants that discharge treated wastewater to the Hudson River. When individual wells served the area, most water was returned to the aquifer through individual septic systems.

Groundwater Flow

Groundwater flow in the Newark basin aquifer is constrained by anisotropic bedrock structure in which regional groundwater flow is predominantly parallel to bedding strike. Relatively smooth, progressive declines in water levels observed along bedding strike support this interpretation. Steep groundwater gradients across bedding strike generally reflect impediment of groundwater flow. Groundwater flow along strike and nearly perpendicular to the maximum groundwater gradient was documented in the Newark basin in New Jersey by Feshbach-Meriney and others (2003).

Local downdip and updip flow are also expected along fracture zones or planes in recharge and discharge areas, respectively (see fig. 21). Groundwater withdrawals also induce downdip and updip flow to wells, with the proportion of each dependent on the depth at which a fracture is intersected.

The spring 2007 potentiometric surface (fig. 30) overlaid on the bedding-strike lines of figure 16 provides the hydrogeologic framework necessary to delineate the general form of the Newark basin aquifer groundwater flow system (fig. 32). First, general locations of groundwater-divide areas were outlined by identifying the highest groundwater levels within pairs of bedding-strike lines. Groundwater flow is downgradient away from the divides and along the strike of the bedding. Gradual deflection of groundwater flow in response to groundwater gradients can be expected in the aquifer regionally, but shallowest groundwater flow in bedrock may be less constrained by bedrock fabric and, in places, cross bedrock strike in response to groundwater gradients. The widths of the groundwater divides reflect the uncertainty/potential variability in their positions. Seasonal or pumping-induced changes in groundwater levels may shift the divides. Two major divides (A and B), four secondary divides (C, D, E, and F), and three minor divides (G, H and I) were delineated (fig. 32).

Groundwater divides A and B follow major topographic divides, and water chemistry and glacial-deposit thickness can differ markedly on each side of these divides. Groundwater divide A trends diagonally northwest-southeast across the aquifer, roughly along the Palisades Parkway, and partitions regional groundwater flow to the northeast and southwest. Northeastern groundwater flow ultimately discharges to the Hackensack River (contributing to Lake Deforest), its tributaries, and Sparkill Creek. Southwestern groundwater

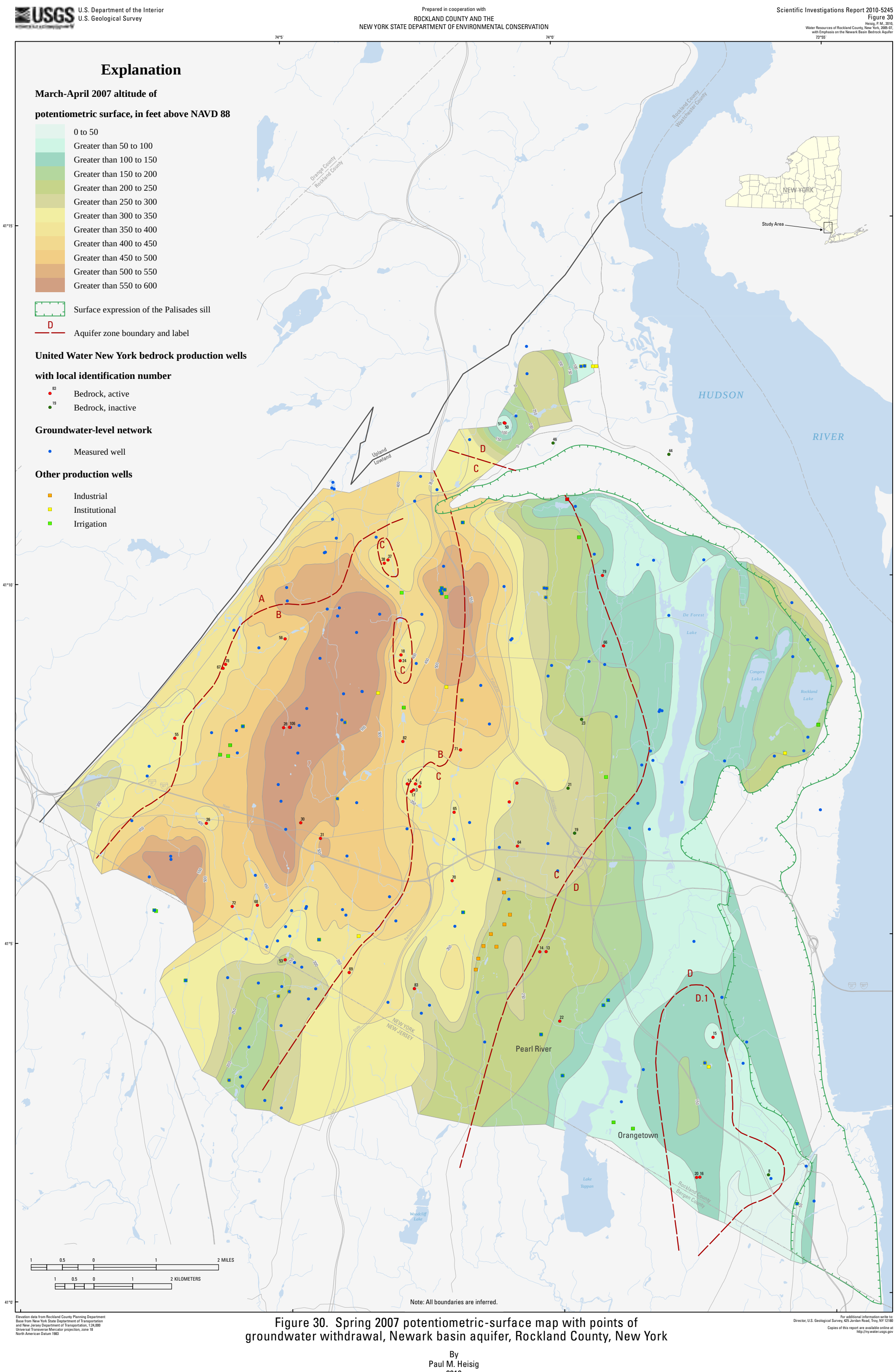


Figure 30. Spring 2007 potentiometric-surface map, Newark basin aquifer, with points of groundwater withdrawal, Rockland County, New York. (Click to view full-size map at http://pubs.usgs.gov/sir/2010/5245/plates/Figure30.pdf)

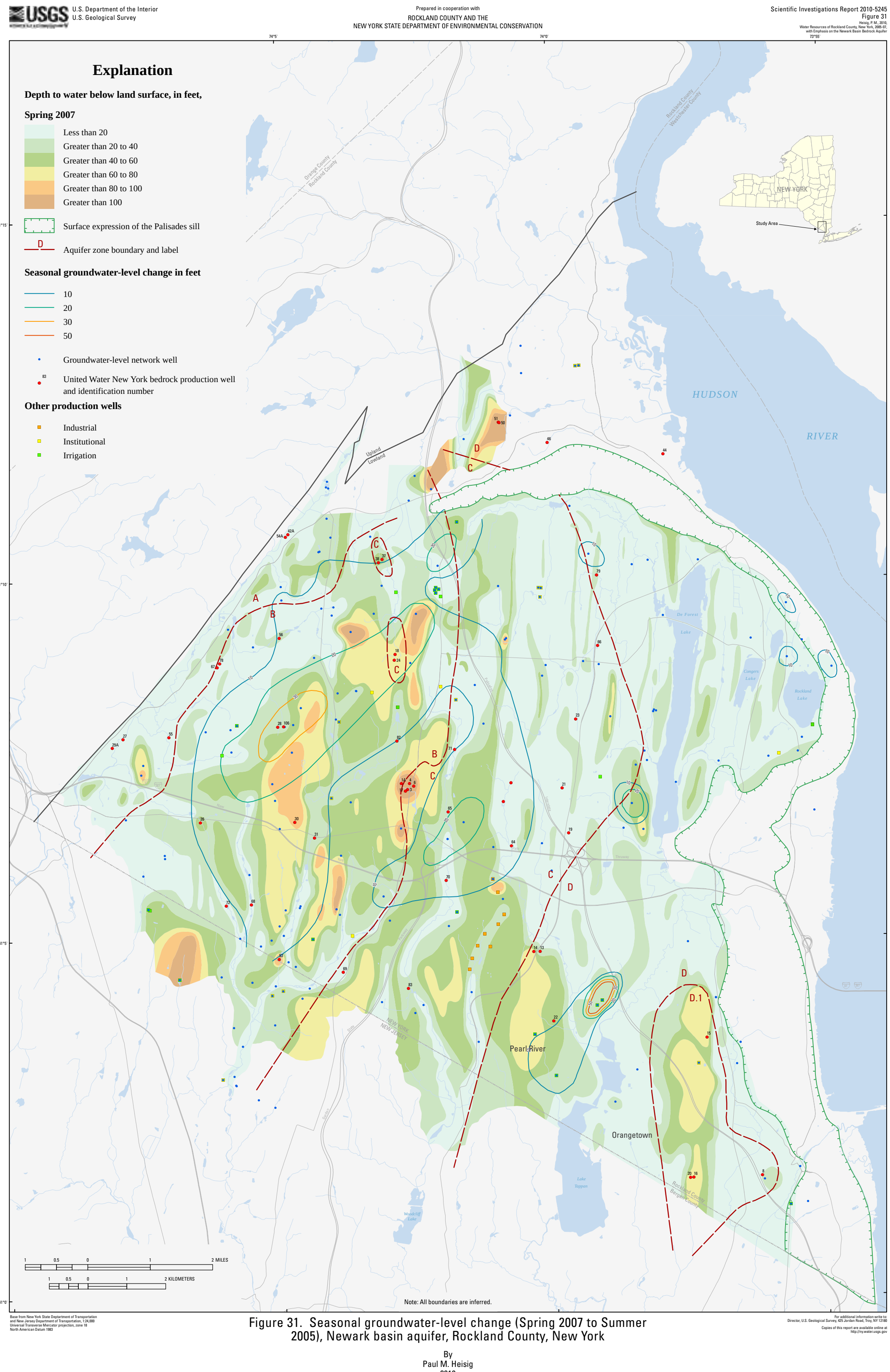


Figure 31. Seasonal groundwater-level change (spring 2007–summer 2005), Newark basin aquifer, Rockland County, New York. (Click to view full-size map at http://pubs.usgs.gov/sir/2010/5245/plates/Figure31.pdf)

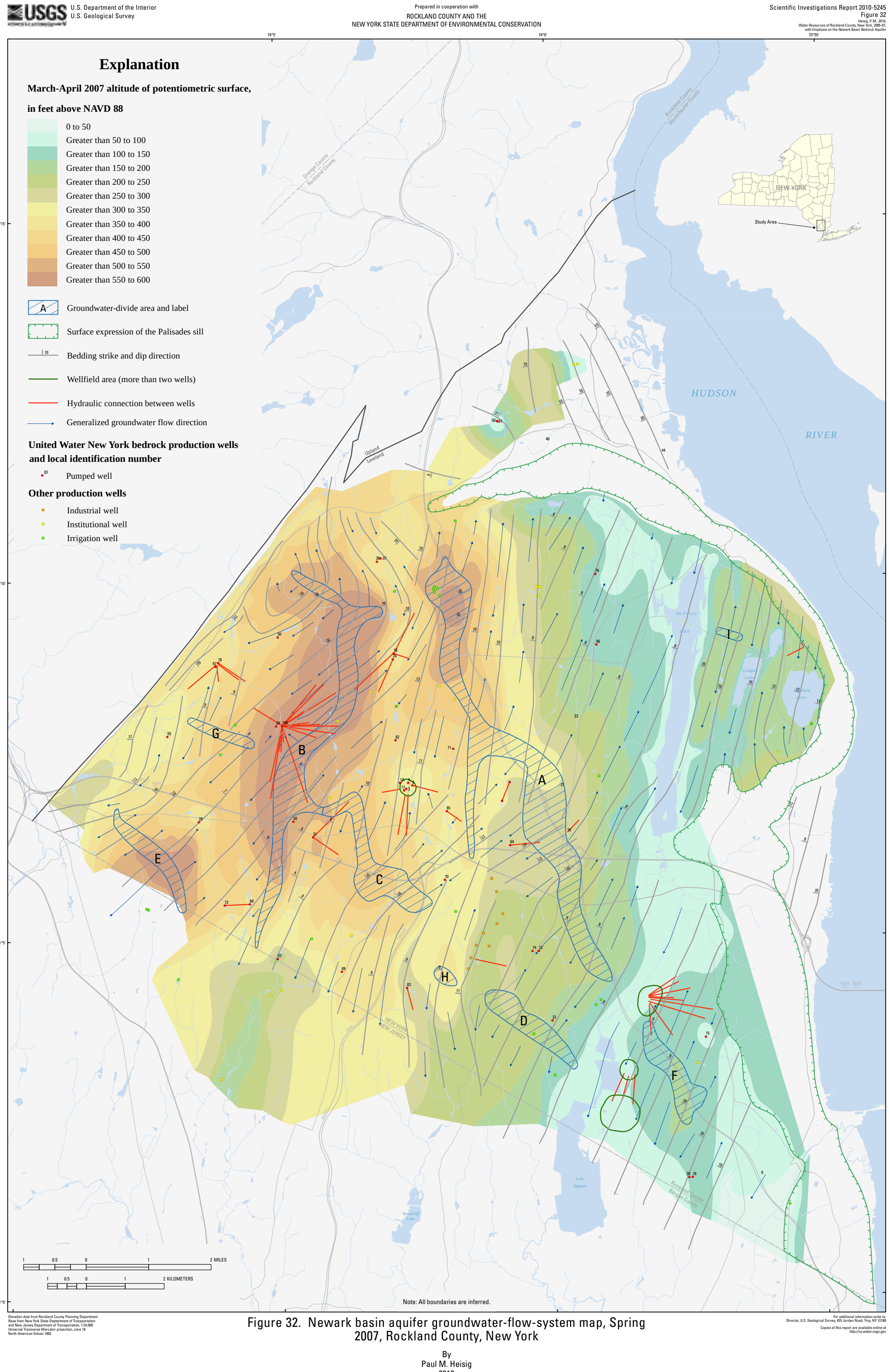


Figure 32. Newark basin aquifer groundwater-flow-system map, spring 2007, Rockland County, New York. (Click to view full-size map at http://pubs.usgs.gov/sir/2010/5245/plates/Figure32.pdf)

flow discharges to the Mahwah River, Saddle River, Pascack Brook, and South Branch Minisceongo Creek drainages. Some of this flow is intercepted by pumping wells—the majority of bedrock production wells are located in the southwestern part of the aquifer. Groundwater divide B generally trends north-south along the highest altitudes in the western part of the aquifer and partitions groundwater flow and discharge between the Mahwah River and Pascack Brook drainages. The upper part of the Saddle River drainage is split by the divide.

The secondary divides are smaller than the major divides but with similar characteristics. It is possible that deep, confined regional groundwater flow toward the southwest may pass beneath some of these divides—in particular, those divides with limited topographic expression (C and D). Divide C is of particular interest because it partitions groundwater flow between the northeast, toward the Spring Valley well field, and the southwest. The divide existed prior to the Spring Valley well field because Spring Valley is a low point along bedding strike that represents a natural sink or groundwater discharge zone. The development of groundwater resources at the Spring Valley well field has lowered bedrock groundwater levels and has diverted groundwater discharge from springs to wells. The divide has shifted south from topographic high points to a low marshy area along the New York State Thruway. In effect, this area has shifted in function from a discharge area under unstressed conditions to a groundwater divide, a high point on the potentiometric surface that receives recharge under current, stressed conditions.

Northward flow to the Spring Valley well field is counter to the regional flow, and southward flow from north of the well field may be mostly intercepted by the well field. At least some of the upgradient regional flow is captured at all well fields; the shape and size of the capture zone is largely dependent on the magnitude and constancy of pumping at the wells, local bedrock structure, groundwater gradients, and fracture permeability.

The minor divides (G through I) are least certain, because they are based more on the form of the potentiometric-surface contours than on definitive local groundwater-level measurements. These divides are most likely to reflect the shallowest part of the bedrock flow system and not regional, confined flow.

Groundwater Chemistry

Variations in the major-ion chemistry of groundwater provide additional lines of evidence for understanding distribution of recharge to the aquifer, directions of groundwater flow within the aquifer, and locations of groundwater discharge from the aquifer. Changes in the chemical composition of groundwater with residence time provide clues as to the relative ages of the groundwaters. The interpretations herein are generally consistent with $^{3}H/^{3}He$ age dates of groundwater samples from selected UWNY production wells in Rockland County (Aeschbach-Hertig and others, 1998) and four samples analyzed for this study. Other specialized analyses (nitrogen and oxygen isotopes of nitrate and organic wastewater compounds) were used to identify probable sources of nitrate and to assess wastewater contamination in groundwater.

Rockland County has experienced numerous instances of groundwater contamination in the Newark basin aquifer, including solvents or other volatile organic compounds (VOCs) from industry (Hoven and others, 1985; Slayback and Rothenberg, 1984), components of gasoline from leaking underground storage tanks, and chloride and sodium from the storage and application of road deicing salts. Identification or documentation of groundwater-contamination sites was beyond the scope of this study; this information is available through the NYSDEC, the U.S. Environmental Protection Agency, and at http://www.toxicstargeting.com. Environmental-consultant reports on contaminated sites were reviewed for hydrogeologic data, including subsurface logs, and for groundwater chemistry, water-level, or flow-direction data. Movement of contaminant plumes in the bedrock aquifer can provide data useful in understanding the regional aquifer system. Data from this study provide an indication of bedrock-aquifer susceptibility to contamination that can be used to address future contamination issues in the county. For example, the thickness of glacial deposits is important because bedrock beneath thin glacial deposits generally is more susceptible to contamination than bedrock beneath thick glacial deposits. Locations of recharge and discharge areas are important because there is less chance of bedrock contamination in discharge areas. Last, knowledge of the bedrock framework is critical for constraining groundwater flow directions.

Water Types

Major-ion water type is the most general classification of the chemical composition of groundwater. Water types are named by the most common cations and anions in water samples. Ions must constitute at least 10 percent of the total molar concentration to be included in the water-type name. The variety of water types in an area can be an indication of the degree of either the natural evolution of water with time in the system or contamination from human activities. The result of water-type classification of 80 groundwater samples from the Newark basin aquifer indicates that this classification is too general to identify the relatively limited natural groundwater evolution that has occurred in this flow system; it also indicates widespread changes in water type because of the wintertime application of deicing salt to roads.

Groundwater type typically evolves from dilute calcium bicarbonate or calcium magnesium-bicarbonate waters of acidic pH to sodium bicarbonate waters of basic pH (greater than 7). Only seven samples were classified as dilute calcium bicarbonate or calcium magnesium bicarbonate water types. Chloride and sulfate anions may increase with time in an aquifer system. In some aquifers, chloride may be present as connate (old) water that leaches slowly from interstices in the bedrock into fractures, although this was not observed in the Newark basin aquifer. The opposite is true in the study area; chloride concentrations typically decrease with depth. Sulfate in groundwater may be derived from dissolution of pyrite, under oxic conditions, and from dissolution of sulfate-bearing evaporate minerals such as gypsum. Gypsum has been reported in well logs from some wells in the northeastern part of the aquifer, although sulfate was the major anion in only one water sample. Sulfate concentrations are greater than 10 mg/L over much of the aquifer, but widespread elevated chloride reduces the overall molar percentage of sulfate.

Application of road deicing salt(s) in the winter since the 1950s and 1960s, with subsequent downward leaching to groundwater, has resulted in major increases in chloride and, ultimately, hardness (calcium and magnesium) in groundwater across much of the aquifer. Sodium chloride is the primary type of salt used for deicing. Chloride concentration at production wells in 1950, 1979, and from 2000–2005 illustrate this dramatic increase (fig. 33). Chloride is conservative (unreactive) in groundwater and is the best indicator of salt input; it therefore has potential as a tracer of the direction of groundwater flow and as a gross indicator of groundwater age in developed areas (either older than or younger than about 1960).

Sodium concentrations in groundwater are not conservative. Elevated concentrations of sodium drive cation exchange in which sodium is adsorbed onto clay minerals, and in exchange, calcium and magnesium are released into the water, which increases hardness. Groundwater affected by road salt leachate can have cation classifications with either calcium or sodium as the dominant cation. Sodium is most commonly the dominant cation in highly affected samples with specific conductance above about 1,300 µS/cm at 25° C.

Eighty-one percent of groundwater samples were affected by road-salt leachate to the extent that it altered their water-type classification. Anions in 40 water-type samples were classified as bicarbonate chloride, and another 25 samples were classified as chloride bicarbonate.

Water Chemistry and Groundwater ($^3H/^3He$) Age Dates

Review of over 300 partial major-ion water analyses indicates that chloride, pH, nitrate, and sulfate provide the best basis for understanding water movement into and within the Newark basin aquifer. Concentrations of chloride, nitrate, and sulfate typically are lower in low-altitude discharge areas than in upgradient recharge areas. Values of pH typically are highest in discharge areas and lowest in recharge areas. Chloride is useful as a tracer of groundwater flow and as a constraint on groundwater age. Nitrate and sulfate are subject to transformation (loss) in reducing (anoxic) groundwater environments, which are more likely in deep areas of the flow system where groundwater circulation is slow. Nitrate is more readily reduced than sulfate, so nitrate concentrations decrease more rapidly with time in the aquifer than sulfate concentrations. However, variations in initial nitrate concentrations and sources, both spatially and from a historic perspective, should be considered. The progressive rise in pH with time in a flow system is also a relative indication of groundwater age, subject to the amount of carbonate in the glacial deposits or bedrock available to react with low pH waters.

The general interpretations of groundwater chemistry and relative time in the groundwater flow system described above were compared with results of groundwater $^3H/^3He$ age dates from supply wells in Rockland County as reported in Aeschbach-Hertig and others (1998) and from four additional samples collected during this study.

Aeschbach-Hertig and others (1998) determined $^3H/^3He$ ages of 17 samples from production wells that tap the Newark basin aquifer. The samples represented unknown mixtures of groundwater from different depths within the aquifer that were penetrated by the wellbores. Without data from individual water-bearing fractures, an infinite number of mixing models can be used to interpret the groundwater ages in fractured bedrock. The simplest approach (no mixing) yielded $^3H/^3He$ groundwater ages between 6.1 and 23.3 years. However, application of a plausible exponential mixing model decreased the model age of a number of samples by about half. Five samples were thought to have older true ages than the $^3H/^3He$ age dates indicated; three samples were interpreted as having old water (pre-1952) with no ^3H as part of the mixture, and two samples were interpreted to have degassed some ^3He.

The $^3H/^3He$ ages provide a framework of general groundwater age at withdrawal points within the flow system. Aeschbach-Hertig and others (1998) identified several trends in the flow system: increases in $^3H/^3He$ ages towards the southwest part of the county (with decreasing regional topographic altitudes) and with increases in well depth, and decreases in ion concentration with increasing $^3H/^3He$ age. Last, the youngest $^3H/^3He$ age date at well UWNY 65 was attributed to water contributions induced from local streams.

Mixtures of "old" water with water containing ^3H are likely commonplace in most deep wells (greater than about 300 ft deep) because deep waters of low specific conductance were noted in several fluid logs. This observation underscores the uncertainty of absolute ages from the $^3H/^3He$ age-dating results.

The general distribution of $^3H/^3He$ age dates from Aeschbach-Hertig and others (1998) is consistent with their location within the flow system as interpreted in this report. The interpretation of older true ages than the $^3H/^3He$ ages at UWNY 79, UWNY 16, and UWNY 20 is consistent with the long distance between UWNY 79 and the groundwater divide and the degree of confinement from thick glacial deposits at, and upgradient from, the Tappan well field (UWNY 16, 20). The UWNY 51 well is outside the defined flow-system area, but the age of the water, interpreted as older than the $^3H/^3He$ age (23.3 years), is consistent with thick, confining glacial deposits, including till, in that area. Groundwater in this well water is also characterized by low specific conductance.

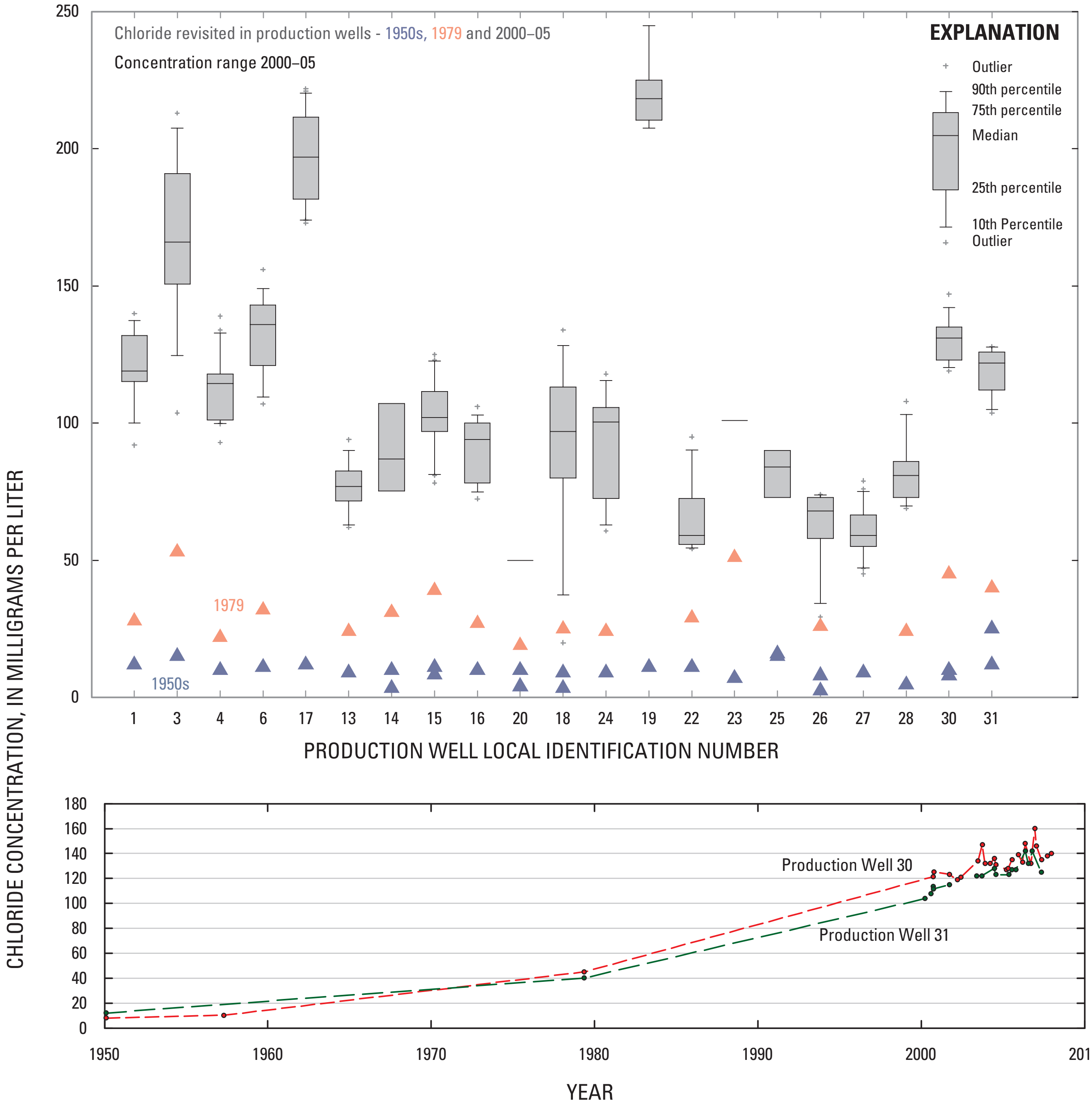


Figure 33. Changes in concentration of chloride in selected United Water New York production wells since the 1950s, Rockland County, New York.

The ^{3}H/^{3}He ages from Aeschbach-Hertig and others (1998) were compared with corresponding pH and specific-conductance data collected during that study and nitrate concentrations from samples collected the following year by UWNY (fig. 34). The ^{3}H/^{3}He age dates from two production wells sampled during the current study (appendix 6) and corresponding pH, specific conductance, and nitrate values are also included. Sulfate was not analyzed in well water by UWNY. Values of pH generally increase with ^{3}H/^{3}He age (fig. 34), and specific conductance and concentrations of nitrate generally decrease with ^{3}H/^{3}He age, with some exceptions.

Well UWNY 65 plots outside of the pH and nitrate trends but within the specific-conductance trend (fig. 34). Data collected during this study support the interpretation of Aeschbach-Hertig and others (1998) that some water at this well is induced infiltration from the East Branch Pascack Brook. Sand and gravel overlies bedrock in the reach of the East Branch adjacent to well UWNY 65. The reach of East Branch Pascack Brook near UWNY 65 is a broad, well-developed channel within a valley. This reach was dry in September 2005—the largest dry stream during a survey of all Rockland County streams over or adjacent to the Newark basin aquifer. Infiltration from a reach of the West Branch Pascack Brook is also possible. This stream flows directly over bedrock to the south, along bedding strike from UWNY 65. Streamwater samples from lowland areas of the county were nearly all between pH 7.2 and 8.3, and nitrate concentrations were nearly all less than 2 mg/L as nitrogen, which is consistent with the deviations from the trends in figure 34. Part of the water pumped from well UWNY 65 is from an area to the east overlain by thick till; water derived from this type of area would likely have increased contact time with the till, which would have increased pH and decreased nitrate concentrations.

Values of pH were nearly a full pH unit lower at wells UWNY 79 and UWNY 73 than wells with corresponding ages (fig. 34). These wells are located generally along strike in a band of bedrock characterized by low carbonate content (Savage, 1967), which limits the buffering capacity of the bedrock (fig. 16B). Thin glacial deposits over much of the area, except in the vicinity of well UWNY 73, limits contact time of water with glacial deposits and thus buffering capacity. The groundwater pH, alkalinity, and hardness values in this area have historically been among the lowest in the aquifer (Perlmutter, 1959; Leggette, Brashears & Graham, Inc., 1979) and are described in the "pH" subsection of the "Regional Distributions" section of this report.

Three wells plot above the trend of decreasing specific conductance with ^{3}H/^{3}He age—two Spring Valley well-field wells (UWNY 4 and UWNY 17) and UWNY 30 (fig. 34). All of these wells are affected by infiltration of road-salt leachate into the aquifer. The high local road density and proximity of the New York State Thruway account for the high values of specific conductance.

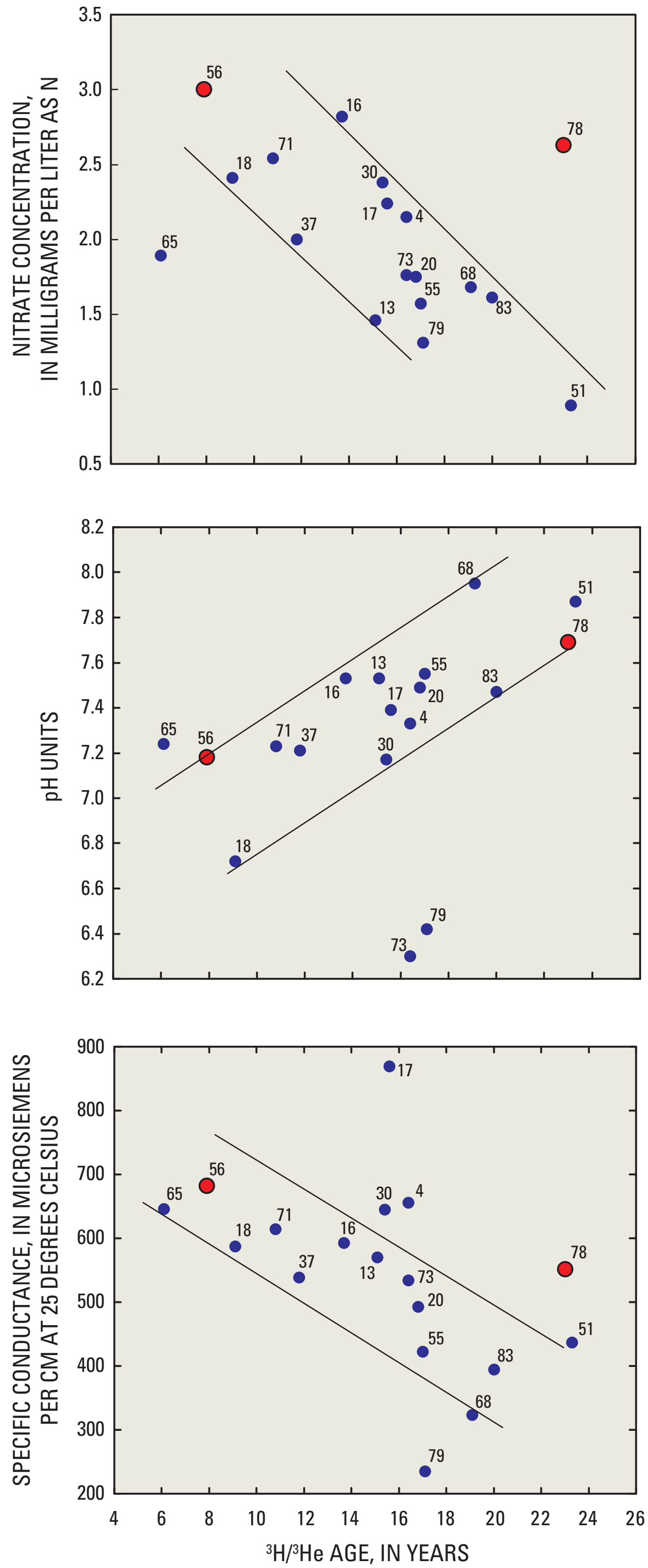


Figure 34. Nitrate, pH, and specific conductance as a function of ^{3}H/^{3}He (tritium/helium) groundwater age dates at selected United Water New York production wells, Rockland County, New York. Groundwater age dates, pH, and specific conductance from Aeschbach-Hertig and others (1998) in blue; samples analyzed for this study in red.

The conceptualization of groundwater chemistry and groundwater age is further supported by a vertical profile of water chemistry in samples collected from discrete zones in a deep flowing well (Ro-1289) located in a valley near the southern edge of the county (aquifer zone B, fig. 20). Packers were used to isolate three intervals—50–150 ft, 150–335 ft, and 335–494 ft—all of which flowed. Samples were collected from the upper and lower zones, and the characteristics of the middle zone were determined by mass-balance calculations (fig. 35). Changes in concentrations with depth parallel the interpretations of regional data. The $^{3}H/^{3}He$ age dates from the upper and lower zones (22.9 and ≥48 years, respectively) constrain the range of aquifer groundwater ages in this regionally low-altitude discharge area. The presence of relatively old water within 150 ft of land surface underscores that this is mostly a bedrock discharge area, substantially downgradient from the primary recharge areas. The distribution of flow contributions from each depth interval provides an indication of the degree of mixing among young and old waters intercepted by the wellbore (fig. 35) and the decrease in aquifer permeability in the deepest isolated interval, despite the high head values.

Regional Distributions

The distributions of chloride, nitrate, pH, and sulfate described in the following sections primarily are from domestic wells, which typically are 250 ft or less in depth. The subset of samples from deeper production and industrial wells have contributions from deep groundwater, but the depth-yield data presented earlier indicate that most well water is derived from the upper 200 to 300 ft of the aquifer. Therefore, the data presented here are considered representative of the upper, most-active part of the aquifer flow system.

These constituent distributions were compared with historic data, where available, and viewed in terms of the conceptualization presented above and depicted in figure 36. The effects of mostly till glacial deposits are also highlighted. Thick till can confine bedrock and prevent recharge or reduce the amount of recharge and increase the contact time of infiltrating water with overburden sediments. Time within the till can facilitate more complete neutralization of acidic precipitation through reaction with carbonates, allow for reduction of nitrate (especially in the presence of organic carbon), or increase sulfate through dissolution of pyrite, where present. Thin, permeable till, in contrast, may be leached of carbonates or other reactive minerals and have minimal effect on infiltrating water.

Chloride

As described earlier, chloride concentrations in groundwater have increased by as much as two orders of magnitude over the past 50 years (fig. 33), largely in response to the application of deicing salt to roadways. Concentrations of chloride in water from production wells during the 1950s were typically less than 10 mg/L. Present-day concentrations in domestic wells away from roads (mostly in the Highlands or Palisades sill) are about 5 mg/L. Chloride concentrations in the Mahwah and Ramapo Rivers around 1900 were 1.4 mg/L (Jackson, 1905).

Today (2007), only small localized areas of the Newark basin aquifer have chloride concentrations less than 20 mg/L (fig. 37). Concentrations are low in shallow groundwater in areas of low road density or in topographically low areas where old water with low chloride concentrations is present beneath streams or rivers. Chloride concentrations are generally highest in areas with thin glacial deposits, with base-line concentrations between 50 and 100 mg/L. Areas with thick glacial deposits have base-line concentrations of about 20 to 50 mg/L. Apparently, some of the shallow, high-chloride water stays within the glacial deposits, especially where the water table is above the bedrock surface, and discharges to streams without entering bedrock. Both settings have areas of high concentration (greater than 100 or even 200 mg/L) typically associated with (1) major roadways such as the New York State Thruway, the Palisades Parkway, and State and county roads (fig. 37), (2) current or former road-salt storage areas, or (3) areas with high residential road densities (fig. 1).

Three large high-chloride areas are present across the southern half of the aquifer, along the path of the New York State Thruway (fig. 37). The first area, in the west near Suffern, is most likely associated with salting of the Thruway and State Route 59, which parallels the Thruway. The chloride data suggest a northeastern movement of elevated chloride water toward the Viola well field, but groundwater-level data do not support this interpretation. Low heads in deep, confined fractures may draw water towards the wells, but evaluation was beyond the scope of this study. The second area is centered on Spring Valley, which has a high density of residential roads and county highways as well as proximity to the New York State Thruway. High pumping rates at the Spring Valley well field have drawn in high-chloride groundwater. Water levels, chloride data from the distribution map, and chloride concentrations at wells 3 and 17 on the south (Thruway) side of the well field (fig. 33) indicate that the well field captures some water from beneath the Thruway, which has largely prevented shallow high-chloride groundwater flow to the south. The groundwater divide in that area (divide C; fig. 32) has been shifted south by the groundwater withdrawals at Spring Valley. The third area is centered where the Thruway, the Palisades Parkway, and Route 59 intersect. There is also a State Department of Transportation Facility with salt storage (presently stored within a storage building) in the area. This area is also situated on a groundwater divide; regional groundwater flow along bedding strike is indicated by moderately elevated chloride groundwater flowing northeast toward the north end of Lake DeForest and higher chloride concentrations that have been transported southwest to an industrial well field. The northern flow accounts for the high chloride concentrations in groundwater from well UWNY 19. The gap in elevated chloride just north of the divide is evidence of the good

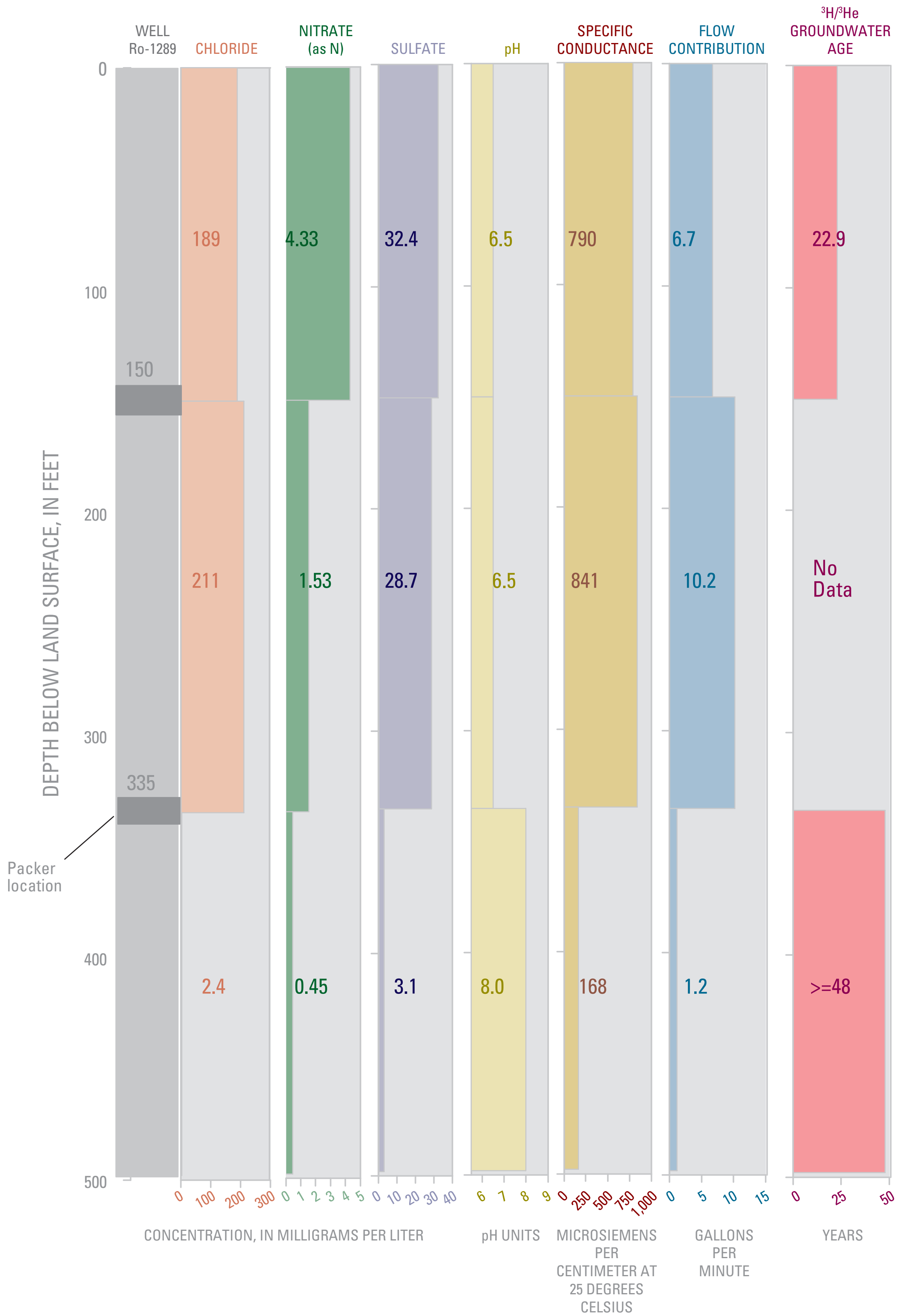


Figure 35. Vertical changes in chemistry, flow, and $^3H/^3He$ (tritium/helium) age dates in the Newark basin aquifer at well Ro-1289, Rockland County, New York.

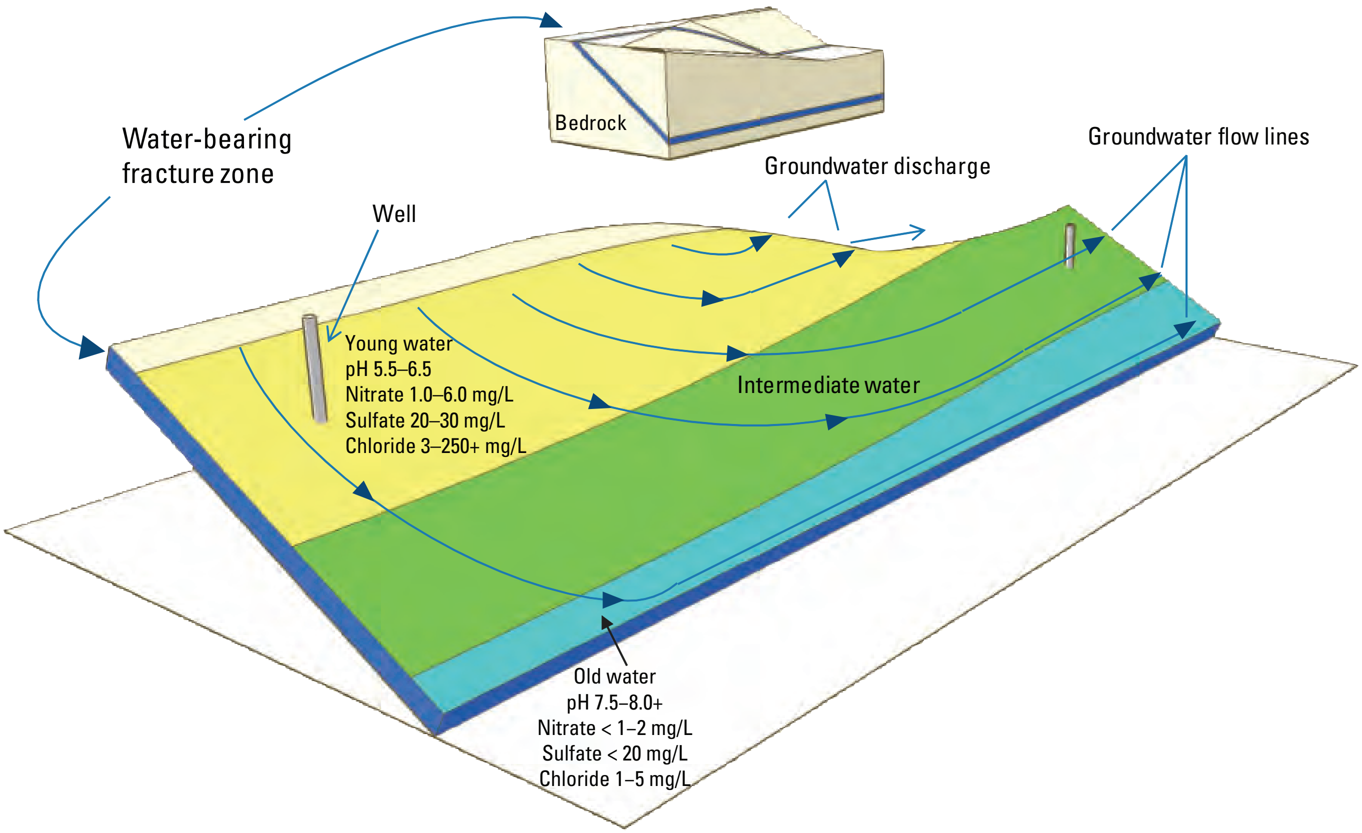


Figure 36. Regional conceptual water-chemistry section along a water-bearing fracture zone of the Newark basin aquifer, including pH, nitrate, chloride, sulfate, and groundwater age, Rockland County, New York.

hydraulic connection between groundwater and surface water; the gap represents shallow, salty groundwater discharge to the Demarest Mill Brook. Groundwater that passes under this stream (beneath the shallowest part of the flow system) is likely less concentrated or is diluted by subsequent recharge along the flow path to the north. High specific conductance, which corresponds to elevated chloride concentration, was measured in this stream reach, which supports this interpretation.

Most of the locales where chloride concentrations exceed 100 mg/L represent areas where recharge along roadways is focused by drainage or where the glacial deposits are thin or permeable. Some areas reflect current or former road-deicing-salt storage locations.

Nitrate

The widespread occurrence of nitrate (as nitrogen) concentrations in excess of 1 mg/L, and as high as 7 mg/L, in the Newark basin aquifer in Rockland County is greater than background concentrations in the Highlands and traprock areas, which typically have nitrate concentrations less than 1 mg/L. Although the nitrate concentrations are not high enough to be of concern from a drinking-water perspective (http://www.epa.gov/safewater/contaminants/index.html#inorganic, accessed September 14, 2007), the source of nitrate is of interest because other contaminants can be associated with the primary sources for nitrate—wastewater from septic systems or leaking sewer lines and fertilizers applied to lawns, golf courses, or for agriculture (currently limited, but formerly widespread). Wastewater sources contain organic wastewater compounds (OWCs), which can include pharmaceuticals, personal care products such as DEET, fire retardants, and derivatives from plastics, among others. Lawn, golf course, and agricultural fertilizers may also include a range of pesticides including herbicides, insecticides, and fungicides.

Fertilizer, rather than wastewater, is indicated as the primary source of nitrate from analysis for OWCs in four UWNY production wells (UWNY 1A, UWNY 28, UWNY 37, and UWNY 83; fig. 38). The wells selected for sampling were characterized by moderate to high concentrations of nitrate,

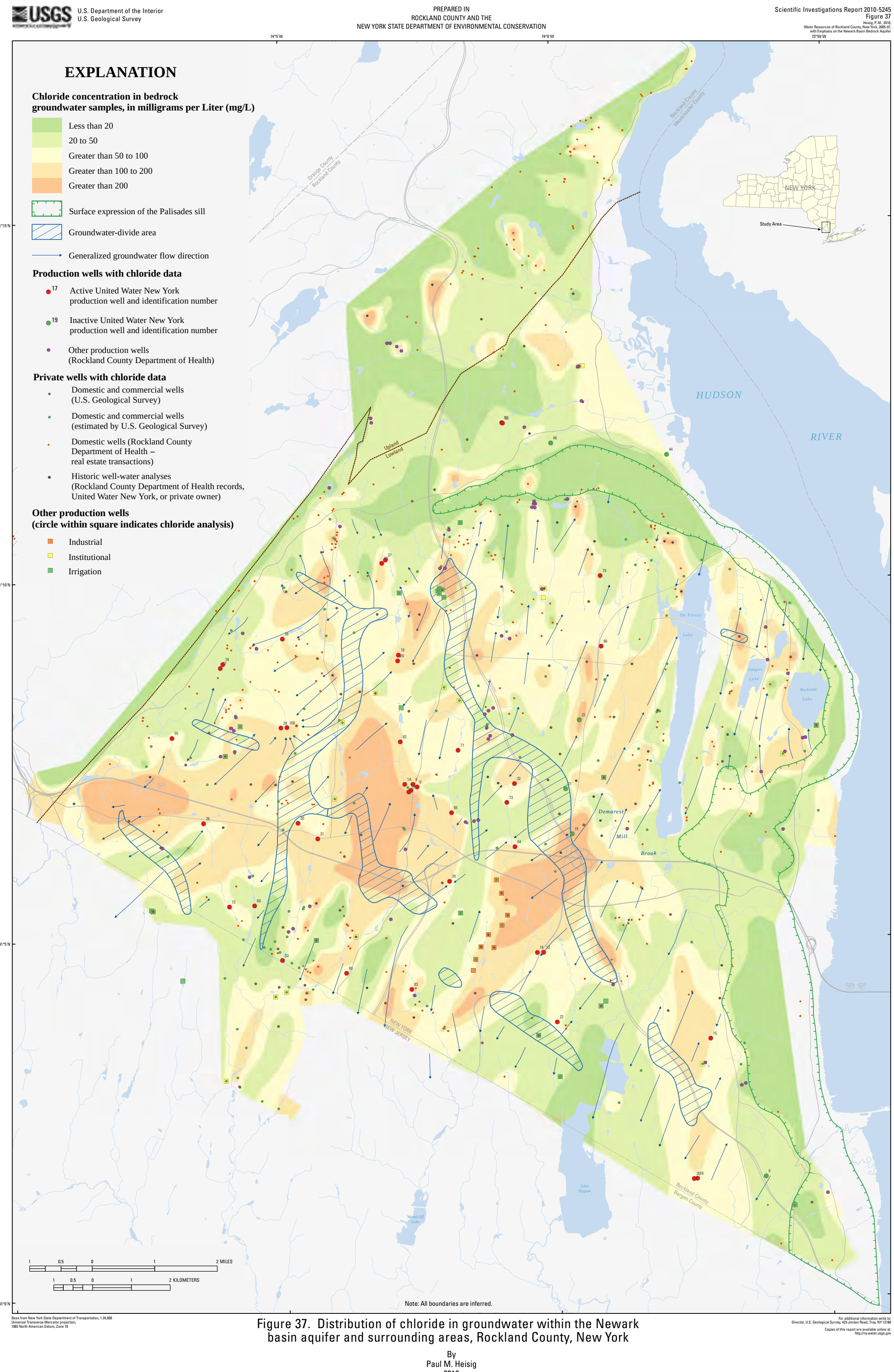


Figure 37. Distribution of chloride in groundwater within the Newark basin aquifer and surrounding areas, Rockland County, New York. (Click to view full-size map at http://pubs.usgs.gov/sir/2010/5245/plates/Figure37.pdf)

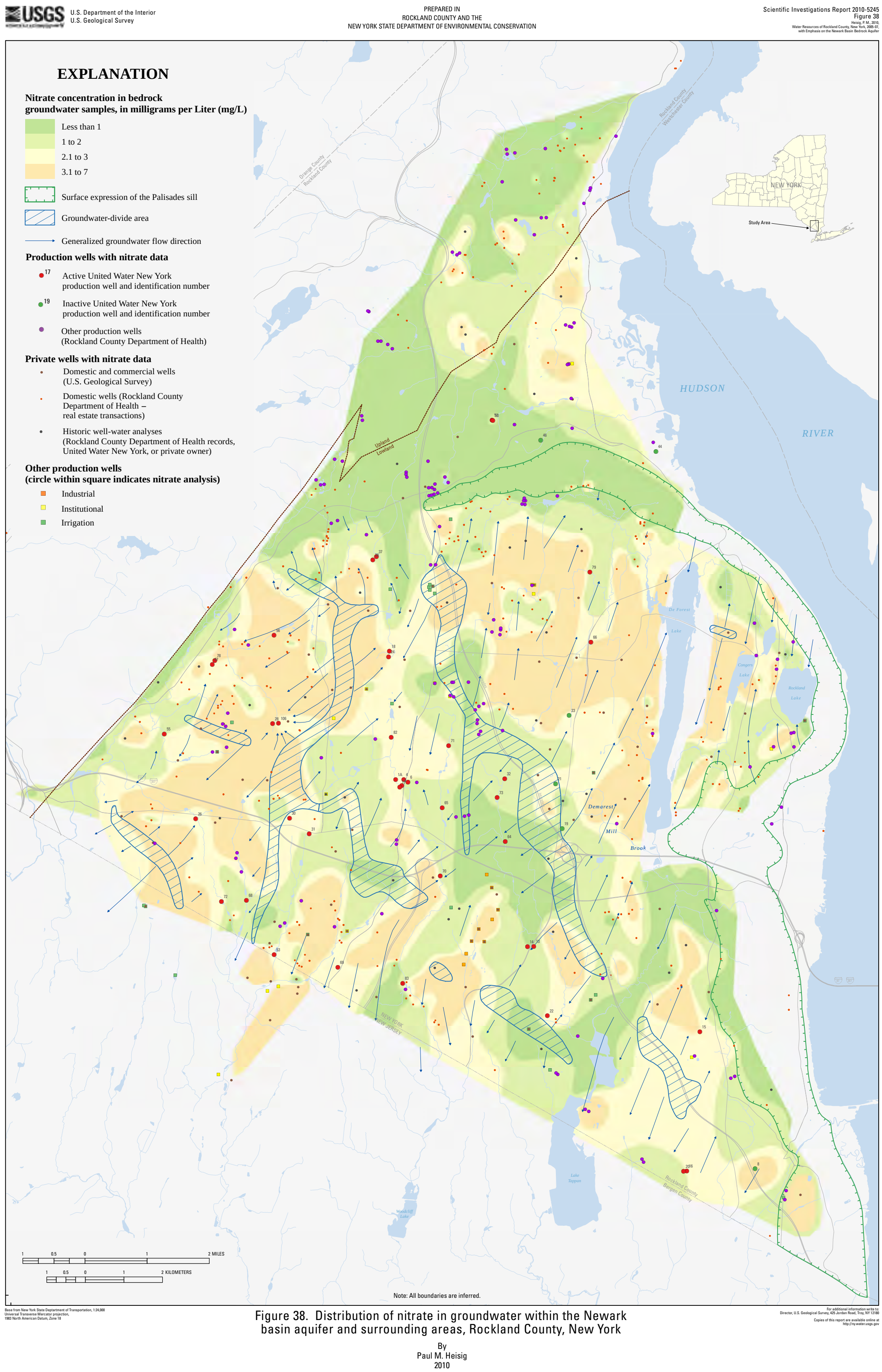


Figure 38. Distribution of nitrate in groundwater within the Newark basin aquifer and surrounding areas, Rockland County, New York. (Click to view full-size map at http://pubs.usgs.gov/sir/2010/5245/plates/Figure38.pdf)

and all wells showed the absence of OWCs except for low concentrations (near the detection limit) of tetrachloroethylene at well UWNY 1A and isophorone at well UWNY 37 (appendix 7). The absence of OWCs and the presence of elevated concentrations of nitrate at these wells suggest that leakage from sanitary sewers is not the source of nitrate.

Analysis of nitrogen and oxygen isotopes that make up nitrate molecules in groundwater was used in an effort to determine if the source of groundwater nitrate was wastewater or fertilizer. Groundwater samples from two wells with elevated nitrate (NO_3) concentrations (Ro-1260 and Ro-1284; fig. 38) were analyzed for nitrogen and oxygen isotopes. Both samples had similar isotope ratios, suggesting a common source, but the ratios indicated that either source was possible (appendix 8; Kendall and others, 2007). If denitrification occurs in the groundwater, then the fertilizer source is favored. Denitrification is the bacterially mediated transformation of nitrate to nitrogen gas.

Historic concentrations of nitrate point to fertilizer as a primary source of nitrate. Nitrate concentrations at production wells in the 1950s (Perlmutter, 1959) were generally higher than concentrations at the same wells from 2000 to 2005. Rockland County was largely rural and agricultural in the 1940s to mid 1950s. Low population and widespread farming would be consistent with a fertilizer source of nitrate rather than a septic-wastewater source. This is especially likely because bedrock production wells pull in water from large contributing areas; high nitrate concentrations at such wells would require widespread areas of high nitrate concentration.

The distribution of nitrate across the aquifer is a function of (1) the presence of nitrate sources, (2) residence time in the glacial deposits and aquifer, and (3) redox conditions within the aquifer (fig. 38). High concentrations of nitrate in groundwater can indicate either a concentrated source or minimal removal of more widespread sources. Areas with golf courses or farms, where data were available, indicated elevated concentrations of nitrate in groundwater. Low concentrations may indicate either loss of nitrate through denitrification or the absence of nitrate sources in a given area. Limited data from neighborhoods where fertilizers are not widely used indicate low nitrate concentrations in the underlying groundwater.

In general, long residence times correspond with low nitrate concentrations (figs. 34–35). If a nonpoint (widespread) source of fertilizers is assumed, areas of high nitrate indicate areas where nitrate readily enters the bedrock aquifer—areas most favorable for recharge. In fact, areas with nitrate concentrations greater than 3 mg/L closely match areas with thin till (figs. 7 and 38). Areas of thicker till have moderate to low concentrations of nitrate. Less and slower recharge occurs in areas of moderate till thickness, and little or no recharge occurs where till is thickest. Aquifer areas confined by glacial deposits and regional discharge areas (at the major rivers and streams) have the lowest nitrate concentrations.

Disposal of domestic wastewater through septic systems in Upper Saddle River, NJ, appears to result in higher concentrations of nitrate in groundwater than in adjoining residential areas in Rockland County, which are sewered. Fertilizers are applied to lawns in both areas. Nitrate concentrations in Upper Saddle River were consistently in the highest range but lower than drinking-water standards, unless the well was located in the valley and, therefore, likely to tap older groundwater with low nitrate concentrations. These concentrations were elevated despite generally moderate till thicknesses.

pH

Precipitation is acidic and oxygenated. As precipitation infiltrates the soil zone, bacterial decomposition of organic material also contributes to low pH. Carbonate minerals, if present in the glacial deposits or bedrock, can undergo some dissolution, which raises the pH either in the unsaturated zone or within the aquifer flow system. Infiltrating water or groundwater can remain acidic if carbonate minerals are absent from the glacial deposits or bedrock. Carbonate minerals may be either naturally absent or may have been dissolved (leached out) by infiltrating water. Groundwater can remain acidic until it has been in the groundwater flow system long enough to be neutralized. If bedrock has a high carbonate-mineral content, pH will rise more rapidly with time in the flow system than in areas with low carbonate content. However, high groundwater velocities in areas affected by pumping wells can result in less contact time between groundwater and bedrock; groundwater is thus less neutralized than would occur under natural flow conditions. Contact time in glacial deposits will increase as the thickness increases and as permeability decreases.

Carbonate content in the Newark basin sedimentary rocks in Rockland County is variable. Savage (1967) measured carbonate content in outcrop samples across the county and found greater than 2 percent carbonate in most samples, except within a north-northeast–south-southwest trending band in the east-central part of the county (mostly within aquifer zone C). Carbonate clasts are common in the coarse-grained rocks in the western part of the aquifer (aquifer zones A and B). Historic pH data (Perlmutter, 1959) indicated pH values greater than or equal to 7 across most of the county, with an area of pH less than 7 that corresponds to a low-carbonate zone described by Savage (1967).

The pH distribution compiled in this study (fig. 39) shows similarities with the historic distribution, with low values (below 6.0 in several wells) within the low-carbonate area and high pH values (≥ 8.0) in and near the Palisades sill. The primary difference is a decrease in pH from about 7.5 to below 7.0 in the high-altitude area of aquifer zone B. This decrease is attributed to the increases in groundwater pumping in this area, which have decreased groundwater contact time with bedrock. Glacial deposits are thin, permeable, and likely leached of most carbonate in this area.

Values of pH in water from production wells since the 1950s have either remained the same or are lower. Again,

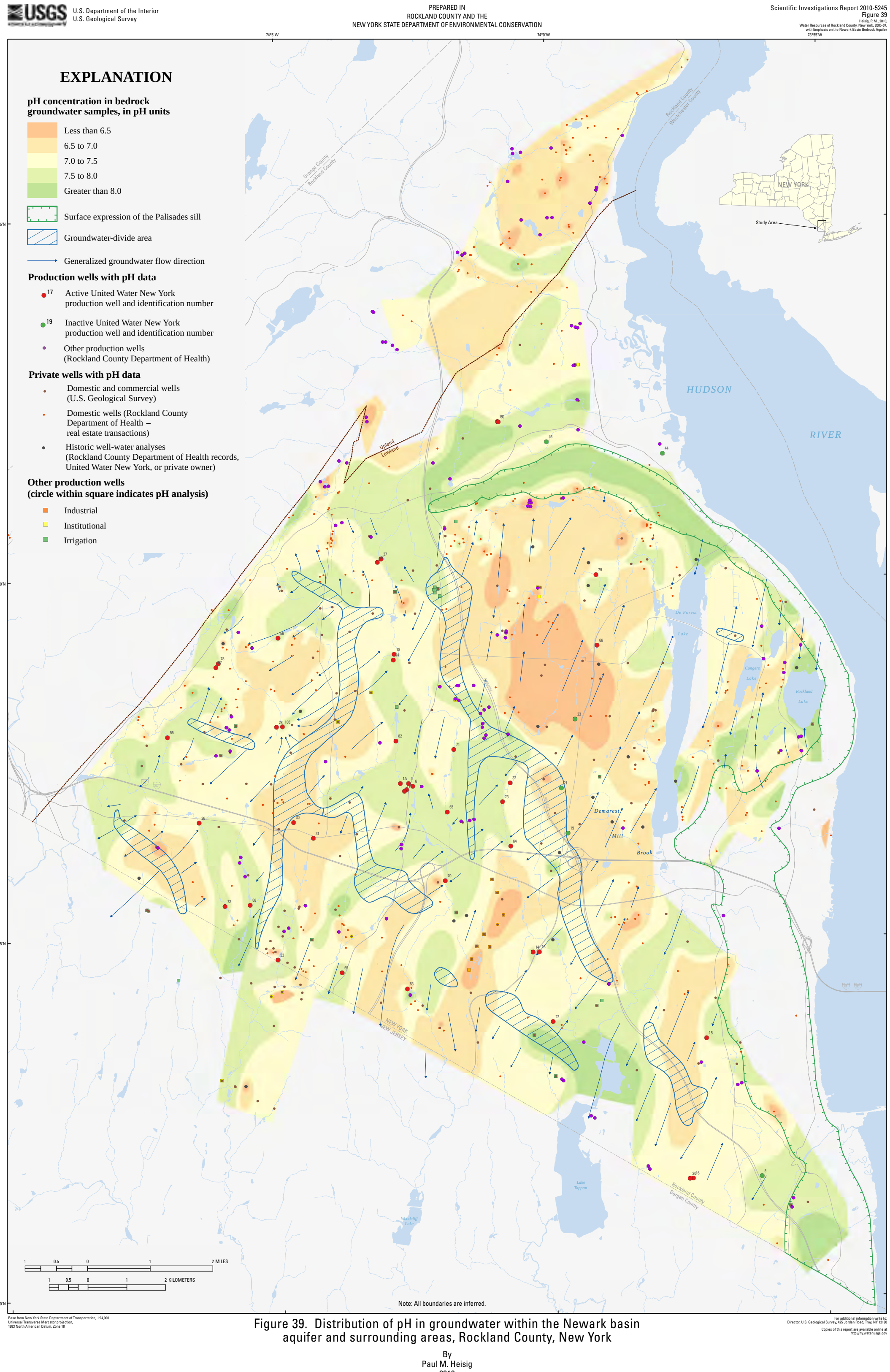


Figure 39. Distribution of pH in groundwater within the Newark basin aquifer and surrounding areas, Rockland County, New York. (Click to view full-size map at http://pubs.usgs.gov/sir/2010/5245/plates/Figure39.pdf)

lower present-day pH values presumably indicate shorter contact times with aquifer material as pumping has increased.

The response of pH to the thickness of glacial deposits and location within the flow system is pronounced. Low pH values (less than 7.0) correspond to areas of thin till, which are considered to be the most favorable areas for recharge. These areas also correspond to areas of high nitrate concentrations (greater than 3 mg/L as nitrogen). Likewise, areas of thick till are characterized by pH values from 7.0 to as much as 8.0 and presumably low recharge rates. This is best illustrated by the differences in pH on each side of groundwater divide A. High pH values (about 8.0) are most common in regional discharge areas in stream valleys at the southern edge of the county and along the Mahwah River valley.

Sulfate

The highest sulfate concentrations coincide with the presence of gypsum in the northeast corner of the aquifer near the Palisades sill, and along the northern half of Lake DeForest (fig. 40). High concentrations in deep UWNY test wells (and low yields at depth) in this area indicate that the active groundwater flow system is shallow and that the wellbores intersect zones that have had little if any exposure to groundwater flow (fig. 40). Proximity to the poorly permeable Palisades sill has likely restricted development of the local flow system and, therefore, the depth of active groundwater circulation. High sulfate concentrations (greater than 250 mg/L; the U.S. Environmental Protection Agency secondary maximum contaminant level) can make water aesthetically unpleasing and act as a laxative (http://www.epa.gov/safewater/contaminants/unregulated/sulfate.html, accessed September 14, 2007). Zones of high sulfate concentrations associated with the presence of gypsum have also been documented within the Newark basin in New Jersey (Michalski and Britton, 1997).

In general, the highest concentrations of sulfate outside of the aforementioned area occur at or near groundwater divides and the lowest concentrations occur in regional discharge areas. The distribution of sulfate concentrations in excess of 20 mg/L appears to be most indicative of recharge of more recent origin. Lawn fertilizers are a likely source of sulfate to groundwater, given the extensive suburban development in the study area. Low concentrations of sulfate in discharge areas may be the result of bacterially mediated reduction or simply lower concentrations in older groundwater. The latter scenario is more likely because nitrate is also present in most samples and would be transformed to nitrogen gas before sulfate. Low concentrations of sulfate in older, deeper water are illustrated in figure 35. Historic sulfate data (Perlmutter, 1959) are limited, but low concentrations (5–15 mg/L) were reported in areas with recent (2005-07) concentrations of 20 to 30 mg/L.

Surface-Water Conditions

Surface-water conditions (quantity and quality) have changed over the past 50 years in response to suburban development in the county. Increases in the degree of impervious surface have changed the flow regime by increasing stormflows and their intensity and by reducing base flows (fig. 41). Increases in the amount of groundwater pumped and the shift from domestic-well withdrawals distributed across the aquifer to more concentrated withdrawals and localized stresses by high-capacity production wells in both bedrock and sand and gravel have decreased streamflow, particularly during the summer. These changes can be subtle and are most easily documented during dry summer periods.

Surface-water quality has been improved in many respects, with regulation of industrial discharges to streams and routing of wastewater to wastewater-treatment plants on the main rivers rather than small facilities scattered within the aquifer area. Surface water, however, has been degraded in other ways, including widespread increases in chloride from road-deicing salt application. Streamflow measurements at current and formerly gaged sites and a comprehensive streamflow and specific-conductance survey, conducted during a dry summer-fall period, were used to assess surface-water conditions.

Comparison of Current (2005–06) and Historic (1961) Streamflows

Ongoing changes associated with residential and commercial development in the county complicate the comparison of streamflow conditions from the early 1960s with those of 2005–06. All stream drainages overlying the Newark basin aquifer had some degree of development in the early 1960s. Streamflows were altered from natural conditions by discharges from wastewater-treatment plants and industry and by regulation from upstream ponds, reservoirs, and mills (Ayer and Pauszek, 1963). Impervious surfaces began to increase peak stormflows and decrease base flows. These alterations have changed over the years as impervious surfaces have increased, regulation has generally decreased, and wastewater has been diverted to treatment plants along the Hudson and Ramapo Rivers. Comparisons are also hampered by seasonal and annual climatic differences between measurement periods. The 2005–06 period was wetter than 1961 in annual and June–October precipitation totals, although late summer 2005 was the driest period. The spatial distribution of precipitation is also a factor because it is highest in the Highlands and decreases toward the southeast corner of the county (fig. 3) but can also vary because of localized summer thunderstorms. Location with respect

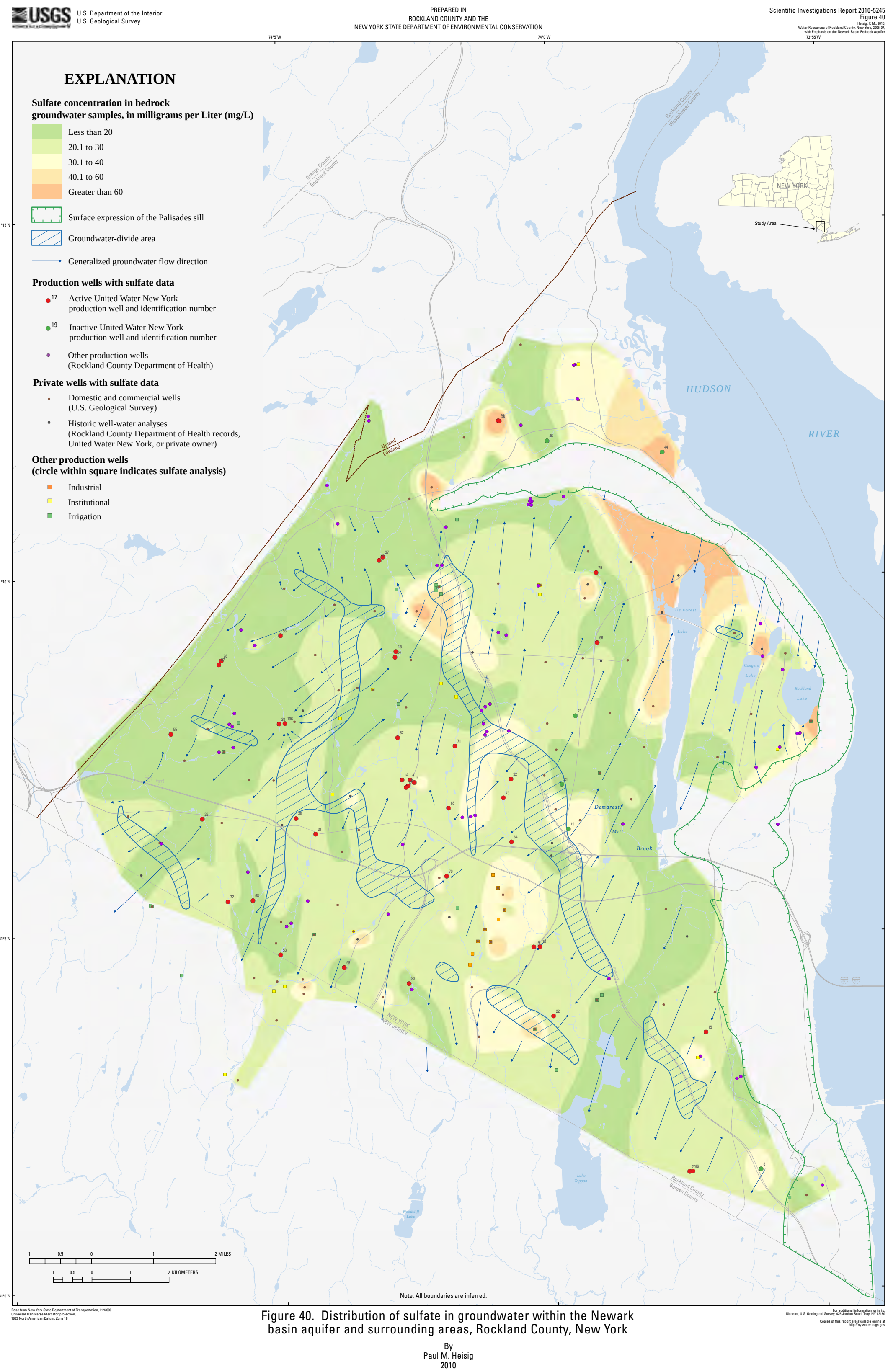


Figure 40. Distribution of sulfate in groundwater within the Newark basin aquifer and surrounding areas, Rockland County, New York. (Click to view full-size map at http://pubs.usgs.gov/sir/2010/5245/plates/Figure40.pdf)

A *B*

Figure 41. Streamflow extremes in two Rockland County, New York, streams: *A,* stormflow at a tributary of Demarest Mill Brook and *B,* the dry streambed of a tributary of Pascack Brook. Photographs by the author.

to aquifer discharge areas, how deeply incised the streams are, and drainage-area size may also be important factors in some areas. Deep incisement potentially means greater head differential between surface water and groundwater and more impetus for groundwater discharge.

Three sets of streamflow measurements were made under base-flow conditions during 2005–06 at a subset of sites from the early 1960s streamgage network. Flow-duration values associated with each set of measurements were determined from the 1985–94 and 2006–07 duration curve from the Mahwah River near Suffern, NY, streamgage (no streamflow data collection from 1995-2005). The Mahwah River duration statistics give a general idea of flow statistics for the other streams, although duration characteristics are likely different among Rockland County streams because of differences in physical drainage-basin characteristics, levels of suburban development, and precipitation. Percent exceedance refers to the percentage of daily average flows that exceed a particular streamflow during a given year. For example, the 95-percent exceedance flow is exceeded by 95 percent of the daily average flows in a given year, and the 50-percent exceedance flow is the annual median flow, exceeded by 50 percent of flows. Measurements in March and July 2006 represented nearly the same percent exceedance flows (71 and 73 percent, respectively), and the September 2005 measurements represented about 99-percent exceedance flows. The measurements made in this study and corresponding 71-, 73- and 99-percent exceedance flows from 1961 duration curves from each streamgage (Ayers and Pauszek, 1963) are shown in figure 42. Flows are expressed as flow per unit area (cubic feet per second per square mile of drainage area) to facilitate comparisons with 2005–07 data. General differences in drainage rates within and among surveys are described in the following paragraphs.

The March 2006 measurements (about 71-percent exceedance flow at the Mahwah River streamgage) show distinctly higher flow rates (about 0.8 $ft^3/s/mi^2$) in the higher precipitation areas in the north-northwest of the county (Cedar Pond Brook and its tributary, the Lake Tiorati Brook, the upper Hackensack River and its tributary, the Demarest Kill) and at Saddle River than in the south-southeastern areas (about 0.6 $ft^3/s/mi^2$) of lower precipitation (Pascack Brook at Pearl River, Nauraushaun Brook, and Sparkill Creek at Tappan (figs. 42 and 5). Mahwah River flow was lower than at other drainages with contributions from the Highlands; this was likely because of groundwater withdrawals. Saddle River, a small headwater drainage in the south-central part of the county, had higher flows per square mile than other nearby drainages. The downgradient, low-altitude position of the Saddle River in the permeable aquifer zone B and the high degree of incisement of the main-stream channels favor groundwater discharge from the aquifer. Pine Brook, another headwater tributary of the Saddle River drainage (fig. 5), had consistently lower unit flows than Saddle River in every survey. This stream is about one-third less incised than Saddle River and is downgradient from the Spring Valley well field (fig. 32). Withdrawals from this well field have shifted the

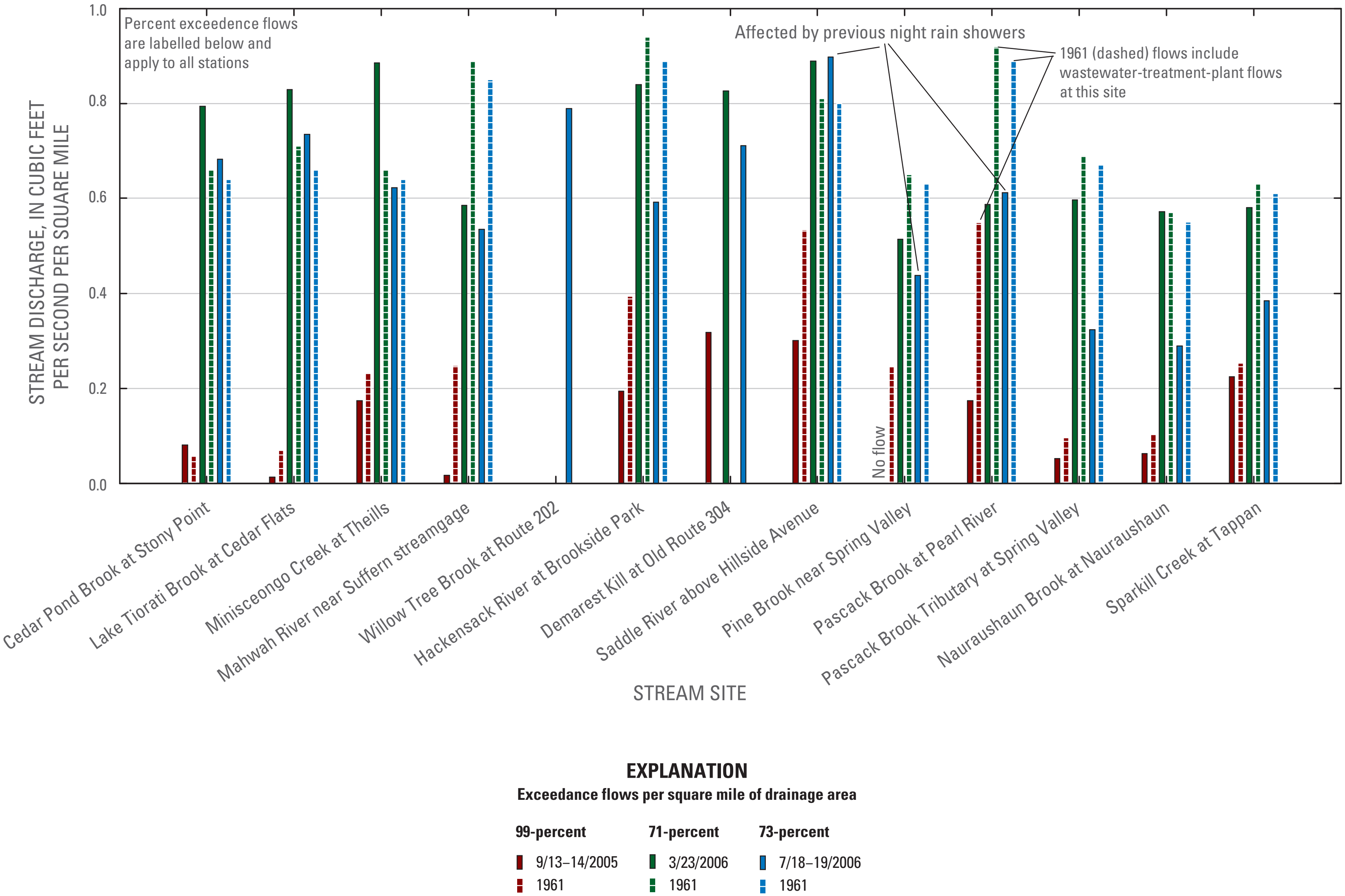


Figure 42. Streamflow measurements, expressed as flow per square mile of drainage area from 2005 to 2006 at formerly gaged sites and corresponding 71-, 73- and 99-percent exceedance flows from 1961, Rockland County, New York. Exceedance statistics for streamflow measurements were determined from 1985–1994, 2006–2007 streamflow data from the Mahwah River near Suffern, New York streamgage.

local groundwater divide south, which has likely decreased the amount of groundwater discharge to the Pine Brook drainage.

Similar within-survey differences in flow rates among streams were measured in the July 2006 survey (73-percent exceedance), except (1) the flow rate at the Mahwah River was similar to flow rates in the other drainages with Highlands flow contributions and in the upper Hackensack River, and (2) flow at three south-southeastern streams were increased by local rain showers (noted in fig. 42).

Flow measurements in September 2005 represented 99-percent exceedance flows—the lowest flow measurements during the study. This was also a period of large groundwater withdrawals. Streams with the highest flow rates (about 0.2–0.3 $ft^3/s/mi^2$) were in the Newark basin lowlands in areas with few production wells (upper Hackensack River and upper Sparkill Creek) or incised drainages (lower Pascack Brook and Saddle River). The lowest flow rates were associated with the Highlands (Lake Tiorati Brook), where aquifer storage is limited, and the Mahwah River and Pine Brook (dry), where groundwater withdrawals are substantial within or upgradient from the drainage areas.

The same flow exceedances (71-,73-, and 99-percent) were compiled from the 1961 flow data (Ayer and Pauszek, 1963) and included in figure 42. These flow rates are not directly comparable because (1) 1961 was a drier year during June through October than all but 2 years used for the duration statistics, although 2005 had the driest late-summer period and (2) the 1961 duration statistics were derived from streamgage data from each stream rather than extrapolated from the Mahwah River only. The 1961 71- and 73-percent exceedance flow rates are, in general, 0.5 to 0.65 $ft^3/s/mi^2$ across much of the county, with the exception of higher flow rates (about 0.8 $ft^{3/s}/mi^2$) from the Mahwah River, Hackensack River, and Saddle River drainage areas. The high flow rates at Pascack Brook at Pearl River are attributed to additional flows from the former Spring Valley wastewater-treatment plant (Ayers and Pauszek, 1963). The 1961 71- and 73-percent exceedance flow rates are generally within the range of the March and July 2006 flows of the same exceedance; streams with drainage areas in the uplands (Highlands) were most similar to the July 2006 flow rates and streams that drain the Newark basin lowlands were more similar to those from March 2006.

The 99-percent exceedence flows of 2005 are generally lower than those of 1961 by about 0.2 $ft^3/s/mi^2$. Exceptions include similar 1961 and 2005 flows at Cedar Pond Brook, Lake Tiorati Brook, Minisceongo Creek, Pascack Brook tributary at Spring Valley, Nauraushaun Brook, and Sparkill Creek at Tappan. Increases in groundwater withdrawals since 1961, paired with dry conditions in September 2005, are the likely cause of the lower 99-percent exceedance flows in 2005.

In summary, areas with the highest rainfall have the highest base flows under 71- and 73-percent exceedance flows. The Highland area of the county and the northern part of the Newark basin constitute the area of highest precipitation. During base-flow periods of about 99-percent exceedance flow, flows from Highland areas are among the lowest because there is less storage and steeper topography in the Highlands than in the Newark basin lowlands. Groundwater withdrawals within or near stream drainage areas may also reduce base-flow rates, and industrial and municipal discharges to streams increase flows. Deeply incised streams in the Newark basin, especially those that drain the most permeable bedrock (aquifer areas B and C), are likely to have more sustainable and higher base flows than areas with the opposite characteristics. Base flows of 71- and 73-percent exceedance in 1961 and 2006 are comparable. Base flows of about 99-percent exceedance were generally lower in 2005 because of particularly dry conditions in August and September of that year. These general differences reflect year-to-year variations in precipitation rather than any long-term trend. The greatest differences between 1961 and 2005 flow rates are either because of increased groundwater withdrawals and amount of impervious surface since 1961 or decreased municipal or industrial discharges to streams. Changes resulting from increased groundwater withdrawals are most easily observed during periods of lowest base flow.

Mahwah River Streamflow

The Mahwah River near Suffern streamgage is the only long-term, unregulated streamgage in the county (1959–1995, 2006–present). The drainage area (12.3 mi^2) is underlain by about equal parts of Newark basin sedimentary rock and Highlands igneous and metamorphic rock. The Newark basin part of the drainage area has undergone residential development over the period of flow measurement, while the Highlands part has remained predominantly forested parkland. Thus, the effects of development are less extreme than in fully developed drainage areas such as Saddle River and Pascack Brook, which have been gaged since 2005.

The period of record at the Mahwah River near Suffern streamgage is depicted with percent-exceedance statistics from each full year of record and with corresponding precipitation data (fig. 43).

Comparison of flow data and precipitation data indicate that variations in the amount, distribution, and intensity of precipitation are the dominant controls on annual streamflow statistics. Effects of development within the drainage area are largely discernable only at the extremes of the annual flow regime. Increases in groundwater withdrawals, installation of sanitary sewers that route pumped water out of the drainage area, and increased impervious surface area are the primary hydrologic changes associated with development.

Withdrawals from bedrock wells in the drainage area and one alluvial well field (UWNY 42A and UWNY 54A), about 3.1 mi upstream, has increased over the years, but the effects on streamflow are muted and only distinguishable during the lowest flows of the year. The mid-1960s drought is the driest period on record, with the lowest summer rainfall totals (fig. 43); minimum daily flows and 95-percent exceedance flows were between 0.5 and 2.0 ft^3/s. This period was used for comparisons with subsequent years. If more recent flows

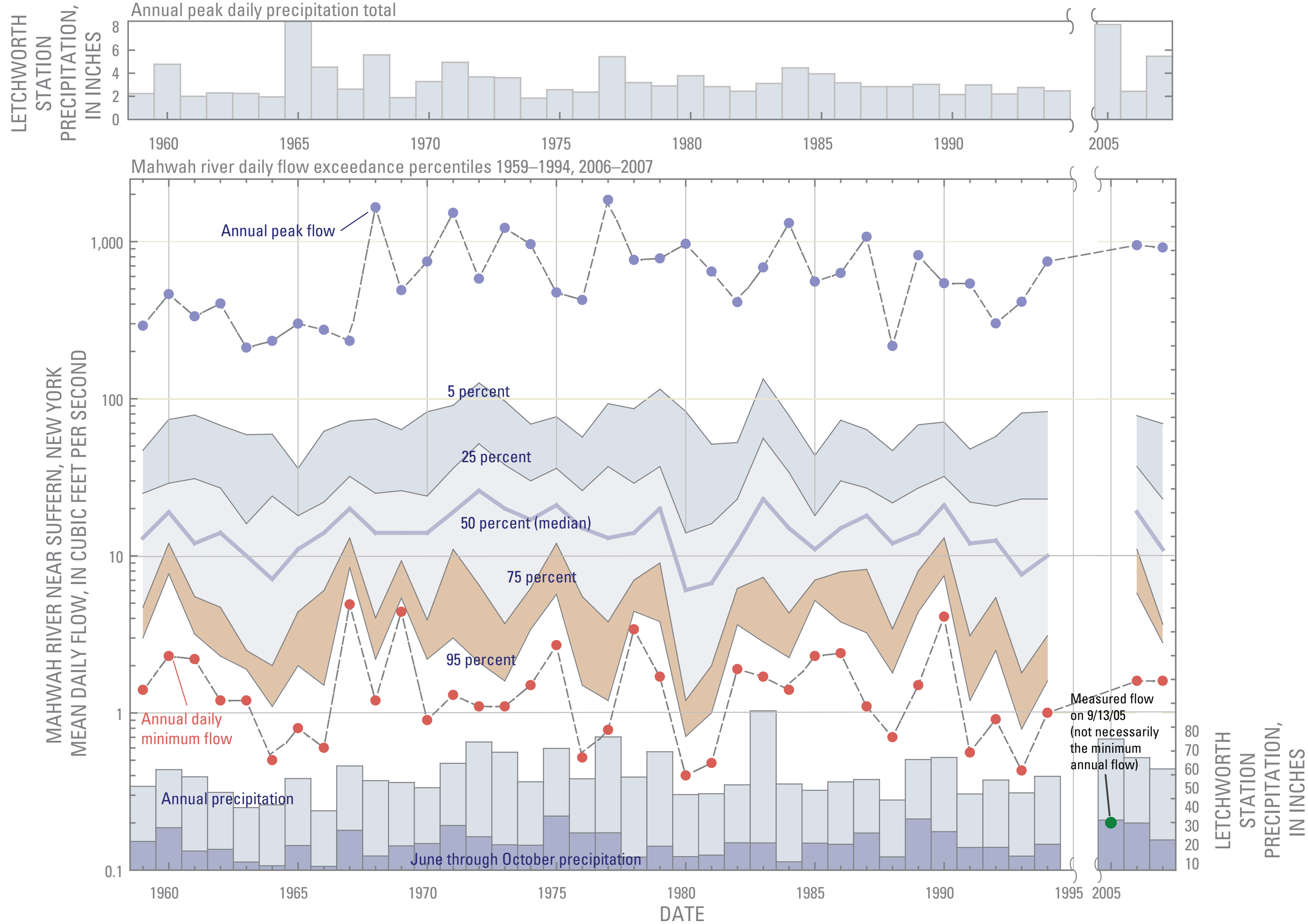


Figure 43. Annual (1959–94, 2006–2007) percent-exceedance statistics for the Mahwah River near Suffern, New York, streamgage and corresponding precipitation data from the Letchworth streamgage, Rockland County, New York.

equal or exceed flows from the drought, changes other than rainfall amount are indicated. In fact, figure 43 indicates that low flows similar to those of the 1960s drought have occurred during 1976, 1977, 1980, 1981, 1988, 1991–94, and in 2005[3]. Flows from 1995–2005 were not measured. All of these low flows occurred during years and summers with more rainfall than during the 1960s drought; 1977 rainfall exceeded 60 in.

Flow maintenance in the Mahwah River is important from a water-resource standpoint because downstream alluvial wells depend on the river as a source of water. The two high-capacity alluvial well fields (UWNY 27 and UWNY 29A) downstream from the streamgage appear to have a major effect on flow in the Mahwah River. Streamflow records from a short-term streamgage (Mahwah River at Suffern, NY, 2.4 mi below the long-term streamgage), active in 1960 and 1961 and with sporadic measurements since, indicate either a lack of flow increase or a decrease in flow below the alluvial wells about 1.1 mi downstream from the long-term streamgage. The first alluvial well went on line in 1961 and pumped an average of 630 gal/min (1.4 ft^3/s) that year. Comparison of duration curves for 1960 and 1961 among the two Mahwah River streamgages indicates substantially lower flows in 1961 than in 1960 at the downstream streamgage relative to the upstream long-term streamgage. Flow exceedances of 90 percent or greater at the downstream streamgage were 1.5 to 5 ft^3/s lower in 1961 than in 1960, whereas those at the upstream streamgage were 0.2 to 1.0 ft^3/s lower in 1961 than 1960.

Comparison of the average daily flow at the long-term Mahwah River streamgage with a streamflow measurement made at the lower streamgage site on Oct. 13, 1982, when both wells UWNY 27 and UWNY 29A were in service, showed a downstream decrease of 3.45 ft^3/s in Mahwah River flow, despite a drainage area that is 70 percent larger. The average pumping rate from both well fields during that year was 617 gal/min (1.37 ft^3/s). The summer pumping rate was likely higher because this was an annual average. For comparison, the average pumping rate from these wells was 1,027 gal/min (2.29 ft^3/s) the next year (1983).

Increased impervious surface area (about 3.6 percent in 2005) has increased peak flows since the late 1960s (fig. 44). Comparison of stream stage (height of water in the streambed) and peak flows between 1961 and 2004 from 1 in. of rainfall indicated a more pronounced hydrograph peak and higher flows in the 2004 storm (fig. 44). The two storms occurred at the same time of year and had similar antecedent rainfall conditions.

Increases in annual peak flows in the Mahwah River are also depicted in figure 43. Annual peak flows increased from an average of about 305 ft^3/s from 1959 to 1967 to

[3] The 9/13/2005 low-flow measurement of 0.2 ft^3/s is the lowest recorded streamflow at this site (apart from an artificially low October 1971 flow that was affected by pumping from the stream at the streamgage site).

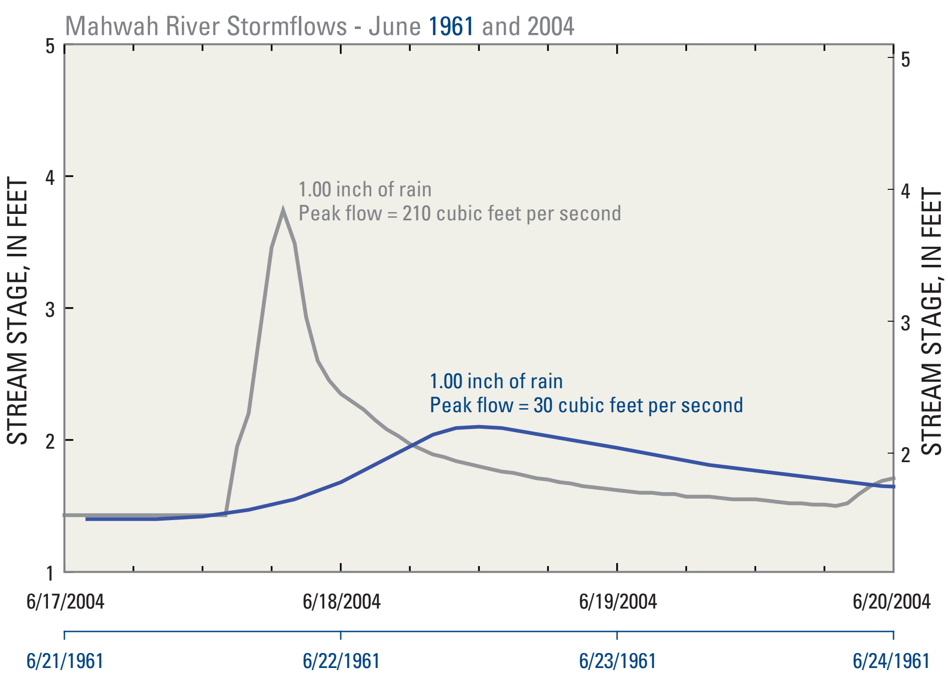


Figure 44. Hydrographs of two storms of similar magnitude with similar antecedent conditions (1961 and 2004) recorded at the Mahwah River near Suffern, New York streamflow-measurement gage, Rockland County, New York.

about 801 ft^3/s from 1968 to 1994 (fig. 43). This increase is largely in response to regional climatic conditions; peak-flow data from other streamgages in southeastern New York show similar patterns. Smaller increases in peak flow from increases in impervious surface area are indicated in figure 44 but are not discernable in the figure 43 peak-flow data.

Another approach to discerning subtle changes in flow regime at the long-term Mahwah River streamgage was to minimize annual climatic differences by comparing the distribution and frequency of daily average flows among years with similar total and June through October rainfall. The year 1961 was chosen as the reference year for comparison because it was (1) prior to initiation of pumping (1967) at the upgradient alluvial well field (wells 42, 54); (2) prior to the mid-1960s drought; and (3) the year of most widespread collection of surface-water data in the county.

Total precipitation in 1961 was 49.14 in., and June through October rainfall was 17.99 in. (Letchworth precipitation station). The years 1978, 1986, 1992, and 1994 were selected for flow comparison because their annual and June through October precipitation totals and storm intensity and distribution were similar to those of 1961 (fig. 43).

Daily flows from each year were ordered from lowest to highest and plotted on a semi-log plot as a function of the number of daily flows during the year (or percent daily flows per year) a selected daily flow exceeds (fig. 45). Both magnitude of flows and flow-frequency trends illustrate flow differences, particularly between 1961 and the other years.

The distribution of flows in 1961 is characterized by a long log-linear trend from the lowest flow (2.2 ft^3/s) to flows of nearly 30 ft^3/s for 270 days of the year (73 percent of daily flows); the magnitudes of these flows were about mid-range of those from the other years. Only one other year (1978) exhibited a single linear trend in this range of flows, likely in response to greatly reduced pumping at the upgradient alluvial well field during the 1970s and a preceding year with the second highest annual precipitation (fig. 43). All other annual trends in this range of flows are characterized by two or three linear segments, with those between flows of 8 and 30 ft^3/s typically more frequent (more days, lower slopes) than those of 1961. Flows less than about 8 ft^3/s were typically less frequent (fewer days of flow within the range) than those in 1961 but had steeper slopes (more rapid and greater declines in low flows) than 1961, no matter the magnitude of flow. The higher decline rates below 8 ft^3/s nearly paralleled one another (fig. 45) and occurred at least as far back as 1968 (not shown in fig. 45). Flows within this range are most indicative of changes in flow regime in the Mahwah River as development and groundwater use have increased in the Mahwah River drainage area. The lowest flows among the years depicted occurred in 1992 and 1994.

Ordered flows between 30 and 80 ft^3/s are characterized by a nearly log-linear trend in 1961 data that represent higher flows and greater frequencies (77 days or about 20 percent of daily flows) than in all other years except 1978. The minimum flow frequency within this range was only 31 days (9 percent of daily flows) in 1992. Ordered flows greater than 80 ft^3/s are similar to one another, except for the magnitude of maximum flows, which was greatest in 1978.

Stream Survey, September–October 2005

A low-flow survey of Rockland County streams on or adjacent to the Newark basin aquifer was performed between September 7 and October 5, 2005, to (1) document flow conditions under a dry summertime period of high groundwater-withdrawal rates, and (2) evaluate the degree of interconnection between groundwater in the bedrock aquifer and streams. Streamflow at each site was estimated visually as a range of flow (see “Methods of Investigation” section), rather than a single value (fig. 46), and specific conductance of the water was measured at 239 sites (fig. 47). Specific conductance is a measure of the overall concentration of ions or the mineral content of water. Specific conductance parallels chloride concentrations in most areas of Rockland County; differences are most likely where dissolved carbonates contribute substantially to ion concentrations.

Streamflow across the county was particularly low during the survey period because rainfall was minimal, ranging from 0.78 to 1.56 in. at stations in the area (United Water New York, written commun., 2006). Streamflow during dry periods is largely sustained by groundwater discharge. Thus, streamflow and specific-conductance data reflect shallow groundwater conditions.

Dry streams indicate that shallow groundwater levels are below the bottom of the streambeds. Dry streams were most common (1) where storage in bedrock is limited and hillsides are steep, such as the igneous and the metamorphic rocks of the Palisades sill and the New York–New Jersey Highlands adjacent to the Newark basin aquifer, and (2) in the Newark basin aquifer, where groundwater withdrawals have lowered groundwater levels in aquifer zones B and C (figs. 30, 31). Areas of dry streams over the Newark basin aquifer are highlighted in figure 46.

Streams on the northeast side of groundwater divide A maintained a greater degree of flow than streams on the southwest side (fig. 46). Streams in two areas adjacent to the middle section of Lake DeForest were dry, but most of the Hackensack River drainage upstream from Lake Deforest and underlain by the Newark basin aquifer had flow. Groundwater levels on the northeast side of groundwater divide A are closer to land surface and have small seasonal fluctuations. Groundwater withdrawals from production wells are small relative to those on the southwest side of groundwater divide A.

The two largest areas of dry streambeds on the southwest side of groundwater divide A (fig. 46) coincide with the greatest densities of well fields. These areas cover nearly the same area as those areas with seasonal groundwater levels that fluctuate more than 10 ft (fig. 31). The larger of the two areas covers the majority of aquifer zone B (fig. 11) and includes several incised headwater tributaries of Saddle River

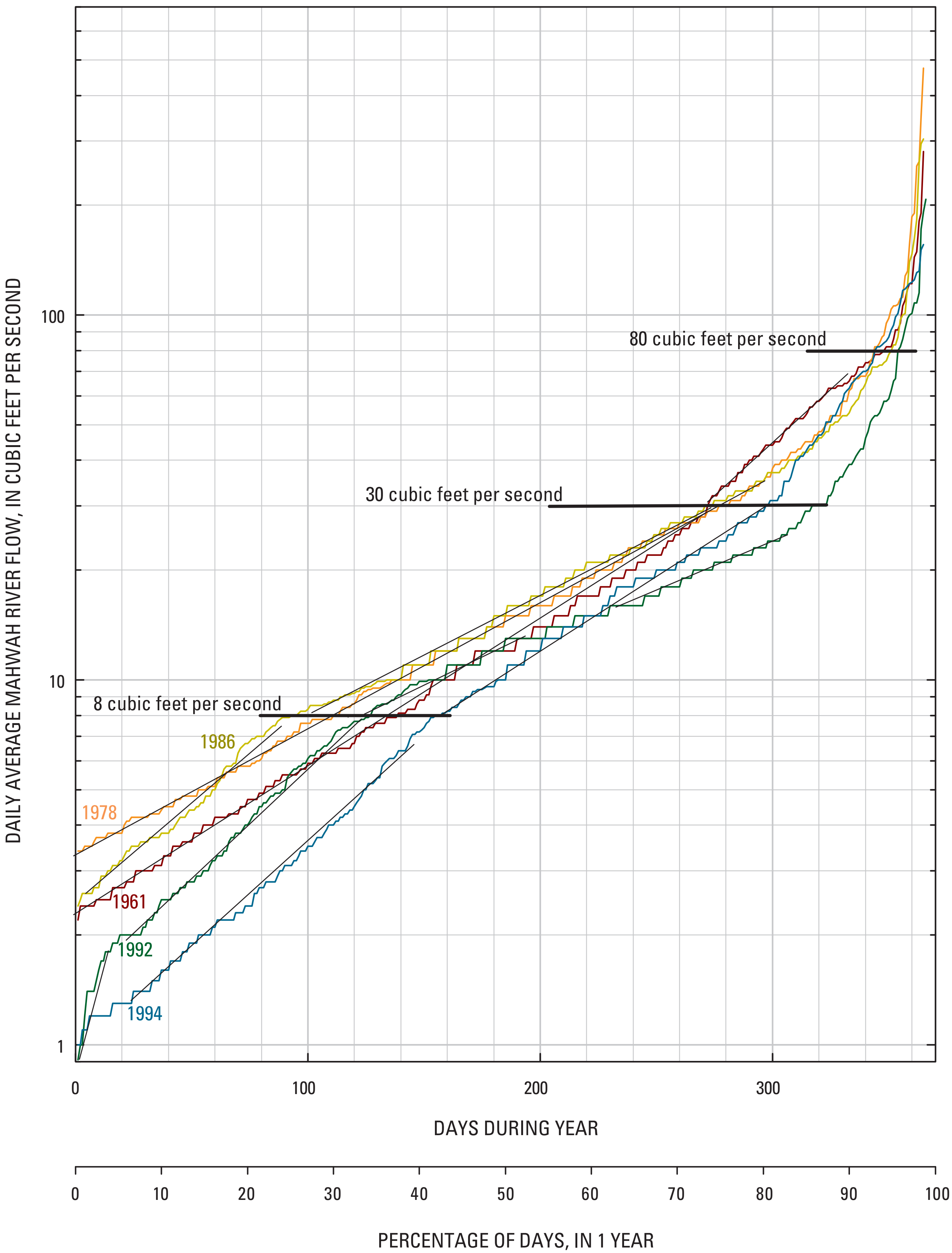


Figure 45. Ordered daily flows from 1961 and years with similar precipitation (1978, 1986, 1992, and 1994) from the Mahwah River near Suffern, New York, streamflow-measurement gage, Rockland County, New York.

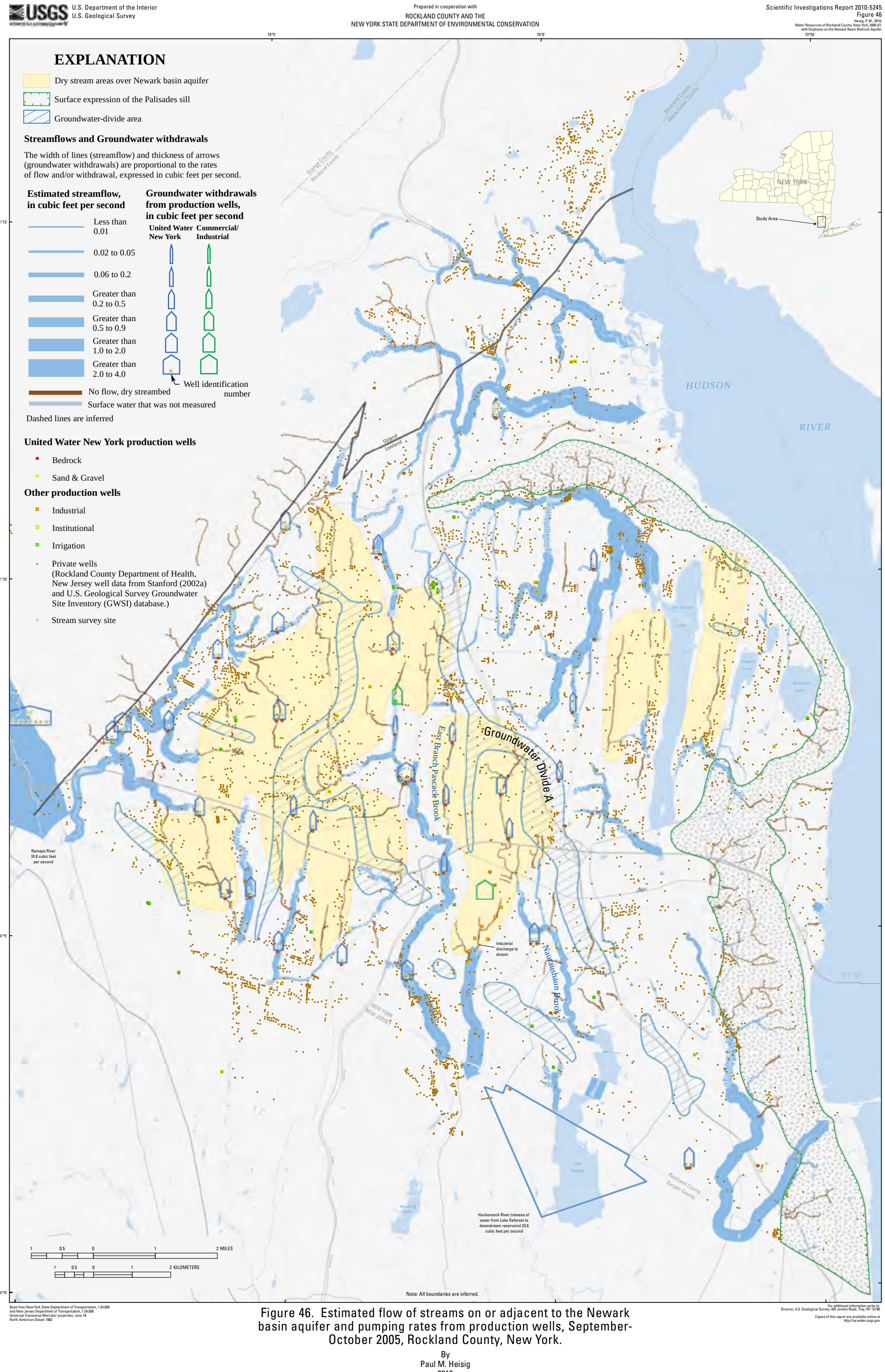


Figure 46. Estimated flow of streams on or adjacent to the Newark basin aquifer and pumping rates at production wells, September–October 2005, Rockland County, New York. (Click to view full-size map at http://pubs.usgs.gov/sir/2010/5245/plates/Figure46.pdf)

and Pascack Brook. The second area overlies aquifer zone C (fig. 11) and includes large upper reaches of Nauraushaun Brook and the incised main stem of East Branch Pascack Brook. The absence of flow in large streams coinciding with high summertime groundwater withdrawals in the same areas is strong indication of the interconnection of groundwater and surface water.

Values of specific conductance in low streamflow compared with values in groundwater also indicate strong interconnection of bedrock groundwater with stream base flow. The specific conductance and estimated flow of streams and the specific conductance of groundwater are depicted in figure 47. A strong correspondence between specific conductance of low streamflow and that of the underlying or upgradient groundwater is indicated. Stream specific conductance in headwater reaches is typically within the same range of specific conductance as the underlying shallow groundwater. Specific conductance in downstream reaches may also match but more commonly shifts toward the specific-conductance range of the underlying groundwater.

The distribution of specific conductance in streamflow and groundwater (fig. 47) shows a strong connection with land use (major roadways and road density (see fig. 1)). Most areas of elevated specific conductance are associated with major roadways, particularly the Thruway and the Palisades Parkway. Areas of high local road density, such as Spring Valley, also have elevated specific conductance. Specific conductance and chloride concentrations parallel one another (see fig. 37).

Effects of Impervious Surfaces on Streamflow

The addition of impervious surfaces to a watershed generally increases the volume of stormflow and decreases the volume of base flow in streams (U.S. Department of Agriculture, Forest Service, 2002; Seaburn, 1969; Waananen, 1961; Stankowski, 1974). Peak stormflows increase where drainage infrastructure connects impervious surfaces to streams. Reduction of infiltration also translates to reductions of ET from vegetation, soil moisture, and groundwater recharge. Reduced groundwater recharge decreases groundwater levels in the aquifer and results in less groundwater discharge to streams, which sustains stream base flow during dry periods.

Types of impervious surface range from roadways, buildings, and parking lots to individual homes, driveways, and sidewalks. Data on these types of impervious surfaces were available for Rockland County, but not all types were considered in the following analysis. The degree of connection between impervious surfaces and drainage infrastructure was used as a guide to select which types of surface to include in the calculation of percentages of impervious surface in watersheds. Roadways, parking areas, buildings (including interconnected homes or businesses), and associated paved areas are included in calculations of percent impervious-surface area. If impervious surfaces are isolated, runoff from the surfaces may be only locally diverted to adjacent land surfaces where infiltration into the soil zone and replenishment of groundwater may occur. Freestanding homes, sidewalks, and driveways were excluded from impervious-surface totals, although exceptions regarding connection with drainage infrastructure were noted. Selection of the aforementioned types of impervious surfaces also facilitates working with datasets in adjacent areas of New Jersey where information on impervious surfaces was limited.

A preliminary evaluation of effects of impervious surface on stormflow peaks and volume was carried out with data from three gaged watersheds with different percentages of impervious-surface area in Rockland County, NY, and Bergen County, NJ (fig. 1). The three gaged sites, their drainage area, and impervious-surface area (roads, large buildings, and associated parking areas) are listed in table 5.

A storm in November 2005 was selected to illustrate the differences in responses to storms at the three gaged sites (fig. 48). The Pascack Brook hydrograph shows a rapid rise and fall and the highest peak flow from the storm, and the Saddle River hydrograph is also responsive with a somewhat lower peak flow. The Mahwah River hydrograph is least responsive with a low peak followed by sustained flows more than double those at the other two streamgages. The Mahwah River hydrograph is indicative of more recharge than the other two hydrographs. The inset plot in figure 48 shows a positive correlation between peak stormflows and impervious-surface area. Peak flows at Pascack Brook and Saddle River were 2.3 and 1.7 times higher than the peak flow at the Mahwah River streamgage. The flow data from each streamgage in figure 48 are plotted as flow per unit area for direct comparison of the hydrograph responses. Basin shape also affects the shape of hydrographs—equidimensional watersheds are likely to show responsive hydrographs with relatively sharp well-defined peaks, and long, narrow watersheds are likely to show lower peaks and more sustained higher flows (Strahler, 1964). Impervious surfaces can rapidly route stormwater to streams and fundamentally change the shape of hydrographs (Leopold, 1968). The Mahwah River hydrograph is most like that of an undeveloped elongated basin, with minimal change imparted by a low percentage of impervious surface area. The Saddle River watershed is equidimensional, so increased impervious surface serves to heighten the rapid response and magnitude of stormflow peaks. The Pascack Brook watershed is the narrowest and longest of the three, yet its storm hydrograph is as responsive as that of the Saddle River, its storm peak is the highest, and recovery to base-flow conditions is rapid. Apparently, the high percentage of impervious surface applied to this watershed has changed storm hydrographs from something initially similar to that observed at the Mahwah River to something that approximates a more equidimensional watershed like that of the Saddle River. Routing of stormflow from impervious surfaces has greatly reduced stormflow traveltimes from the upper reaches of the watershed and increased stormflow volumes.

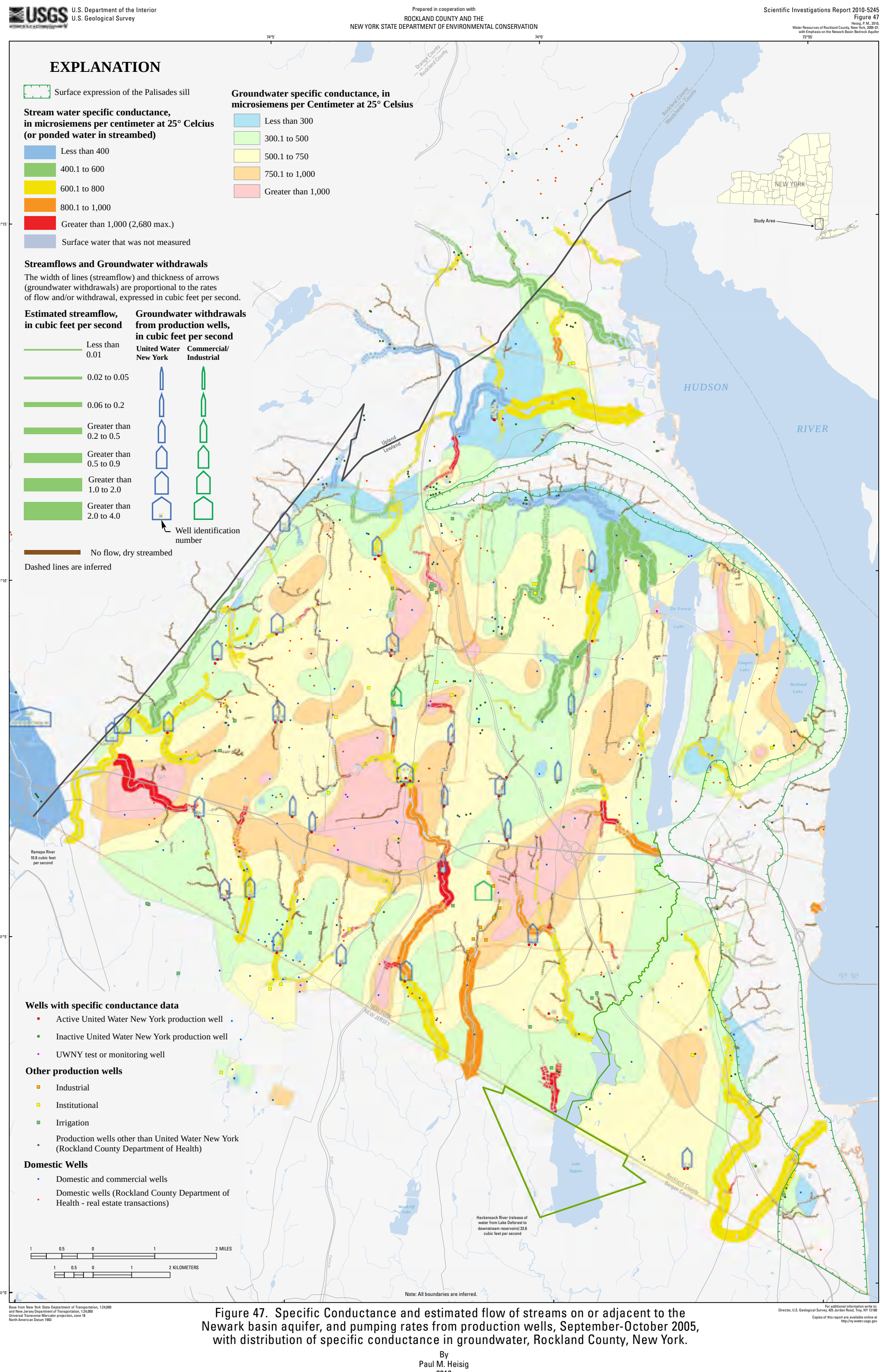


Figure 47. Specific conductance and estimated flow in Rockland County streams on or adjacent to the Newark basin aquifer and pumping rates at production wells, September–October 2005, with distribution of specific conductance in groundwater, Rockland County, New York. (Click to view full-size map at http://pubs.usgs.gov/sir/2010/5245/plates/Figure47.pdf)

Table 5. Characterisitics of currently gaged watersheds, rainfall-runoff coefficients for selected 2004 to 2006 storms, and estimated annual stormflow volume increases in each watershed, Rockland County, New York and northern Bergen County, New Jersey.

[ID, identification; mi, mile; mi², square mile; ft, feet; ft³, cubic feet]

Streamgage (site ID)	Drainage area (mi²)	Impervious area[1] (percent watershed area)	Average basin slope (ft/mi)	Basin storage[2], (percent watershed area)	Basin forested area (percent watershed area)	Maximum linear watershed distance from streamgage (mi)	Rainfall-runoff coefficient (storm runoff as fractional percentage of rainfall volume)		Annual Stormflow 2005–2006 average[3] (inches) (PART Program)	Increase in storm runoff per year over the watershed area			Increase in storm runoff per year per square mile	
							Median low-intensity storm	Median high-intensity storm		Depth in Inches	Millions of cubic feet	Millions of gallons	Millions of cubic feet	Millions of gallons
Mahwah River near Suffern, NY (01387450)	12.3	3.6	13.27	3.08	61.3	5.9	0.03	0.18	9.0	0.1	2.86	21.4	0.23	1.74
Saddle River at Upper Saddle River, NJ (01390450)	10.9	11.9	6.34	0.55	15.3	4.5	0.09	0.25	10.9	0.8	20.3	151.5	1.86	13.9
Pascack Brook at Park Ridge,NJ (01377370)	13.4	17	5.73	0.75	12.6	8.1	0.15	0.34	13.4	1.7	52.9	395.9	3.95	29.54

[1]Impervious surface area is the percentage of land area composed of roads, large buildings and associated parking areas.

[2]Basin storage is the percentage of lake, pond, and wetland area.

[3] Mahwah River annual stormflow from 2006 only.

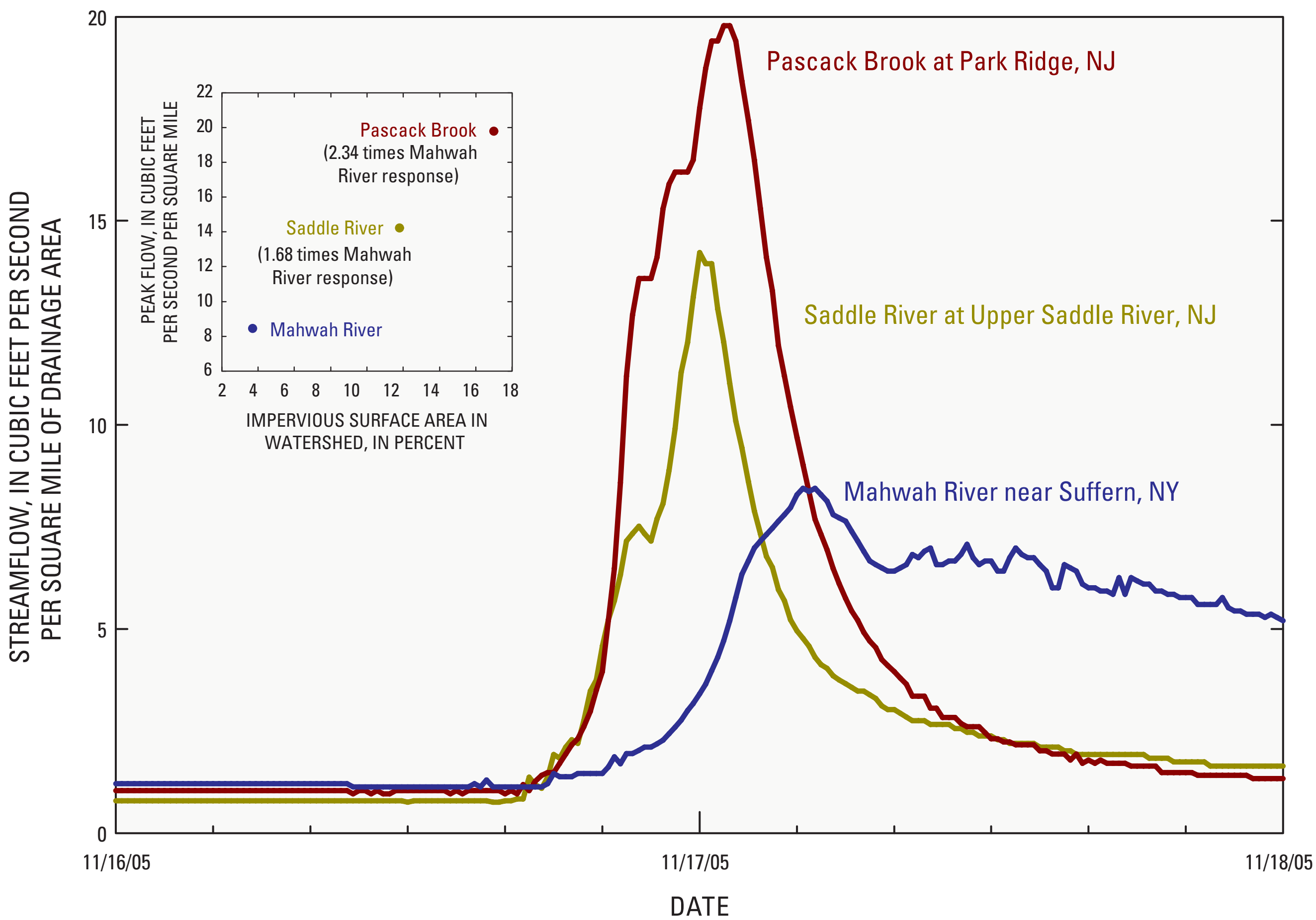


Figure 48. Comparison of storm hydrographs, in flow per square mile, from three watersheds with different percentages of impervious surface, November 2005, Rockland County, New York, and northern Bergen County, New Jersey.

The low, drawn-out stormflow peak recorded at the Mahwah River streamgage is likely a function of several aspects of the drainage area in addition to impervious-surface area and the shape of the drainage area. The Mahwah River drainage has four to five times the basin storage area (lakes, wetlands) and forested area of the other two basins. Both these characteristics slow the movement of stormwater within a drainage area. However, these characteristics are offset an unknown amount by an average basin slope that is more than double that of the other two drainage areas.

The uneven recession at the Mahwah streamgage was caused by the periodic burial of the orifice pipe by stream sediments. This pipe connects the stream to the streamgage, and high stream-stage readings result when it is buried. The true recession generally follows the troughs of the recorded recession.

Differences in stormflow volume, in relation to total storm-event rainfall, were evaluated at each of the streamgages. Manual hydrograph separations were performed on about 20 storm events from each gaged basin (2004–05; unpublished data from Mahwah near Suffern streamgage), and stormflow volumes were calculated. Rainfall volumes were also compiled from nearby precipitation gages. The fractional percentage of rainfall volume represented by stormflow volume was determined for each storm event at each basin. This measure is termed the rainfall-runoff coefficient. Rainfall-runoff coefficients ranged from about 0.01 to 0.42.

Examination of the results indicated that stormflow volumes increased with impervious-surface area by as much as 13 to 17 percent but also that the highest rainfall-runoff coefficients were from large, intense storms (rainfall accumulations over 0.25 in. per 15 minutes) that could raise rainfall-runoff coefficients about 15 percent above those from less-intense storms. The Pascack Brook streamgage is equipped with a precipitation gage that records at 15-minute intervals. Rainfall-runoff coefficients of intense storms were about 15 percent higher than from less-intense storms at all streamgages, regardless of, and in addition to, any effects of impervious-surface area (fig. 49). Intense storms produced peak stormflows of greater than or equal to 150 ft^3/s at the Mahwah River streamgage, 350 ft^3/s at the Saddle River streamgage, and 450 ft^3/s at the Pascack Brook streamgage.

Annual stormflow volumes for 2005 and 2006 were determined at each basin with the hydrograph-separation software program PART (Rutledge, 1998). The average values are shown in table 5.

The Mahwah River gaged area has only 3.6 percent impervious-surface area, and an estimated 2.9 percent of low-intensity rainfall becomes stormflow. If 2 percent is chosen as the gaged-area response under conditions of no impervious surface, increases in rainfall-runoff coefficients of rainfall relative to impervious surface can be determined (fig. 49).

Likewise, if high-intensity storms generate rainfall-runoff coefficients of about 0.17 at drainage areas with no impervious surface (1 percent less than in the Mahwah River gaged area), increases over natural conditions can be estimated. Percentage increases over natural conditions are generally consistent over both high- and low-intensity storms in the Mahwah and Saddle River watersheds but increase an additional 4 percent in the most impermeable watershed (Pascack Brook) during high-intensity storms (fig. 49).

Percentage increases of low- and high-intensity storms for each gaged basin were averaged and then used to estimate the annual increases in storm runoff in response to impervious-surface area. The fractional percentage of runoff increase was estimated by determining the average number of low- and high-intensity storms over 2 years of record (2004–05) and then calculating the additional annual percentages of stormflow. Annual storm runoff for each watershed was calculated with the software program PART (Rutledge, 1998) and is listed in table 5. Annual storm runoff values were divided by one plus the fractional percentage of runoff increase to get the zero percent impervious-surface runoff value. This value was then subtracted from the annual storm runoff value to obtain the runoff increase, in inches per square mile, at each gaged basin. The estimates of increased runoff in each watershed are Mahwah River, 0.1 in.; Saddle River, 0.8 in.; and Pascack Brook, 1.7 in. table 5. The changes at the watersheds in different units are listed in table 5. These values were then plotted against the corresponding percentage impervious areas in figure 50. A linear regression line was fitted to the data. The increases in stormflow runoff with increases in impervious surface provide an indication of the magnitude of change that has occurred or can be expected within watersheds or other land areas. These estimates are from relatively wet years and variations in the distribution and amount of rainfall and the number of high-intensity storms each year could result in substantial variation in the amount of additional runoff produced by impervious surfaces.

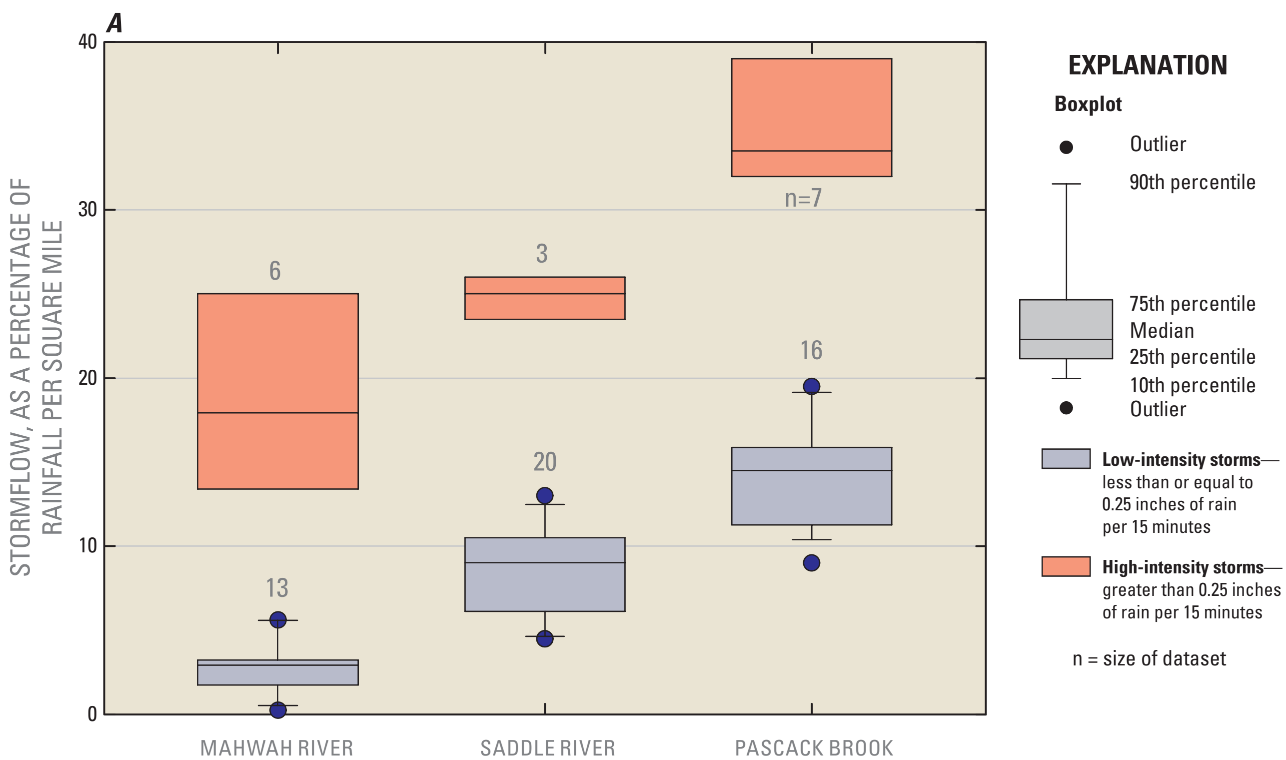
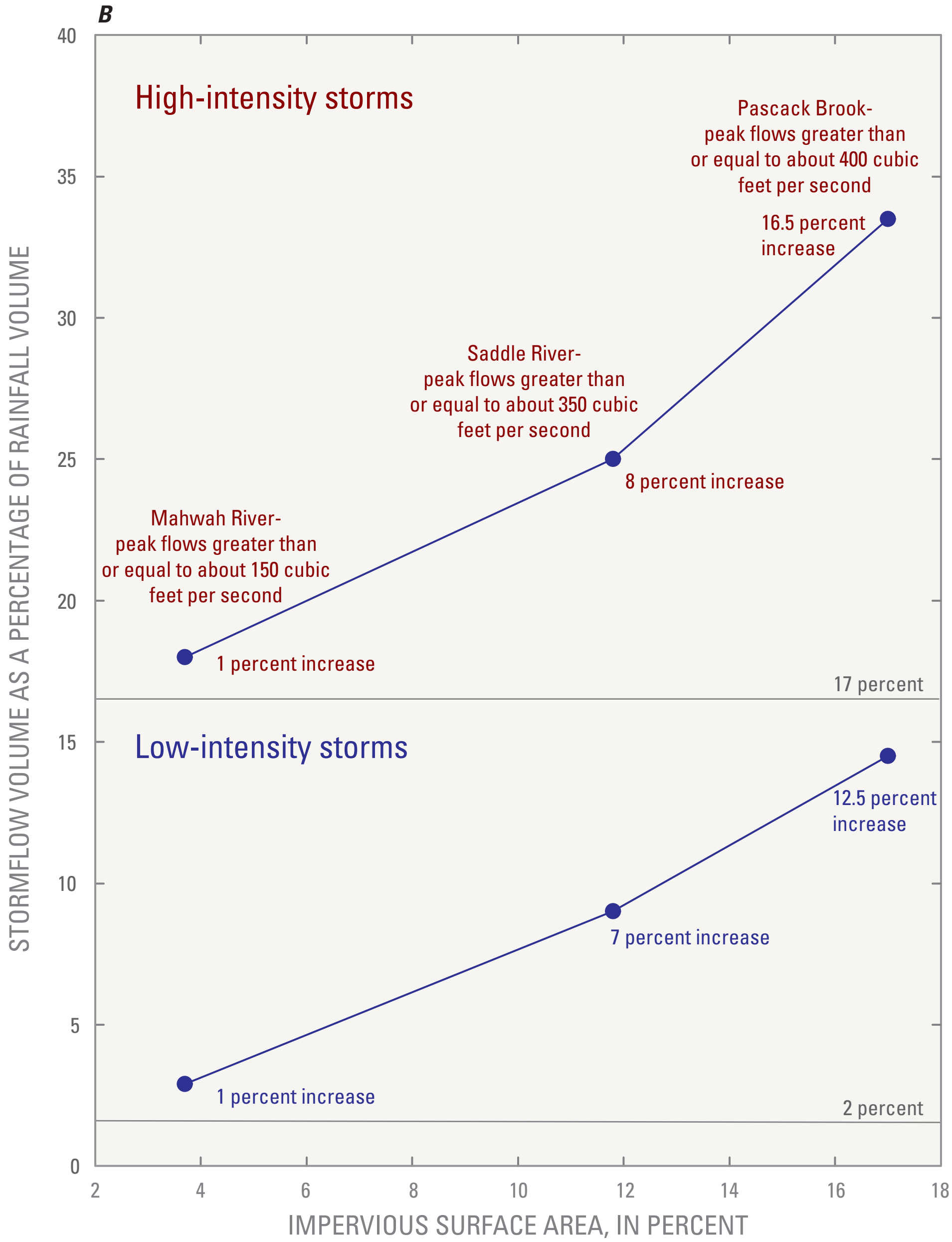


Figure 49A. Rainfall-runoff coefficients from 2004–2005 storms at three gaged watersheds in Rockland County, New York, and northern Bergen County, New Jersey: *A,* boxplots of rainfall-runoff coefficients, *B,* average rainfall-runoff coefficients as a function of percent impervious surface.



Mahwah gage:
Low-intensity storm median volume= 52,800 cubic feet
High-intensity storm median volume= 458,400 cubic feet
(8.7x increase)

Figure 49B. Rainfall-runoff coefficients from 2004–2005 storms at three gaged watersheds in Rockland County, New York, and northern Bergen County, New Jersey: *A,* boxplots of rainfall-runoff coefficients, *B,* average rainfall-runoff coefficients as a function of percent impervious surface.

Increased storm runoff does not translate to lost recharge only; rapid routing of stormwater from impervious areas also eliminates or decreases ET that could have occurred in those areas. Therefore, a general approximation of 50 percent of the increase in storm runoff is potential recharge that has been prevented from infiltrating into the subsurface. For example, the Newark basin aquifer south of South Mountain covers about 80.7 mi^2 and has about 12.6 percent impervious surface area. Substituting 12.6 into the regression equation from figure 50 indicates that a 1.1 in. increase in stormwater runoff is occurring each year. Over an area of 80.7 mi^2, that translates to 1.54 Ggal/yr of water exported downstream from Rockland County. About half of that water (770 Mgal/yr) can be viewed as potential recharge that has been lost because of impervious surface area in this part of the county.

Recharge Estimates

Recharge, the part of precipitation that replenishes groundwater, is of great interest where groundwater resources are utilized. Recharge across Rockland County for any given year is variable, and year-to-year variations can be large. The most important factors are annual precipitation amount and texture and thickness of glacial deposits; impervious surface is also important but is of lesser magnitude. Factors that likely affect recharge are illustrated in figure 51.

Till is the predominant glacial deposit in upland areas, and sand and gravel (outwash and alluvium) are mostly limited to valley-bottom areas with flood-plain development. Most recharge of the Newark basin aquifer is through till deposits. Till derived from crystalline rock from the Highlands and coarse sedimentary rocks from the western half of Newark basin is expected to be more permeable than till derived from finer-grained sedimentary rocks in the eastern part of the county, although this has not been verified. Areas of the most well-drained till-based soils (U.S. Department of Agriculture, 1990) correspond to areas of thin till. Water-chemistry data presented earlier indicate that the least evolved (most recent) groundwaters correspond to areas of thin till (less than 40 ft). Recharge can occur in areas of thicker till, but if there is underlying dense lodgement till, recharge may be nearly nil. Till can also be underlain by weathered bedrock in some areas of the county (Malcolm Pirnie, Inc., 1993). The absence of recharge through thick till was indicated by the lack of groundwater-level response to precipitation at well Ro-1234 (fig. 23A).

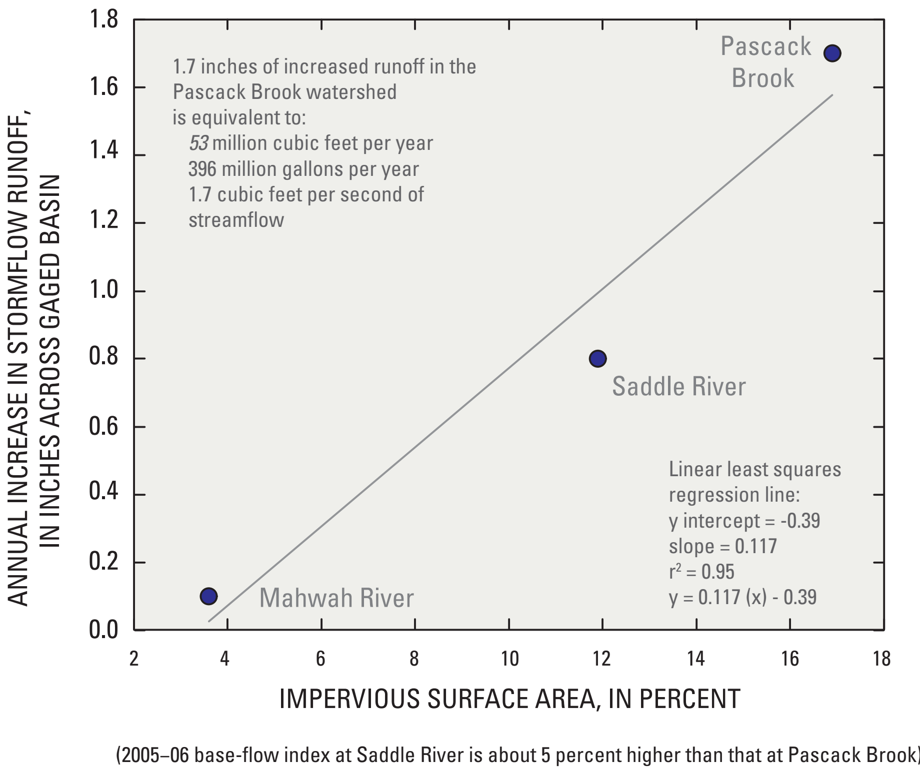


Figure 50. Storm-runoff increase with impervious surface at three gaged watersheds in Rockland County, New York, and northern Bergen County, New Jersey.

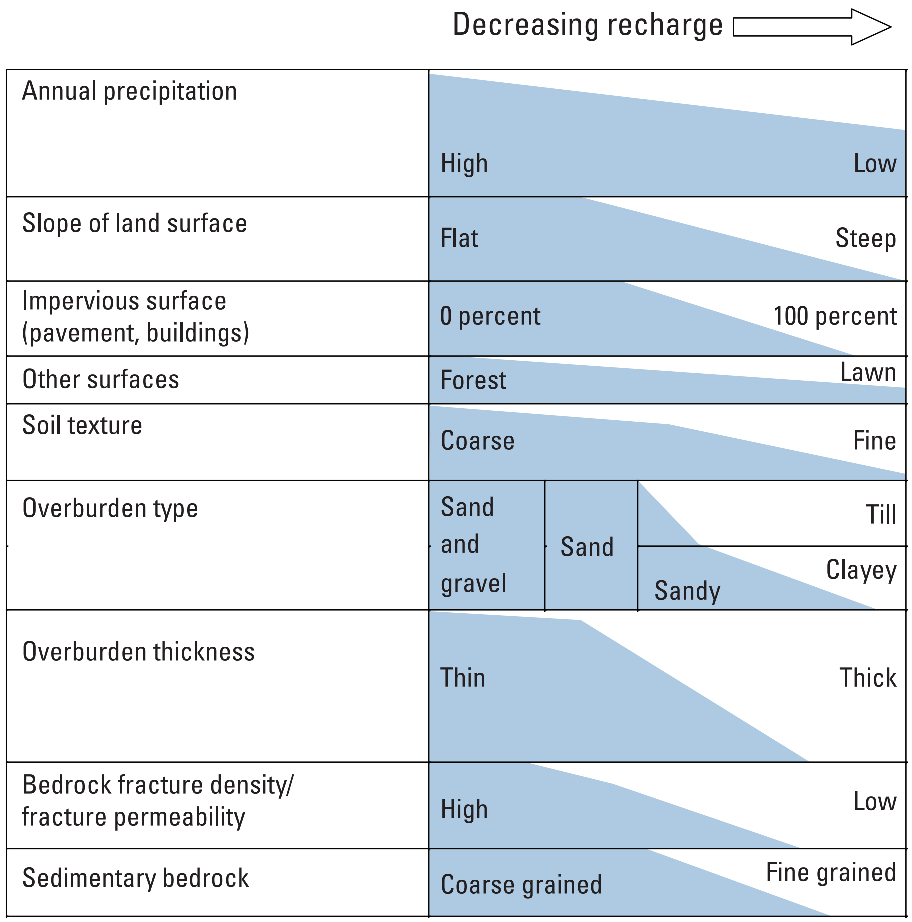


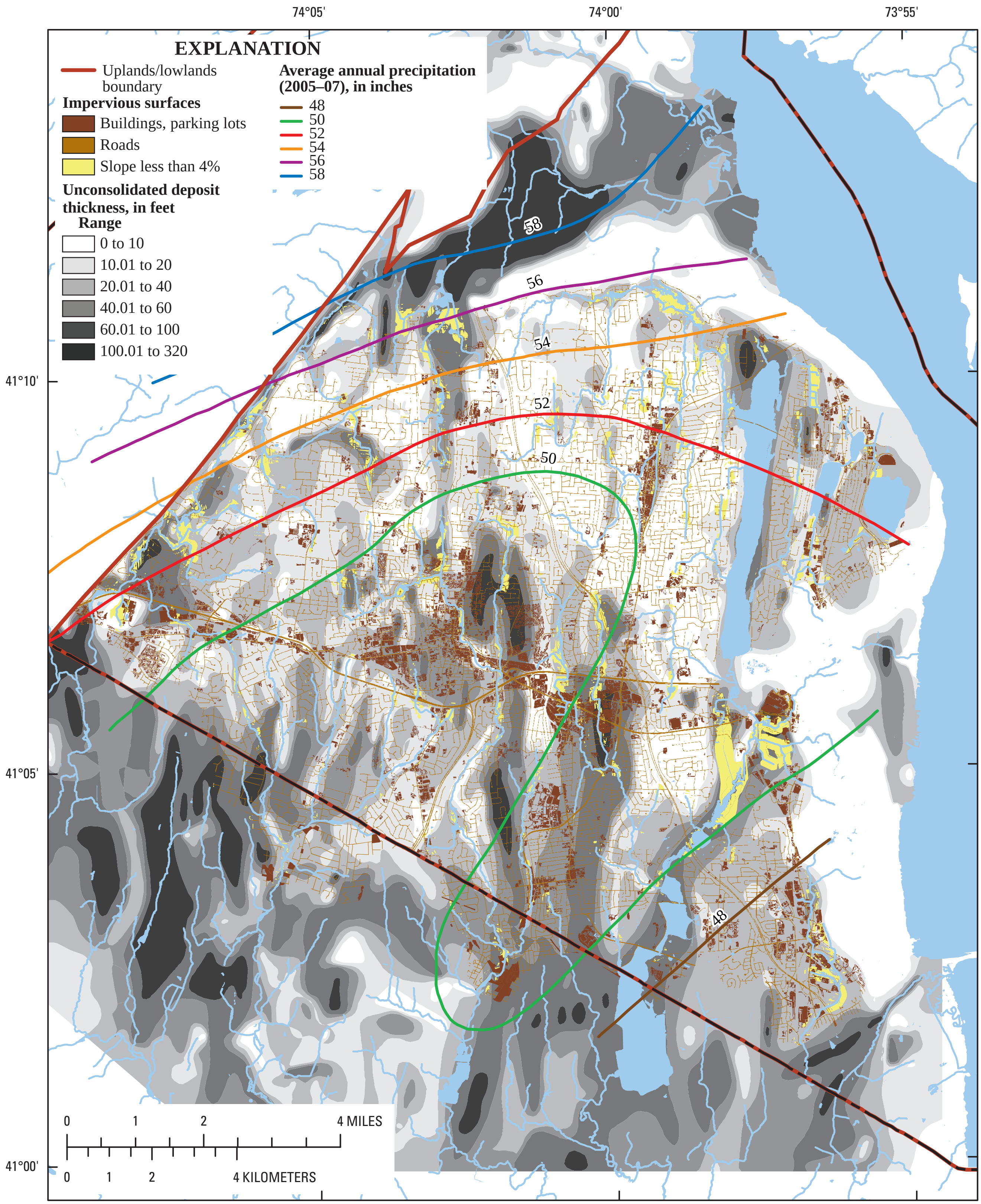
Figure 51. Factors that affect recharge.

Sand and gravel deposits are most favorable for infiltration of recharge. Recharge in flood-plain areas and adjacent hillslopes does not enter bedrock and remains within the shallow groundwater flow system, eventually discharging to the local valley stream. Areas of low slope adjacent to streams account for about 6 percent of land surface above the Newark basin aquifer and can be excluded from bedrock recharge totals under natural conditions. However, this shallow groundwater can be diverted to alluvial well fields or even bedrock well fields where valley-bottom deposits are permeable. If natural groundwater flow to streams is reversed by pumping stresses, stream water becomes an additional source of recharge to alluvial aquifers. The high yields of the Ramapo valley and Mahwah valley alluvial well fields are dependent on induced recharge from the Ramapo and Mahwah Rivers. The distribution of factors that impede or facilitate recharge—thickness of glacial deposits, areas of low slope adjacent to streams, and areas of impervious surface—are delineated in figure 52.

Recharge estimation techniques used in Rockland County ranged from the watershed-scale (physical hydrograph separation) techniques to local-scale (single well, water-level fluctuation) techniques. Each have their own set of assumptions and uncertainties and are described in the following sections.

Hydrograph-Separation Based Recharge Estimates

The hydrograph-separation technique involves separation of the streamflow record (total runoff) into base flow and stormflow (or storm runoff) components. The base-flow component is groundwater discharge that, under natural conditions, is nearly equivalent to the amount of recharge entering the watershed minus losses from ET of groundwater from vegetation near discharge areas and where the water table is near land surface. Groundwater evapotranspiration (GW ET) is estimated at about 1 in/yr, which is the 25th percentile of the range of GW ET estimated as the difference between groundwater recharge and groundwater discharge estimates by Rutledge (1998). Most riparian areas along smaller streams are narrow. Larger streams and rivers could have as much as 2 in. of GW ET. In developed areas, groundwater intercepted by



Base from New York State Department of Transportation, 1:24,000,
Universal Transverse Mercator projection, Zone 18
North American Datum 1983

Figure 52. Distribution of factors that affect recharge across the Newark basin aquifer, Rockland County, New York.

wells is also part of the recharge total. If the area is sewered, as is the case in Rockland County, pumped water is exported from the area, except for conveyance losses from water mains and outdoor uses. Recharge is the sum of base-flow estimates from hydrograph separations, groundwater withdrawals, and estimated GW ET.

Hydrograph separations require determination of when stormflow has effectively ended and when base flow again becomes the dominant component of streamflow. There is a variety of approaches to this task; the software program PART (Rutledge, 1998) was used in this study. This program considers recession rates of less than 0.1 log cycle per day to represent base flow as long as enough time has passed to account for the passage of most stormflow and interflow in the hydrograph. The number of days since peak flow is estimated with the empirical equation $N = A^{0.2,}$ where N equals the number of days since the storm peak, and A is the drainage area, in square miles (Linsley and others, 1982). Daily flow datasets are required, and records of at least several years are preferable. Base flow during stormflow periods is estimated by linear interpolation between base-flow values before and after storms. This method assumes negligible diversion or regulation of flow and that all or nearly all groundwater discharge is to the stream (relatively little pumpage).

Use of this method is limited by the lack of long-term streamgages in the county apart from the Mahwah River near Suffern streamgage. The degree of development and alteration of streamflow by 1961, when streamgages across the watershed were operational, is equally problematic. Many of the gaged streams already had impoundments and regulation or received additional flows from wastewater-treatment plants. Only those gages that have minimal flow alteration are considered in the following analyses. Impoundments and large wetland areas tend to smooth out storm hydrographs, which can lead to overestimates of natural base flow.

New (2004–05) streamgages on the Saddle River and Pascack Brook are primarily affected by high impervious-surface areas that make streamflow more “flashy” (rapid increases in stormflow and rapid decreases (recession) to base-flow conditions). The “N” value (number of days since peak flow) should presumably be smaller under these conditions because pre-storm base flows are attained rapidly. Shorter time intervals in the dataset would better characterize the flow conditions. Nevertheless, use of a larger N value than necessary probably does not inflate base-flow estimates because the hydrographs during base-flow periods are nearly flat.

1961 Estimates

Recharge estimates for 1961 are depicted, by gaged watershed, in figure 53. Annual estimates range from 14.7 to 24.8 in. Estimates include base flow, pumpage minus 16 percent conveyance loss, and 1 in. of GW ET. Gaged basins with the least amount of regulation, diversion, effluent discharge, and impoundment were selected for analysis. The two most-questionable watersheds included in this group were the Saddle River and Pine Brook watersheds, which had a number of small impoundments; estimates from these sites may be skewed high. The 2 in. lower value at Pine Brook than at Saddle River may reflect fewer impoundments and loss of upgradient groundwater discharge because of withdrawals at the Spring Valley well field, which is along strike with the watershed. Comparison of the recharge estimates in figure 53 with the distribution of precipitation in figure 52 indicates a general positive correlation between recharge and precipitation. The precipitation distribution in 1961 was generally similar to that in 2005–07 (fig. 3); it was highest in the Highlands and decreased towards the southeast.

Mahwah Watershed Estimates

Median recharge for 1959–94 and 2006 for the Mahwah River near Suffern watershed was 21.8 in.; the 25th and 75th percentiles were 18.8 and 25.3 in., respectively. Minimum and maximum estimates were 14.3 (1965) and 34.7 in. (1972). Precipitation and recharge amounts parallel one another. Recharge as a percentage of precipitation fell within a narrow range—a median value of 45.7 percent with the 25th and 75th percentiles of 42.9 and 48.4 percent, respectively. The following section discusses this relation.

2006 Estimates

Recharge estimates for 2006 were limited to three current streamgages: Mahwah River near Suffern, NY; Saddle River at upper Saddle River, NJ; and Pascack Brook at Park Ridge, NJ. Recharge values were 27.18, 19.22, and 18.15 in., respectively. Recharge lost because of impervious surfaces is estimated at 0.05, 0.4, and 0.85 in., respectively.

These recharge estimates are higher than recharge estimates in similar areas in 1961. Precipitation totals, however, were 8 in. higher in 2006 than in 1961 at precipitation gages just north of the Mahwah watershed. The difference in precipitation may account for the difference in recharge, as illustrated in the following section.

Water-Table-Fluctuation Based Recharge Estimates

The water-table-fluctuation technique involves determination of the cumulative rise in the groundwater level at a well over a period of interest and then multiplication by the specific yield (*Sy*), which is the effective porosity of the aquifer material (Healy and Cooke, 2002). Software by Heppner and Nimmo (2005) provides an enhanced means of making such estimates and gives a variety of recharge outputs, including daily values. A key assumption of this method is that *Sy* is constant with depth. Other favorable conditions are rapid response of water levels to rainfall, minimal flow in the wellbore, and water levels unaffected by pumping wells.

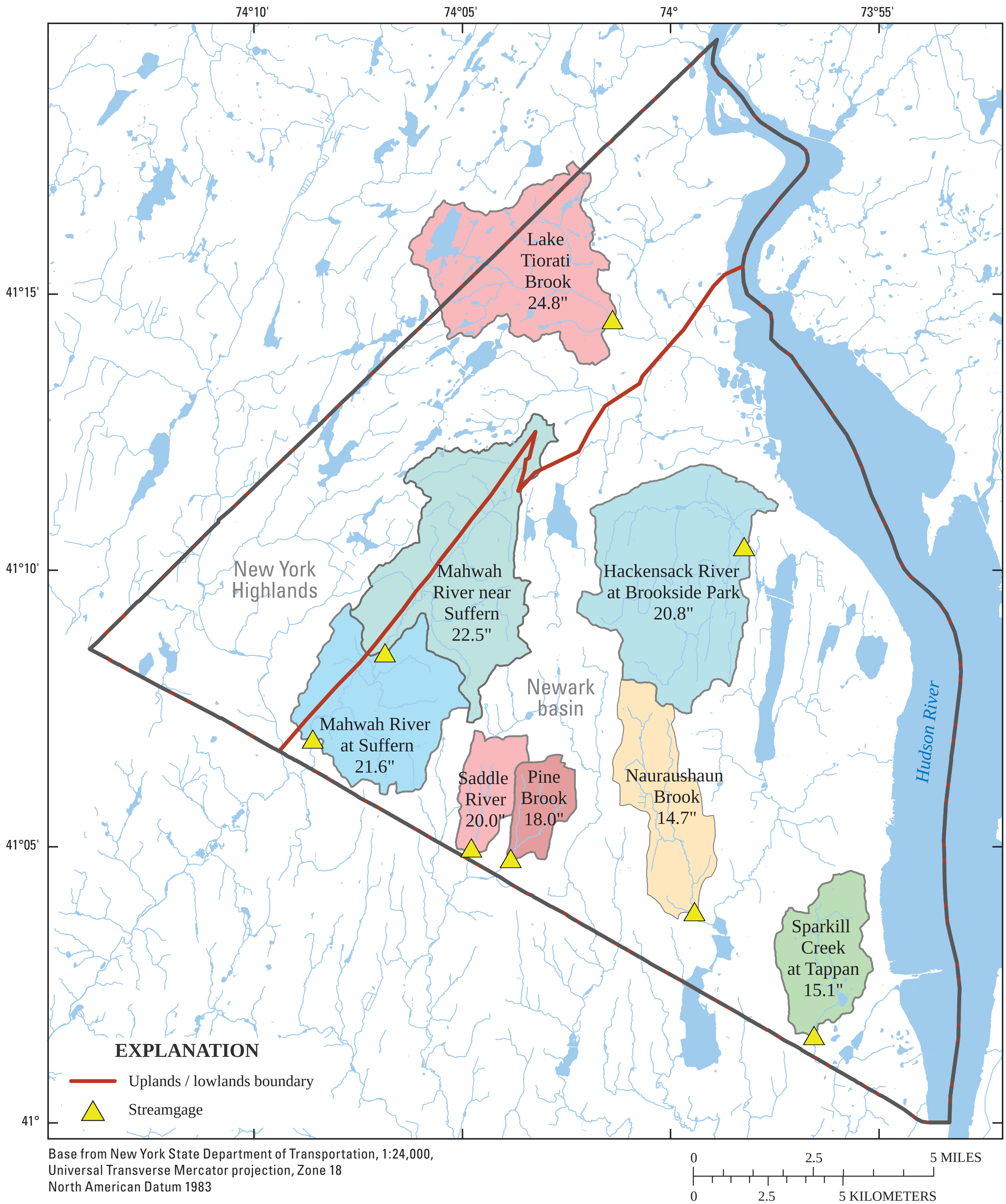


Figure 53. Estimated recharge, in inches, in 1961 from hydrograph separation of selected streamflow-measurement gages, Rockland County, New York.

Groundwater-level decline or recession trends are extended under each peak, and the total annual water-level rise is calculated. *Sy* is the critical estimate used in this type of analysis. Ranges of porosity or effective porosity are available from the literature, but relatively small differences in *Sy* can produce substantial changes in recharge estimates. *Sy* of fractured bedrock is even more variable. Locally based estimates are, therefore, preferable.

2006 Recharge at Well Ro-647 and Green Pond 5 Observation Well, Morris County, NJ

In this study, *Sy* in shallow bedrock at well Ro-647 (fig. 54) was estimated by two approaches. The first was to divide the 2006 recharge estimate (converted to feet) for the Mahwah River watershed (2.27 ft) by the 2006 cumulative rise in water level (in feet) at well Ro-647 (104.81 ft). Total annual groundwater-level rise was determined from the hydrograph by extending recession periods under water-level peaks and measuring and summing all rises in water level. The resulting *Sy*, 0.022, is largely based on streamflow data from a watershed that is roughly half Newark basin sedimentary bedrock and half crystalline bedrock of the NY–NJ Highlands. Because the Highlands receive more annual precipitation than the Newark basin in Rockland County and base flow increases with annual precipitation, this estimate is considered high.

The second approach was to numerically compare the total 2006 hydrograph responses to precipitation of well Ro-647 with that of a USGS observation well completed in sand and gravel, at which *Sy* was estimated. The Green Pond 5 observation well (27-0028; http://nj.usgs.gov/gw-cgi/wldata.pl?UID=270028.rdb, accessed July 9, 2007) is in the NY–NJ Highlands in Morris County, NJ. Comparison of the hydrographs indicated corresponding hydrograph responses to nearly all 2006 precipitation events (fig. 54). Responses to precipitation were smaller at the Green Pond well because it is completed in stratified drift, which is more porous (larger *Sy*) than bedrock in the Newark basin. The Green Pond well is near a precipitation gage at the Oak Ridge Reservoir, and 2006 precipitation in the area (54.08 in.) was similar to that in the Mahwah watershed (about 55.78 in. during 2005–07). *Sy* at the Green Pond well (0.127) was estimated by dividing an estimate of annual recharge (in feet) from PART analyses of streamgages in the area by the total 2006 groundwater-level rise at the well (13.6 ft). Annual recharge (20.75 in. or 1.73 ft) was calculated by multiplying the mean streamflow from the nearby Green Pond Brook streamgage (01379773) by the average base-flow index of 0.68 from the West Brook near Wanaque, NJ, streamgage (01386000; U.S. Department of Agriculture, 2005), plus an additional inch of water as a general estimate of GW ET. The West Brook base-flow index was used because it is a relatively well-drained basin, which is desirable; Green Pond Brook has two lakes within its watershed that generate a high average base-flow index (0.89) that is not considered representative of groundwater discharge.

The *Sy* of bedrock at the Ro-647 well was then estimated by dividing the *Sy* of the Green Pond well (0.127) by the ratio of the annual cumulative groundwater-level rises at well Ro-647 (bedrock) and the Green Pond 5 observation well (stratified drift):

$$Sy \text{ (well Ro-647)} = 0.127 / (104.81 \text{ ft} / 13.6 \text{ ft}) = 0.0165$$

Application of this *Sy* to the total 2006 water-level rise at well Ro-647 yields a recharge estimate of 20.75 in. Recharge at the Green Pond well is essentially the same.

Annual Distribution of Recharge

Once a reasonable estimate of *Sy* has been made, it can be used in the Master Recession Curve Recharge (MRCR) software (Heppner and Nimmo, 2005) to generate daily recharge values for comparison among wells or at a single well over a period of record. This approach is especially useful because determination of the distribution of recharge is valid whether or not the *Sy* is accurately known. Results for 2006 for the wells discussed above are depicted in figure 55. This illustration shows a strong correspondence in the distribution and timing of recharge at these two wells. The Ro-647 well has only 1.5 years of record, whereas the Green Pond well has 25 years of record. Therefore, it is reasonable to expect that annual recharge distribution from analysis of Green Pond observation well 5 data would parallel annual recharge distribution in Rockland County.

The annual distribution of recharge at the Green Pond well was determined for a 10-year period (1998–2007) and is summarized in figure 56; part A depicts the average percentage of annual recharge that occurs during each month, and part B depicts the range of recharge totals that were determined during the 10-year period. Part A indicates that recharge occurs during every month of the year but that the non-growing season and adjacent months (October through April) are most favorable. March is by far the month with the highest recharge, and July is the month with the lowest recharge. Part B shows the full range of monthly recharge percentages, and the highs and lows are of particular interest. March and October had the highest monthly percentages, approaching 30 percent of annual recharge, and all months reached between 15 and 20 percent of annual recharge on at least one occasion, except for August and November. Low annual percentages of recharge (less than 3 percent) were also possible during all months except November.

Recharge as a Function of Precipitation

Estimates of annual recharge that are based on hydrograph-separation and water-table-fluctuation methods described above show positive correlations with local annual precipitation from year to year (fig. 57). The regression for the Mahwah watershed data is stronger than that for the Green Pond well in part because a longer period of record was used.

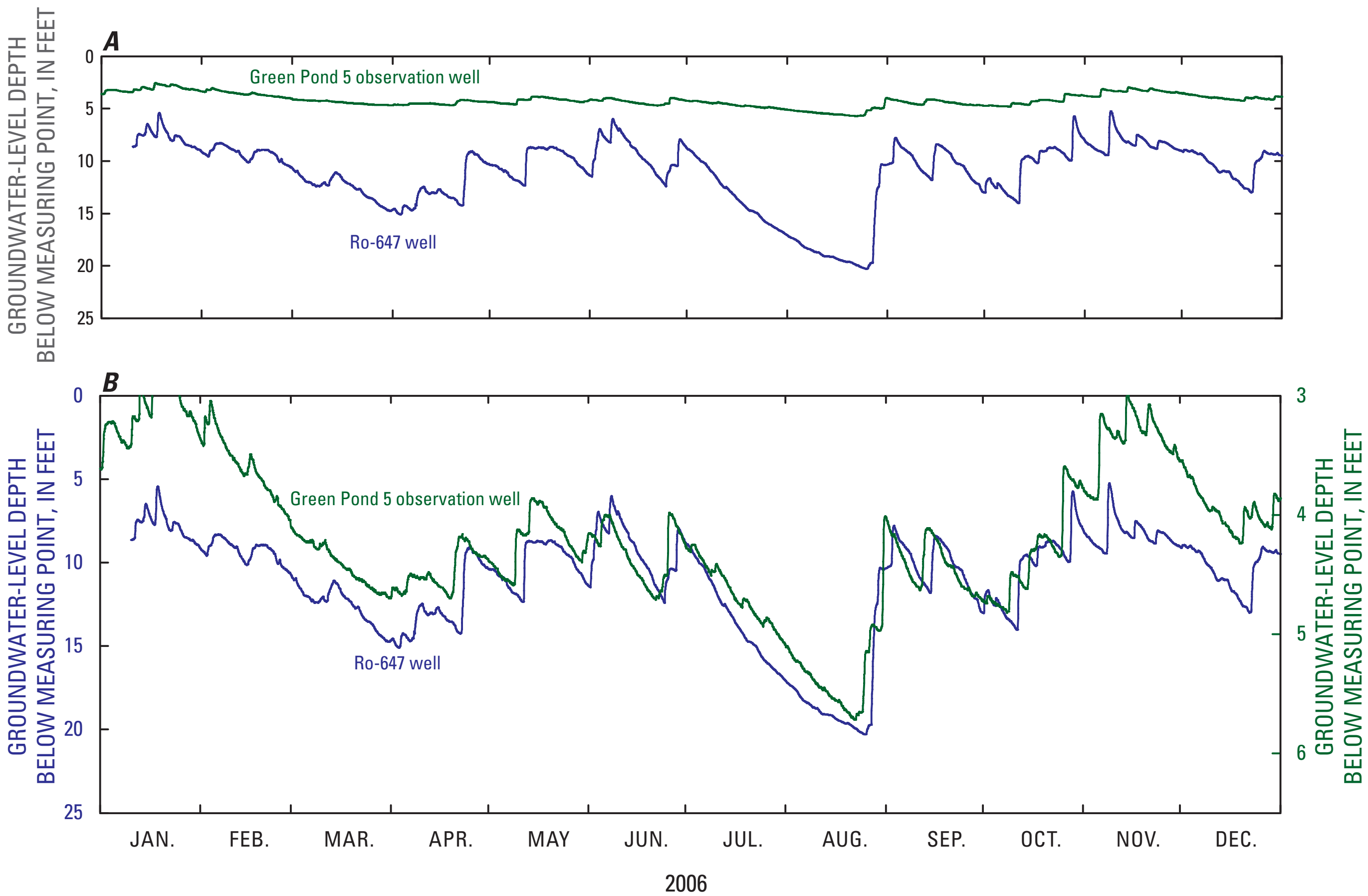


Figure 54. Comparison of 2006 groundwater hydrographs from bedrock well Ro-647 in the Newark basin, Rockland County, New York, and Green Pond 5 observation well completed in sand and gravel in the New York–New Jersey Highlands, Morris County, New Jersey: *A,* plotted on the same scale, and *B,* plotted on separate scales to highlight similarities in responses to precipitation.

The Green Pond data are not normally distributed, but the trend defined by the extreme values is consistent with the general trend within the main body of points. The relations are reasonably strong despite variations inherent in the precipitation data. Variation in the distribution and intensity of precipitation during the year is a major factor; a smaller proportion of precipitation during the growing season is apt to become recharge because of ET than during the nongrowing season, and a few high-intensity rainfall events will result in less recharge than a larger number of low-intensity rainfall events, as discussed earlier. These considerations could be taken into account by weighting precipitation events and developing a modified annual total that reflects recharge potential. These relations, however, provide a foundation for general estimates of recharge where streamflow data may not be available.

A simple means of estimating recharge from precipitation in the Mahwah River gaged watershed is to use the median of the percentage of precipitation represented by recharge estimates over the period of record. The median (and average) value is 44 percent; the 25th percentile of the dataset is 42 percent, and the 75th percentile is 47 percent.

Water Budgets of Watersheds with Streamflow Data

Development within Rockland County has altered the hydrologic system and thus, water budget components, as highlighted in figure 58. The net effect of development has been an increase in the rate of water export from the county. Changes in the Highland part of the county (fig. 58A) are mostly limited to impoundment of surface water for recreation and water supply. Use of groundwater in the Highlands is largely limited to domestic well usage on the periphery of the parklands. Widespread suburban development in the Newark basin lowland area of the county (fig. 58B) has lead to utilization of both surface-water and groundwater resources. Water withdrawn from the Lake DeForest reservoir and from production and domestic wells is used and then transferred

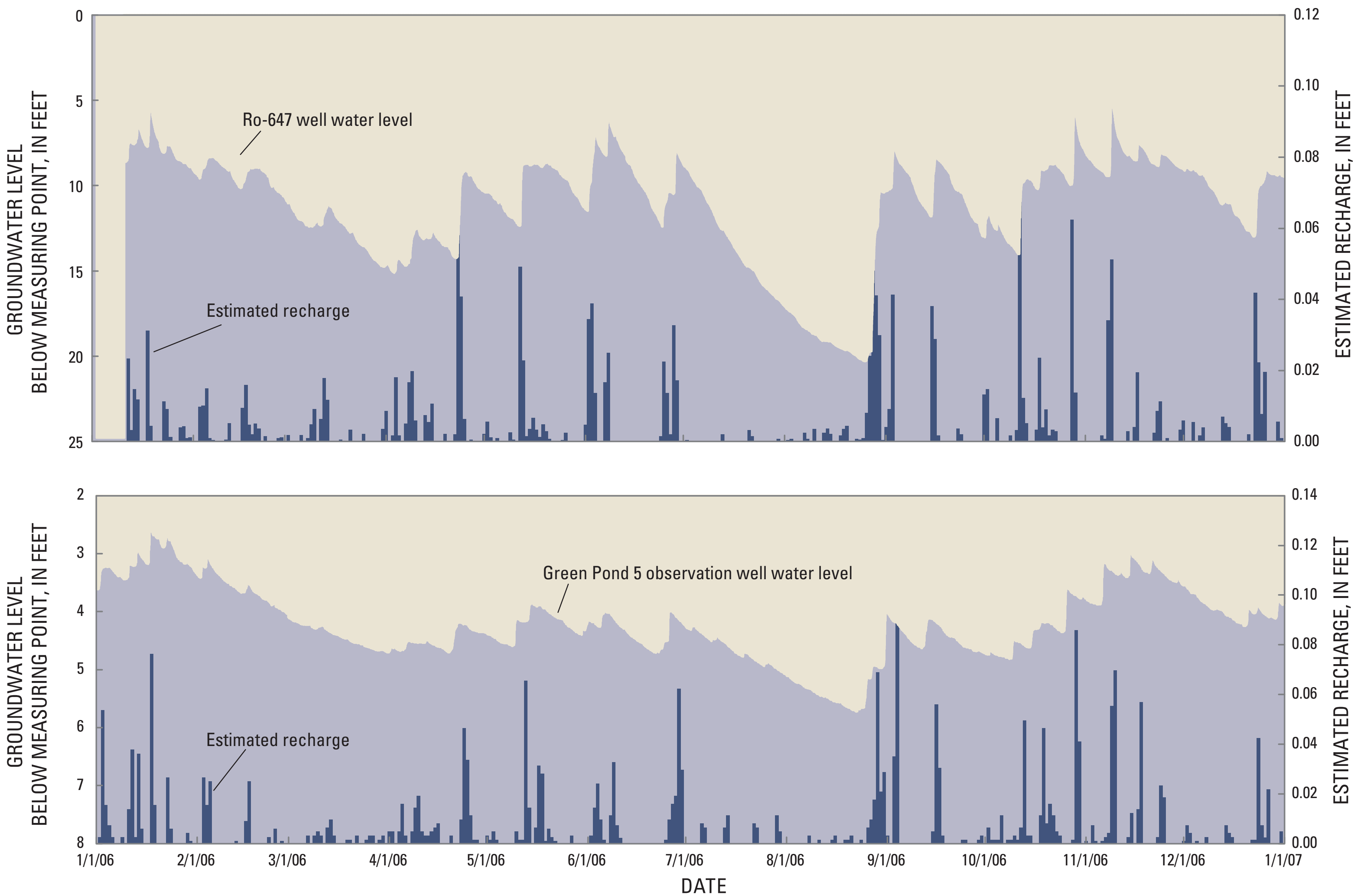


Figure 55. Comparison of 2006 recharge amounts and distribution between the bedrock well Ro–647 in the Newark basin, Rockland County, New York, and Green Pond 5 observation well completed in sand and gravel in the New York–New Jersey Highlands, Morris County, New Jersey.

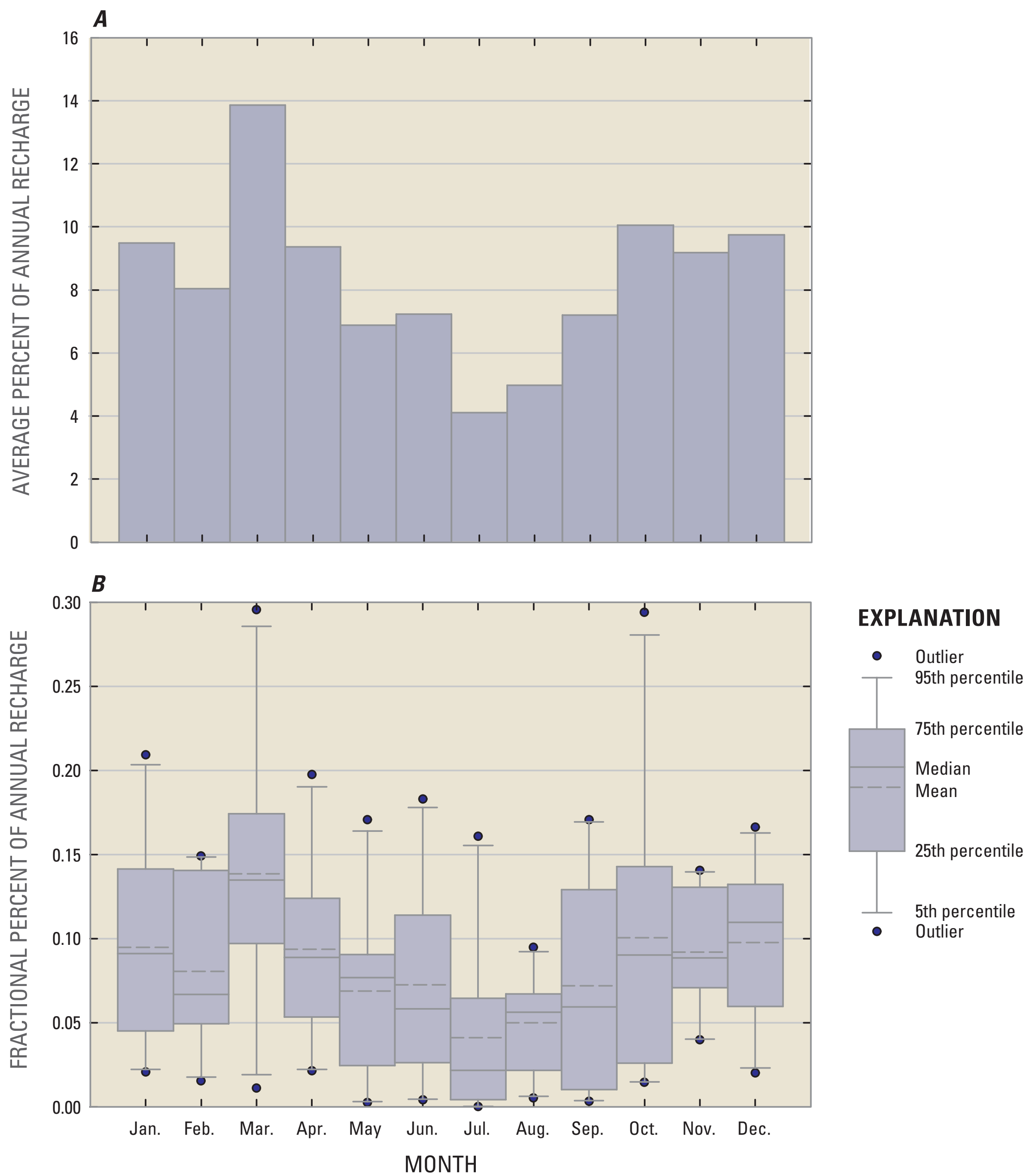


Figure 56. Annual distribution of recharge at Green Pond 5 Observation well during 1998–2007, New York-New Jersey Highlands, Morris County, New Jersey: *A,* average percentage of annual recharge that occurs during each month, and *B,* range of monthly recharge totals as a fractional percent of annual recharge.

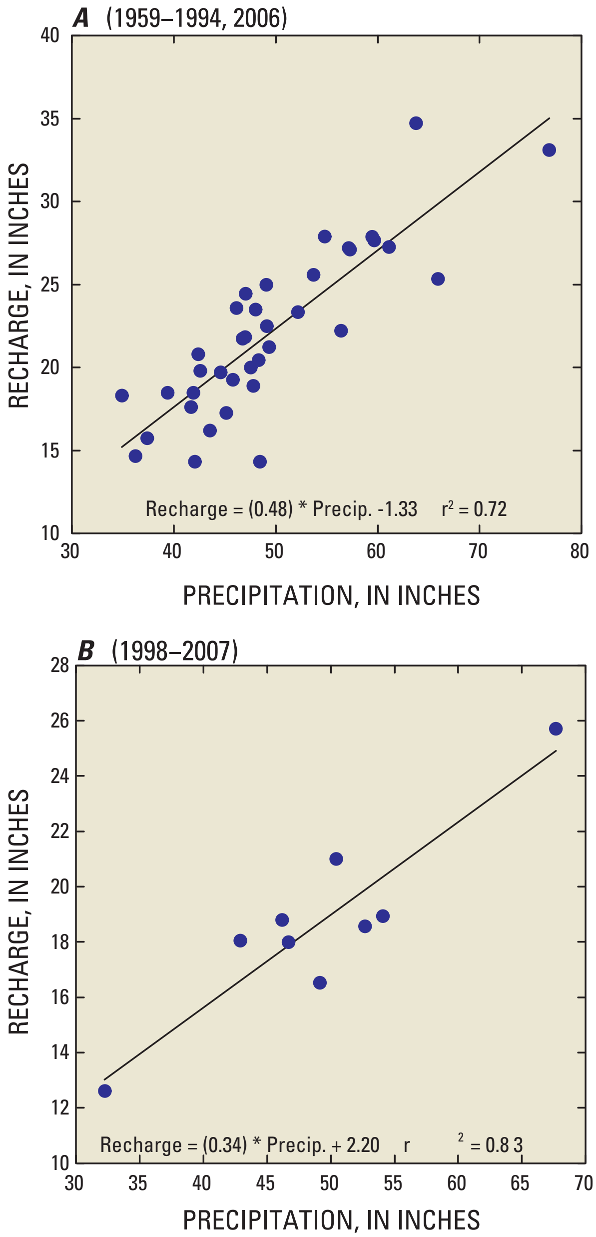


Figure 57. Recharge as a function of precipitation: *A,* from hydrograph-separation method analysis of Mahwah River near Suffern, New York, streamflow data, and *B,* from water-level-fluctuation hydrograph analysis of the Green Pond 5 observation well, Morris County, New Jersey.

via sanitary sewers to wastewater-treatment facilities. Treated wastewater is then discharged (exported) to the Hudson and Ramapo Rivers. Outflows of treated wastewater are significantly increased by inflow of stormwater and infiltration of groundwater into the sanitary sewer system.

The most visible hydrologic change in the county has been the alteration of streamflow regime. Loss of stream base flow has occurred through the combined effects of groundwater withdrawals, increases in impervious surface area, sanitary sewering, and surface-water withdrawals. Gains in stormflows from increased impervious surface area has increased localized flooding and increased export of water from Rockland County. Recharge and evapotranspiration decrease in areas where impervious surface area has increased.

The water budget, or hydrologic-system components that are conceptualized in figure 58 provide an overview of the types of changes that result from suburban development. Quantification of smaller components or changes in the hydrologic system was beyond the scope of this study.

Average values of water-budget components across Rockland County are of limited value because of spatial differences in the hydrologic characteristics of the largely undeveloped Highlands and the suburban Newark basin lowlands (fig. 58A, B). Even within the lowlands (Newark basin aquifer), there are substantial variations in hydrologic characteristics such as rock type, thickness and texture of glacial deposits, topography, precipitation, types of water use, and amount of impervious surface. A water budget that includes such complexities is most realistically estimated with a numerical computer model of the Newark basin aquifer.

A more useful local water-budget picture can be estimated on a watershed basis using precipitation and streamflow data. The follwing data from currently or formerly gaged watersheds in both the crystalline Highlands and the lowlands (primarily the Newark basin aquifer) were analyzed (1) 1961 data from eight streamflow gages, most of which were discontinued; (2) data from the Mahwah River near Suffern, NY, streamgage, the only long-term measurement site in the county; and (3) 2006 data from the only gages that measure unregulated streamflow from Rockland County watersheds. Precipitation stations and streamgages used for these analyses are shown in figure 5 and listed in table 1. Streamflow records provide values of total annual runoff, which can be subdivided by hydrograph-separation techniques into storm-runoff and base-flow components. Water-budget components are expressed in inches of water over the watershed areas.

Groundwater pumpage in the following water budgets represents public-supply pumpage minus an estimated conveyance loss of 16 percent (leakage from pressurized water mains). Withdrawals from private wells are not included in the 1961 water budgets because well numbers by watershed were not available and because most homes were served by septic systems rather than sanitary sewers. Most pumped water (about 85–90 percent; Pebbles, 2003) is returned to the groundwater system when septic systems are used.

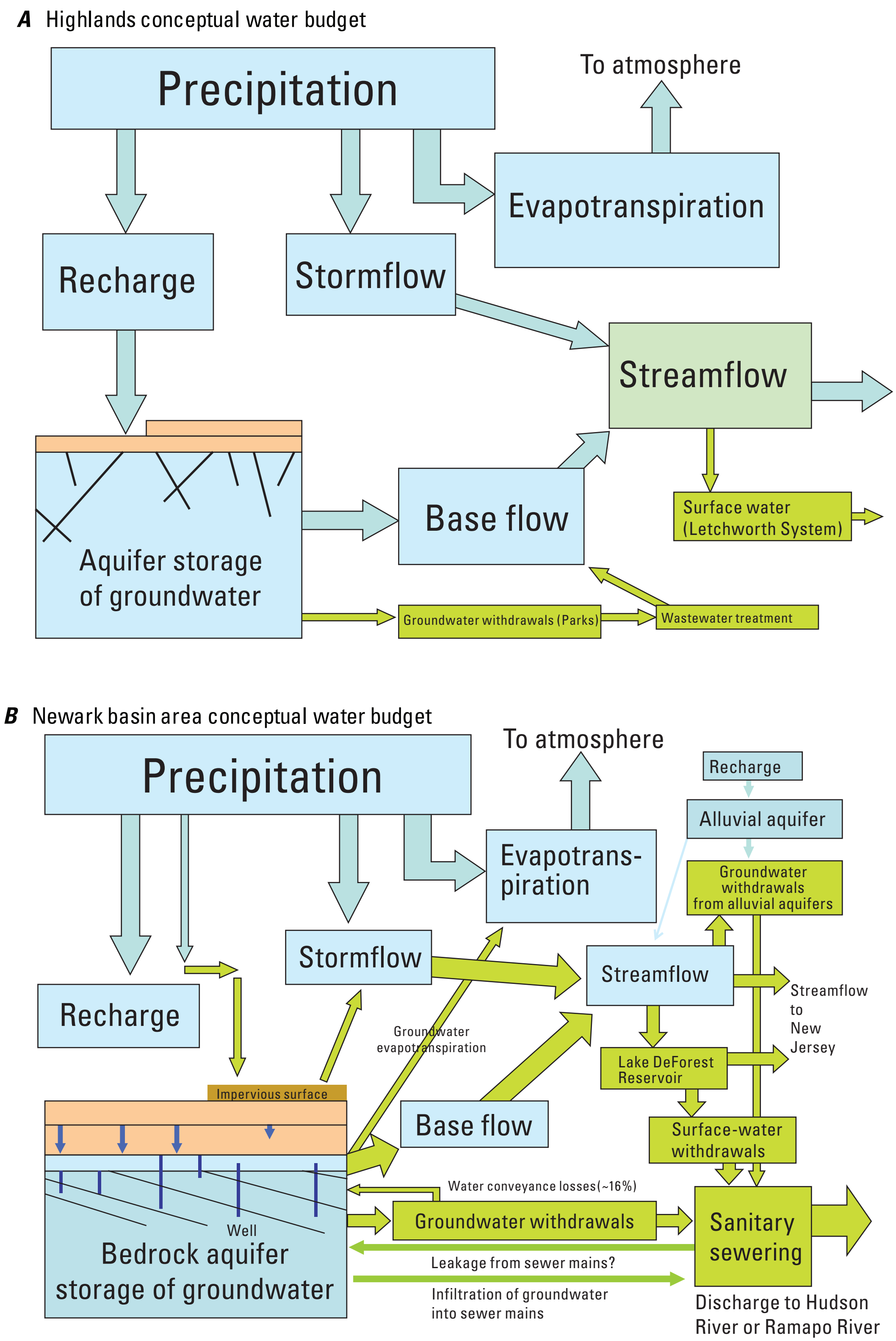


Figure 58. Conceptual diagrams of the hydrologic systems of the *A,* Highlands, and *B,* Newark basin lowlands, Rockland County, NY. Components in yellow represent hydrologic changes associated with development in Rockland County.

1961 and 2006 Streamflow Records

Water budgets for 1961 at selected gaged watersheds depict variability in precipitation, base flow, storm runoff, and groundwater pumpage across the county (fig. 59). Variation in precipitation from southeast to northwest areas of the county is documented in figure 3 and figure 52; base flow follows the same pattern and is a surrogate for recharge (along with groundwater withdrawals and groundwater ET). Relatively thick glacial deposits and degree of development (groundwater withdrawals and impervious surface area) in the southeastern part of the county also contribute to lower base-flow estimates. The positive correlation between precipitation and recharge is discussed in the “Recharge” section of this report. The stormflow component was greatest in the developed southeastern part of the county, also because of the degree of development and impervious surface area. Groundwater withdrawals for public supply varied among the watersheds and, in general, base-flow estimates were lower where groundwater was being withdrawn than in neighboring watersheds with minimal withdrawals.

Water budgets for the three unregulated gaged watersheds for 2006 are also presented in figure 59. The 2006 water budgets are characterized by higher precipitation than in 1961, more groundwater withdrawals and storm runoff, especially within the Pascack Brook and Saddle River watersheds, which have high impervious surface areas, as discussed earlier in the “Effects of Impervious Surface on Streamflow” section. Base flow at these same two watersheds is low relative to most other watersheds, even when groundwater withdrawals are added in, both by direct comparison and as a percentage of annual precipitation. Public-supply pumpage as a percentage of recharge in 2006 at the Pascack Brook and Saddle River watersheds was 18 and 21 percent, respectively. Evapotranspiration is similar across all watersheds.

Long-Term Mahwah River Streamflow Records

The long-term streamflow record at the Mahwah River near Suffern streamgage provides the most continuous record in which to examine the variation of water-budget components from the mid-1960s drought to the wet conditions during the 1970s (fig. 60, table 6; click link to view table 6 at http://pubs.usgs.gov.sir/2010/5245/table/table6.xls). The inherent variability in these components that underlie “average” conditions serves as a caution for water-resource planning. This illustration also highlights the value of collecting long-term streamflow records.

The base-flow estimates from this streamgage (PART program; Rutledge, 1998) may be somewhat inflated by the long length of this watershed, as well as the large amount of forested area in the Highlands part, which serves to slow and therefore spread out stormflow peaks in hydrographs despite relatively high slopes within the watershed. These characteristics result in low stormflow estimates. Keeping that in mind, the use of a consistent method over time still provides a basis for evaluation of component variability.

Three trends are evident in figure 60A. First is the positive correlation between precipitation and base flow, the major component of recharge. The second trend is the increase in pumping rates from production wells in this watershed after the 1960s drought. The third trend is the increase in the stormflow component during years with high precipitation totals. Presumably, there was a higher percentage of large, more intense storms during those years that generated a larger proportion of stormflow, as discussed in the section on the effects of impervious surfaces.

The boxplots of each component provide another way to visualize the variability of water-budget components around their median values (fig. 60B). Evapotranspiration and stormflow show the least variability of the major components, presumably because parkland areas in the Highlands part of the watershed haven’t changed, and developed areas in the lowlands part are forested, and housing density is low (less impervious surface area) compared with other areas of the county.

Groundwater pumpage for public supply is the smallest water-budget component included in figure 60, and has accounted for 12 to 24 percent of recharge over the period of record within the Mahwah River near Suffern, NY, watershed.

Water Use in Rockland County

In 2005, an estimated 12.9 Ggal of potable water was used in Rockland County. The overall annual pattern of water use (from UWNY data) is characterized by growing-season increases that include lawn and garden irrigation, pool maintenance, and cooling (fig. 61). Non-growing season system draft (the total amount of groundwater and surface water extracted) is generally between 25 and 28 Mgal/d, but single-day summer peak demand reached 46.5 Mgal/d in 2001 and 43.6 Mgal/d in 2005 (D. Miller, Rockland County Department of Health, written commun., 2007). The actual use is about 16 percent less than these figures because there is water leakage from the pressurized distribution system (D. Distante, United Water New York, written commun., 2007).

High peak demands are driven by low rainfall amounts and by high temperatures. Periods of peak demand present the greatest water-resource challenge for the county because the yield of the aquifers tends to decrease during dry periods. Peak water use in summer may exceed other times of the year by as much as 60 percent (fig. 61). The year 2005 was a relatively wet year yet still had high peak demands because rainfall was limited to a few large summer storms and because of high temperatures. Daily average system drafts for 2005 were 27.6 Mgal/d during the non-growing season and 34.4 Mgal/d during the growing season, an increase of 25 percent (fig. 61). Lyon and others (2005) have documented such stresses on

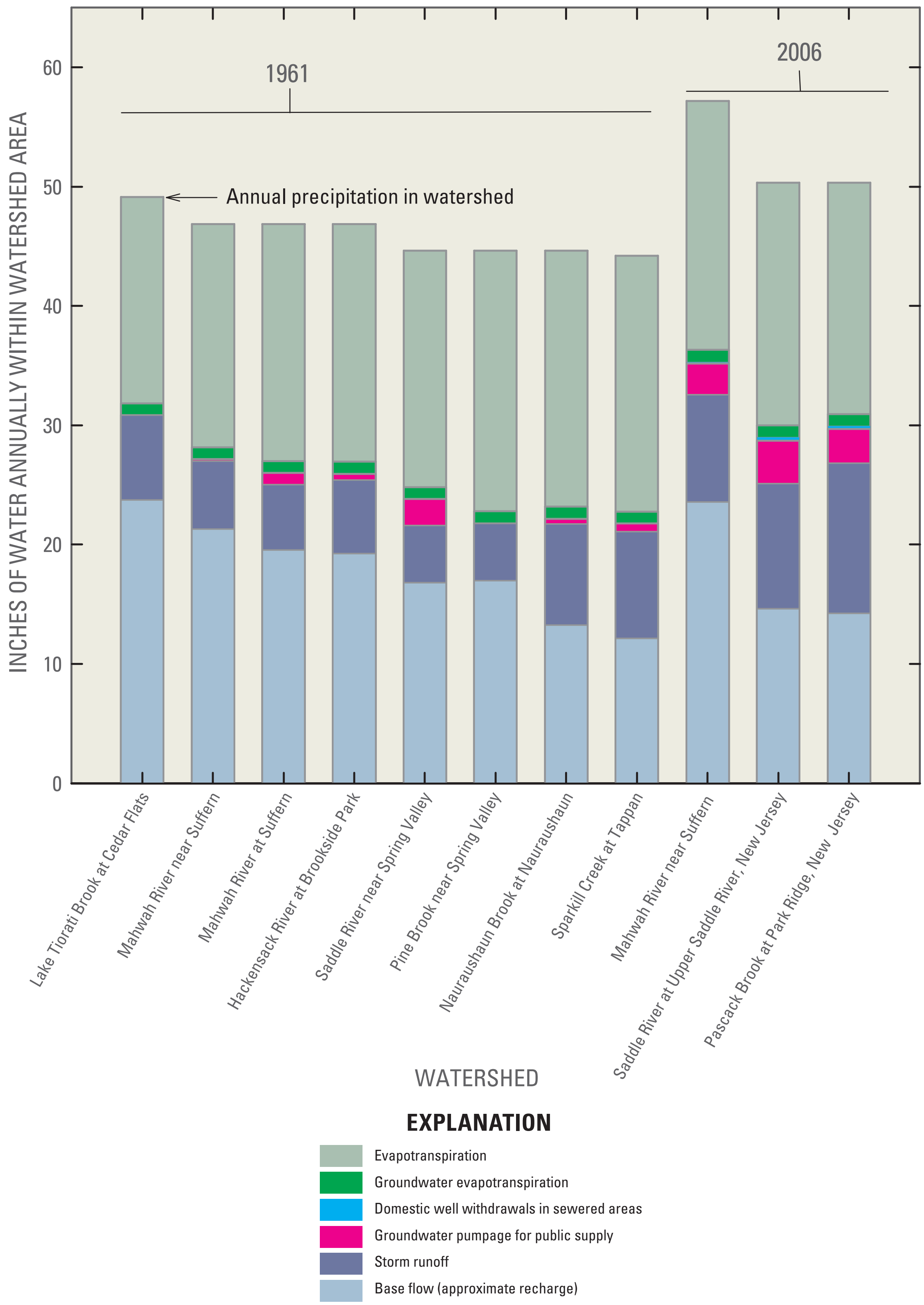


Figure 59. Water budgets for 1961 and 2006 from selected watersheds, based on streamflow-hydrograph separations, Rockland County, New York.

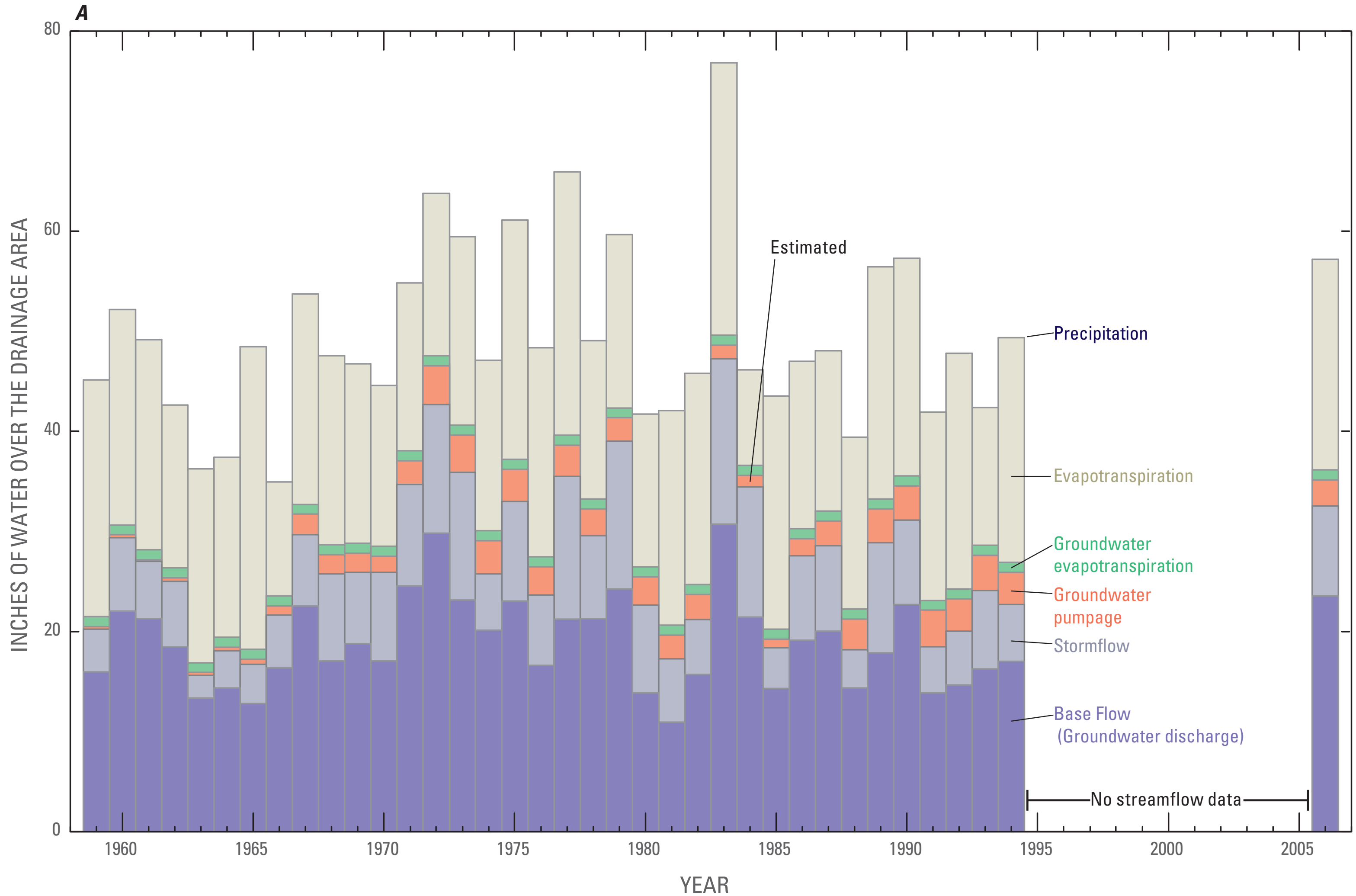


Figure 60. Water-budget components of the Mahwah River near Suffern, New York, watershed (1959–1994, 2006): *A,* by year, and *B,* as boxplots.

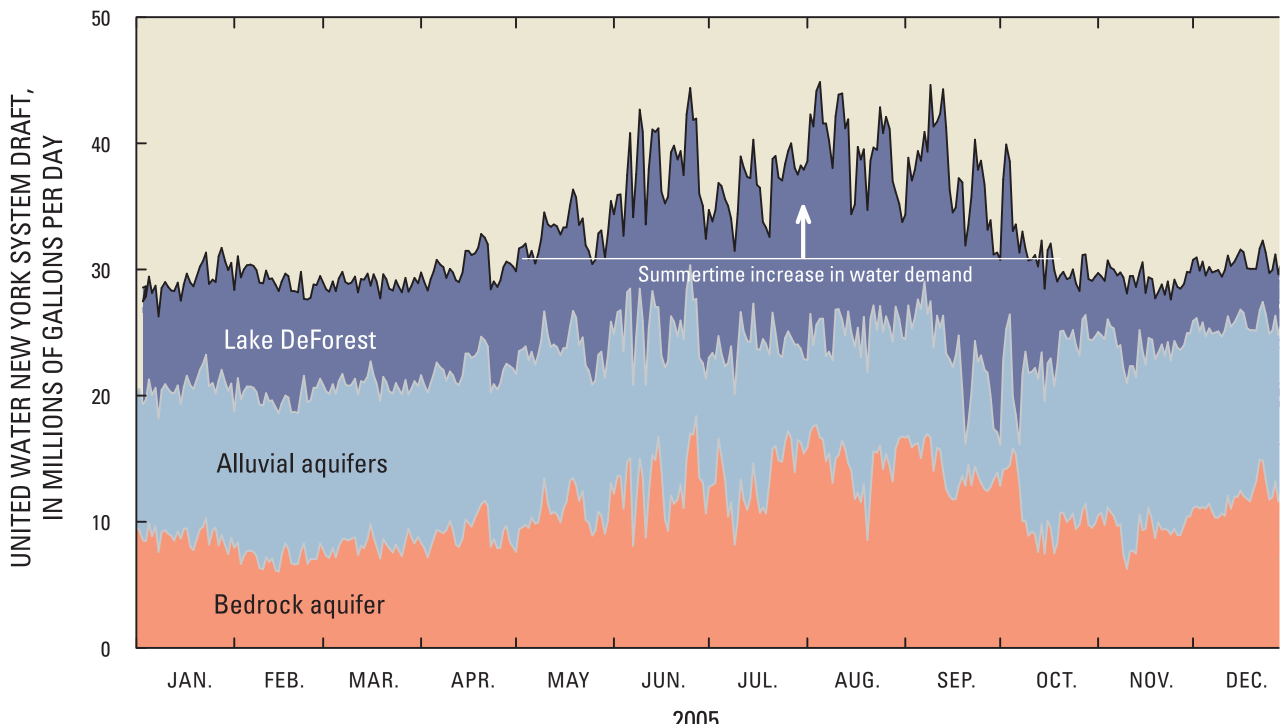


Figure 61. United Water New York system draft (total withdrawals), in millions of gallons per day, 2005, Rockland County, New York.

water resources in Rockland County during periods not defined by drought indexes as "drought" conditions (12-month running average of departures from normal precipitation, the Palmer Drought Severity Index, the Standardized Precipitation Index).

Annual water use in Rockland County was estimated for the following categories: (1) residential (per capita or per person), (2) residential-use increases during the growing season, (3) commercial, industrial, institutional, and governmental, (4) industrial cooling, (5) golf-course irrigation, and (6) nursery, farm, and orchard irrigation. Water-use estimates for Rockland County are presented in table 7. and fig. 62. Water-use coefficients for residential use (per capita, 75 gal/d) and for a variety of commercial, industrial, and institutional uses were drawn from a comprehensive water-use study conducted in southern New Hampshire (Horn and others, 2007; tables 11 and 14). Estimates of irrigation at golf courses and nurseries were derived from a County Health Department water-use survey. Water extracted for cooling purposes was estimated from State Pollution Discharge Elimination System Permit (SPDES) data (S. Vogler, New York State Department of Environmental Conservation, written commun., 2006).

The per-capita water-use estimate (75 gal/d) was applied to the populations served by community water suppliers of Rockland County (from the U.S. Environmental Protection Agency Safe Drinking Water Information System (SDWIS) database; http://www.epa.gov/enviro/html/sdwis/sdwis_query.html, accessed October 3, 2007); the remainder, based on a 2006 county population of 295,000, was attributed to the population served by domestic wells. An estimated 6,000 active private wells are in the county, based on records compiled by the Health Department, and an estimated 5,800 are domestic wells. The total population served listed in the SDWIS database, however, exceeded the county population without considering any domestic-well water use. This discrepancy is mostly attributed to the estimate of population served by UWNY. The number likely reflects (1) the total population *connected* to the UWNY system, rather than the population actively *using* the supply, (2) about 1,800 sole-source wells within the UWNY distribution area, and (3) population-served estimates as a general percentage of county population. About 2,800 wells in Health Department records are located within UWNY service areas and about 3,000 are outside of distribution areas. About 1,000 of the 2,800 wells are also connected to the UWNY distribution system (D. Distante, United Water New York, written commun., 2009) but likely use the connection only if the well cannot meet domestic needs. This is especially true in the areas of New Square and Monsey, where there are high densities of wells despite being in UWNY service areas. The number of wells was multiplied by average occupants-per-house statistics (http://www.empire.state.ny.us/nysdc/census2000/DemoProfiles1.asp, accessed October 3, 2007) to

Table 7A. Water use in Rockland County, New York (2005). Residential and commercial/industrial/institutional/governmental estimates from per capita use and United Water New York data. All figures in millions of gallons, unless noted otherwise. [1](mobile home parks, small communities, apartment buildings served by wells).

[Mgal/d, million gallons per day]

Supplier	Population served (total 295,000)	Base residential use, assuming use of 75 gallons per person per day (Mgal/d)	Commercial, industrial, institutional, governmental water use, (16 percent of base residential use) (Mgal/d)	Total water use, non-growing season (Mgal/d)	Additional average water use during growing season (daily average increase of 24.6 percent (14 percent for Village of Nyack) for the 180-day season, April 15–October 15) (Mgal/d)	Water use, growing season (Mgal/d)	Annual water use subtotal (Mgal)
United Water New York	250,050	18.754	3.001	21.754	5.352	27.106	
Village of Suffern	12,000	0.900	0.144	1.044	0.257	1.301	
Village of Nyack[1]	12,320	0.924	0.46	1.4	0.22	1.6	
Other small community suppliers[2]	3,230	0.242	0	0.242	0.060	0.302	
Domestic wells (5,800)	17,400	1.305	0	1.305	0.321	1.626	
Daily Totals	**295,000**	**22.125**	**3.605**	**25.730**	**6.329**	**32.059**	
Annual Subtotals		**8,075.63**	**1,315.68**	**9,391.30**	**2,310.26**		**11,701.56**

[1] Population back-calculated from 2005 processed-water data (M. Lovaglio, Village of Nyack Water Department, written commun., 2009) minus assumed 16 percent conveyance loss. Commercial, industrial, institutional, governmental water use equals 16 percent of base residential use plus annual water use totals for the Palisades Mall (71.5 Mgal) and Nyack Hospital (33.9 Mgal) (2008-2009 data from M. Lovaglio, Village of Nyack Water Department (written commun., 2009).

[2]Mobile home parks, small communities, and apartment buildings served by wells.

Table 7B. Water use in Rockland County, New York (2005). Estimated annual use from specific commercial, industrial, and institutional users of ground water, in millions of gallons. Based on County Health Department water-use surveys and State Pollution Discharge Elimination System Permit (SPDES) data. All figures in millions of gallons, unless noted otherwise.

[Mgal/yr, million gallons per year]

Water-use type	Industrial cooling water, in Mgal/yr	Non-transient community supplies, in Mgal/yr	Transient community supplies, in Mgal/yr	Seasonal Use, in Mgal/yr			
				Transient community supplies	Irrigation, Golf Courses	Irrigation, nurseries, orchards, farms	
Annual Use	720	4.47	4.73	1.05	400	45	1,175
						Total Annual Use	**12,876.81 Mgal/yr**
							12.88 Ggal/yr
							35.28 Mgal/day

Table 7C. Water use in Rockland County, New York (2005). Percentages of water-use types. All figures in millions of gallons, unless noted otherwise.

Water Use	Millions of gallons annually	Percentages
Residential	8076	62.76
Commercial, industrial governmental, institititional	1316	10.23
Summertime increase	2310	17.96
Industrial Cooling Water	720	5.60
Golf Courses	400	3.11
Nurseries, Orchards, Farms	45	0.35
Totals	12867	100.00

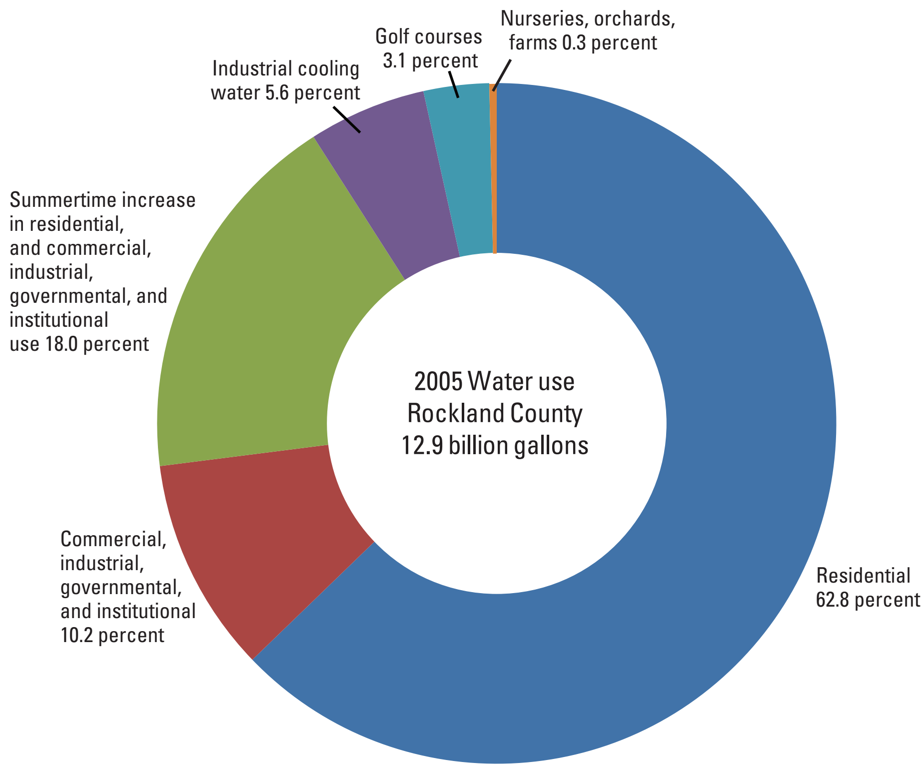


Figure 62. Percentages of water use in Rockland County, New York, 2005.

estimate the population served by domestic wells (17,400). An “effective population” served by UWNY was estimated at 250,050 by subtracting all other populations served from the 295,000 county population. A base (non-growing season) residential water-use estimate for the county was just over 22 Mgal/d.

Increased growing-season water use is part residential and part commercial, industrial, and institutional. In 2005, this water-use component amounted to an additional average of 5.7 Mgal/d UWNY system draft during the growing season. This amount represents an increase of 24.6 percent in average use, and this factor was applied to other suppliers’ base water use to estimate a countywide growing-season demand of about 6.2 Mgal/d (table 7).

Commercial, industrial, and institutional water use was estimated from UWNY data as the difference between total system draft (minus 16 percent conveyance loss) and base residential use. The estimate for this category was 16 percent of base residential use. The same 24.6 percent growing-season increase in usage was applied to this category. Additional estimates for this water-use category included cooling water used by a pharmaceutical company (720 Mgal/yr), irrigation water used by golf courses (400 Mgal/yr), and nurseries, orchards, and farms (45 Mgal/yr).

A water-use total of 12.87 Ggal/yr (35.3 Mgal/d) was estimated for Rockland County in 2005. This estimate is considered conservative because there is no water-use permit system for commercial/industrial wells and water use in New York State (as of 2007); therefore, not all water users are known.

A large amount of nonpotable water is obtained from the Hudson River for cooling purposes at two power-generating stations along the Hudson River in Haverstraw and Stony Point. The allowed SPDES permit flows from these plants (as of 2005) were 912 and 395 Mgal/d, respectively, for a total of about 1.3 Ggal/d.

Wastewater Disposal Outside of Rockland County

Sanitary sewers have been installed more or less in parallel with development in the county. The primary reason for sanitary sewers is to protect groundwater quality, especially in areas with thin soils that do not provide enough contact time with soils/glacial deposits to effectively treat domestic wastewater. The net effect of sanitary sewering is the export of all wastewater to rivers that flow out of the county, primarily the Hudson River but also the Ramapo River. A total of 14.57 Ggal was exported from the county in 2005, with about 0.54 Ggal of the total discharged to the Ramapo River. Names and annual discharges from the five largest wastewater-treatment plants in Rockland County are given in table 8.

Table 8. Wastewater treatment plants in Rockland County, New York, including amounts of water treated and discharged in 2005.

Sewer district / treatment plant	Town(s) / area served	Water treated and discharged in 2005 in (billions of gallons)	Receiving water body
Sewer District 1	Ramapo, Clarkstown	8.492	Hudson River near Piermont
Sewer District 2	Orangetown	3.480	Hudson River near Piermont
Haverstraw Joint Regional Sewer Board	Haverstraw	1.678	Hudson River near Haverstraw
Stony Point Sewer District	Stony Point	0.378	Hudson River near Stony Point
Suffern Treatment Plant	Village of Suffern	0.540	Ramapo River

The average amount of water exported to the Hudson River (about 38.4 Mgal/d) is actually greater than the amount of wastewater generated; average water use in the county that contributes to treated wastewater discharge to the Hudson River in 2005 was estimated at about 24.7 Mgal/d[4] (9.02 Ggal/yr), or a bout 64 percent of the total outflow. Inflow of storm runoff and infiltration of groundwater into sanitary sewers substantially increases flows to the wastewater-treatment plants (Hazen and Sawyer, 1979; Phillips and Dolphin, 1996). Figure 63 illustrates this point during 2005. The highest wastewater-treatment plant outflows parallel wet periods during the year. Fall outflows match stream stage in the Mahwah River, which indicates that the sanitary sewer system is essentially an artificial drainage system similar to surface-water drainages, only engineered to cross topographic highs with pressure mains. Groundwater infiltration into the system appears to occur nearly year-round, as indicated by the summer-long recession of outflow (fig. 63). In some areas of the county, such as along certain stream courses, groundwater levels are perennially high (Phillips and Dolphin, 1996), so that infiltration is likely to occur most of the time (see figs. 31 and 46). The absence of an increase in wastewater outflow as summer water use increases indicates that these increases are largely for outdoor uses, such as irrigation, which do not contribute to wastewater flows.

Prior to major suburban development, most areas of the county were served by septic systems, which returned about 90 percent of the water to the aquifer. An exception was Spring Valley, which was served by a sewage-treatment plant. Thus, water use in much of the county had a relatively minor effect on groundwater levels and the water budget. In contrast, the annual loss of water from the county through wastewater-treatment plants (14.57 Ggal) is equivalent to about double the annual streamflow from the Mahwah River recorded at the streamgage near Suffern. Recycling of even a portion of this water could augment the county's water supply.

Discharge of wastewater to surface or groundwaters in New York State is regulated under the SPDES permit system. Discharges to streams and rivers other than wastewater from sanitary sewering range from industrial cooling water to water pumped from traprock quarries, to wastewater from small treatment plants at popular park areas in the Highlands. Most of these discharges are relatively small; the largest is the discharge of up to 2.8 Mgal/d (624.5 Mgal in 2005) of spent cooling water from a pharmaceutical company into Muddy Brook, a tributary of Pascack Brook. Most of these waters are derived from groundwater and represent a loss from the groundwater system.

Synthesis—Study Objectives

The overall objectives for this study in the form of questions are listed below with findings:

1. Are current rates of groundwater withdrawal depleting the aquifer storage?

Review of pumping-rate and water-level data from the Newark basin bedrock aquifer as far back as 1989 suggests there is not a year-to-year, aquifer-wide downward trend in water levels. There have been periods of several years where water levels at individual wells have shown declines, and groundwater levels have declined substantially in response to new stresses as production wells have come on line, especially if they have been used continuously. Once a pumping stress is initiated, water levels decline toward a new equilibrium, where obtainable. Water levels in a large area in the west-central (most productive) part of the aquifer have declined because of near-continuous withdrawals and are associated with the greatest depths to water measured in the aquifer.

The greatest concern regarding sustainability of groundwater resources is the aquifer response to the annual increase in pumping rate during the growing season, which represented a daily average increase of 25 percent during this period in 2005 (fig. 61). Investigation of pumping rates and water levels during these periods indicates that water levels in most wells declined beyond what is expected under natural

[4] This value represents the non-growing season total daily water use (25.73 Mgal/d) minus the non-growing season daily water use from the Village of Suffern (1.04 Mgal/d), which is served by a wastewater treatment plant that discharges to the Ramapo River (both values from table 6A), plus transient and non-transient community supplies (0.028 Mgal/d) from table 6B. Summer increases in water use were not included in this estimate because treated wastewater outflows show no increase during this time period (fig. 63). Most of the increase in summer water use is attributed to outdoor use, such as lawn and garden irrigation, which does not enter sanitary sewers.

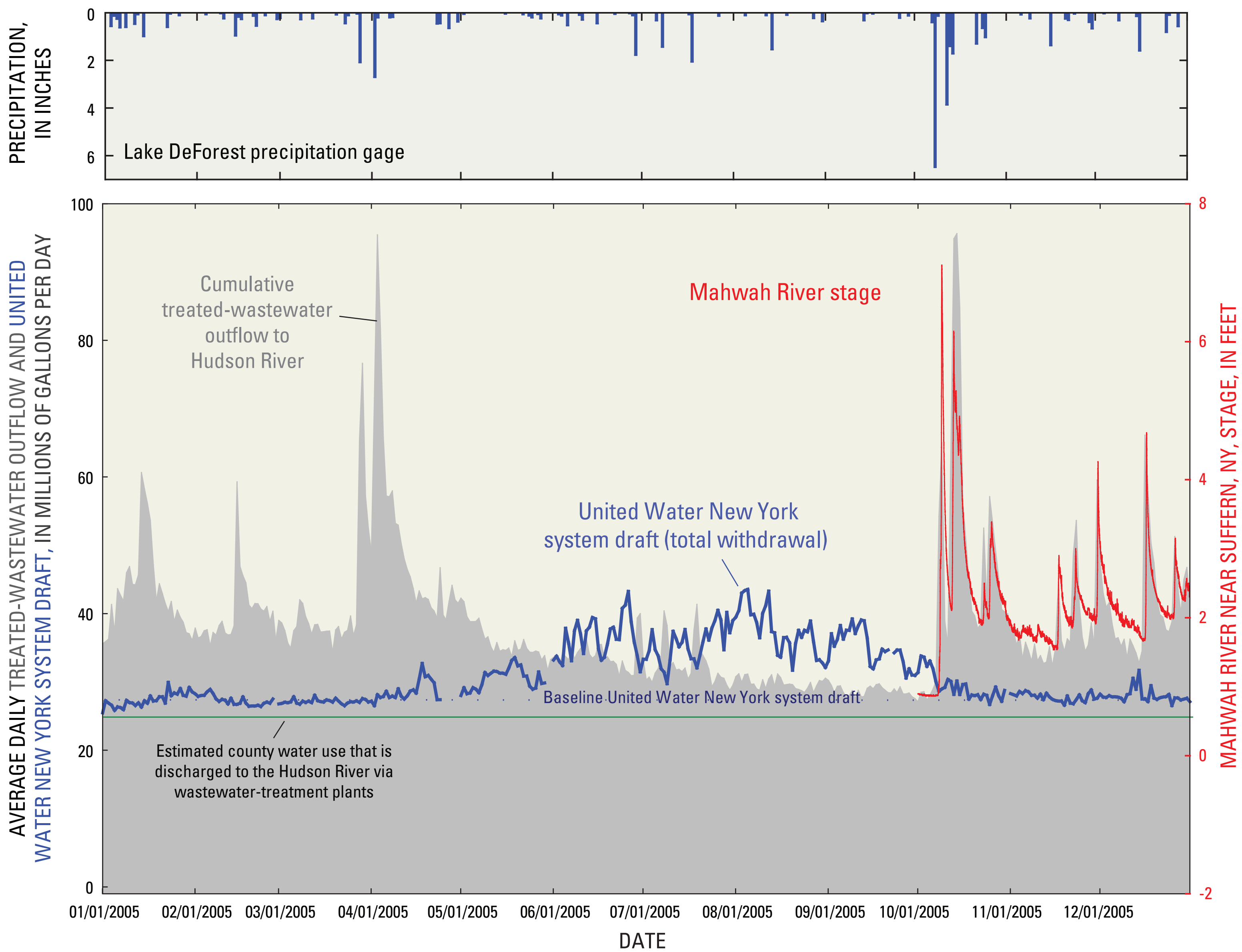


Figure 63. Comparison of 2005 total treated-wastewater outflow to the Hudson River, United Water New York system draft, Mahwah River stage, groundwater level at the U.S. Geological Survey Green Pond observation well (27–0028; http://nj.usgs.gov/gw-cgi/wldata.pl?UID=270028.rdb, accessed July 9, 2007); Morris County, New Jersey), and precipitation from the United Water New York precipitation station at Lake DeForest, Rockland County, New York.

(non-stressed) conditions and that the effective aquifer yield may decrease and entrained air may create problems in the distribution system (figs. 23–28) . Increased pumping rates at certain productive well fields during summer have resulted in decline rates that are not sustainable, resulting in the greatest stresses on the aquifer. Extrapolation of the rates of water-level decline under conditions of continuous pumping (a worst-case scenario, although assuming no change in yield over the summer) indicates that between 25 and 35 percent of production wells would not be able to pump during the entire high-use season. In most cases, pumping rates would have to be reduced as aquifer yield declines. This analysis underlines the fragility of the aquifer given the fact that recent years have been relatively wet. Large seasonal water-level fluctuations in the most productive west-central part of the aquifer indicate that recharge during the non-growing season, thus far, has been enough to replenish the aquifer prior to the next growing season. Seasonal loss of aquifer storage was also indicated by loss of streamflow; nearly all streams in the productive west-central area of the aquifer went dry during the driest periods in the summer of 2005.

2. Can rainfall data serve as a guide for determination of sustainable withdrawal rates for different climatic conditions? If so, what are sustainable rates for well fields that tap the aquifer?

Rainfall data alone cannot be used to determine sustainable withdrawal rates from the large number of production wells in Rockland County. Factors that determine whether a withdrawal rate in a bedrock well is sustainable include (1) the season (growing or non-growing), which determines the likely magnitude of recharge and the amount of aquifer storage; (2) precipitation amount, which is positively correlated with estimates of annual recharge (fig. 57), and thus, groundwater levels; (3) the distribution of rainfall and the duration of periods of high temperature within the growing season, which control the amount of recharge and, as important, water demand; and (4) growing season decline rate(s) associated with each well or well field (figs. 24–8). The amount of groundwater withdrawal from the aquifer during the non-growing season is largely sustainable because aquifer storage is at its annual maximum, and water demand is stable.

Aquifer storage decreases during the growing season both naturally and from groundwater withdrawals as the amount of recharge decreases (more rainfall is taken up by vegetation). Conditions that maximize sustainability of groundwater withdrawals at production wells include (1) high amounts of precipitation during the non-growing season, so that groundwater levels are high at the beginning of the growing season, and (2) evenly distributed rainfall and moderate temperatures during the growing season, which curb demand for outdoor uses and provide some recharge.

Rates of groundwater-level decline (figs. 27–28) for specific pumping rates at production wells (or well fields) are the key factors that are site-specific and intrinsic to the aquifer. Application of the precipitation/recharge factors described above to the decline rates provide a reasonable indication of the sustainability of pumping rates through the growing season.

3. Does induced infiltration of streamflow contribute water to supply wells?

Infiltration of streamflow into the aquifer induced by pumping is the primary source of water in alluvial aquifers of the Ramapo and Mahwah River valleys. In fact, pumping rates at the Ramapo Valley well field are limited by the requirement to maintain specific surface-water flows into New Jersey. Induced infiltration of stream water into the Newark basin (bedrock) aquifer is indicated by fragmentary evidence in a few areas, but most notably at Pascack Brook, near production well Pascack 65 (fig. 34).

The lack of streamflow over a large area in the western part of the aquifer in August–September 2005 indicated that groundwater that would have discharged to streams (base flow) was diverted to pumping wells because of low groundwater levels. Rather than induced infiltration from streams, groundwater is apparently intercepted before it can become streamflow.

4. Does leakage from water-supply mains and sanitary sewers contribute recharge to the aquifer?

Leakage from water mains, referred to as conveyance loss, is estimated at about 16 percent of the water withdrawn from groundwater and surface-water sources (D. Distante, United Water New York, written commun., 2007). Water mains are pressurized to move water and maintain pressure for consumers. This loss represents a return of water (artificial recharge) to the aquifer system.

Leakage from sanitary sewers does not appear to be an important source of recharge to the Newark basin aquifer. Sanitary sewers are gravity fed for the most part and are not pressurized. Wastewater is pressurized in force mains only in areas where local topography must be traversed. On the contrary, sanitary sewering *removes* water from the aquifer as groundwater infiltrates into sewer lines in areas with high groundwater levels (local low-altitude areas in particular). Figure 63 illustrates the slow decline in sanitary-sewer inflows that occurred during the relatively dry summer of 2005. Organic wastewater compounds, which are indicators of wastewater sources, were not identified in four samples from production wells, despite nitrate concentrations of at least 1 mg/L. Organic wastewater compounds were detected in four streamwater samples, however, which indicate that leakage from sewer lines is possible, but that in these cases, the wastewater indicators are entrained in the shallow, local groundwater system and discharge to the local stream.

5. What are the shape and extent of land-surface areas that contribute water to production wells?

The shape and extent of contributing areas to production wells are largely controlled by the orientation of water-bearing fractures, which are typically subparallel to the bedding of the sedimentary strata of the aquifer (fig. 21, fig. 23B).

The contributing area is, therefore, elongated along the strike of bedding and in an updip direction of the fracture to the water table. Downdip contributions are likely small because aquifer yield generally decreases with depth. The width of the contributing area updip is dependent on the dip of the fractures and bedding and topography (fig. 15); low dip angles (5 degrees) widen the contributing area, and high dip angles (15 degrees) narrow the contributing area. Pumping stresses along bedding strike may be increased by high dip angles because there is less updip aquifer storage than in aquifer areas with low fracture/bedding dip angles. Pumping effects translated along the strike of the bedding have been documented as far as 1 mi from a well field (fig. 23A, B). Contributing areas of production wells can be estimated through numerical computer model simulations of groundwater flow.

6. What is the distribution and amount of groundwater pumped from domestic wells?

There are an estimated 6,000 active private wells in Rockland County; 5,800 of these are used for domestic supply (table 7.). About 2,800 wells are within the UWNY service area. The remaining 3,000 wells are mostly on the fringes of the Highlands and the Palisades sill and are largely in the towns of Haverstraw and Stony Point. Base-line water use is about 1.3 Mgal/d, and growing-season water use is about 1.6 Mgal/d. Annual water use from domestic wells is approximately 534 Mgal.

7. What are the annual amounts of precipitation that fall across the county, and how much of that water recharges the bedrock aquifer?

Annual precipitation and other components of the water budget are not uniform across the county. Average precipitation during 2005–07 ranged from about 48 in. in the southeastern corner of the county to at least 58 in. in the north-northwestern part of the county (fig. 3)—a difference of about 21 percent. Estimates of recharge from a streamgage network in 1961 follow the same trend but differed by as much as 69 percent. Factors such as the thickness and texture of glacial deposits, the amount of impervious surface, and forested area affect the amount of recharge (fig. 51, fig. 52). Other factors that can affect estimates from gaged watersheds include impoundments of water, groundwater withdrawals, and discharges of water to the streams. The range of recharge from 1961 streamflow data was 14.7 to 24.8 in.

Recharge estimates from the long-term streamflow records from the Mahwah River near Suffern, NY, streamgage indicate the annual variability in recharge and its relation to precipitation. Recharge over 1959–94 and 2006 ranged between 14.3 and 34.7in. (681,000 to 1,652,000 gal/d/mi^2) with a median value of 21.8 in. (1,036,000 gal/d/mi^2) and were the highest recharge-rate estimates in the Newark basin aquifer; recharge rates to the southeast are considerably less (about 14.7 in. (700,000 gal/d/mi$^{2)}$ in 1961, which was not a dry year; table 6.). These data highlight the inherent variability in recharge from year to year and the danger in using a single value to characterize it across the aquifer. The estimates of recharge from this investigation are substantially higher than estimates from previous studies (Leggette, Brashears & Graham, Inc., 1979; Vecchioli, and Miller, 1973).

8. Are there additional water resources in the county that might be utilized?

There are sources of water within the county with potential for water supply from a hydrologic perspective, but each has its own set of issues and caveats that would have to be addressed. The first four resources are limited, and could be used to supplement water supply during summertime peak water-use periods. The last two options (desalinization of Hudson River water and indirect reuse of recycled water) represent large-volume sources. All sources are presented here briefly as a reference for future discussion.

1. Additional development of the groundwater resource in the Newark basin aquifer—large and small capacity wells and aquifer storage and recovery. A few large-capacity wells with yields on the order of hundreds of gallons per minute are possible in the most productive areas of the aquifer, but these possibilities are limited by existing domestic wells, water quality, lack of land area, and potential interference with existing supply wells. Locations with no existing production wells along bedrock strike would be optimal.
   A number of small developments in the past have been served by local supply wells even in less productive areas of the aquifer (see Perlmutter, 1959). Utilizing the resource in this way distributes the stress of withdrawals more evenly across the aquifer, rather than solely withdrawing water from high-capacity wells. There is potential for wells of this type in areas otherwise served by production wells in minimally utilized areas of the aquifer.
   Aquifer storage and recovery has been proposed as a means of enhancing aquifer storage in areas of high groundwater withdrawal (F. Getchall, Leggette, Brashears & Graham, Inc., written commun., 2009). Distribution-system water would be pumped into the aquifer from a well. This does not represent a major new source—he goal is optimization of the resource.

2. Surface water from the Highlands. Reservoirs could take advantage of the high annual precipitation in this part of the county. UWNY has recently (2006) begun using reservoirs in the Highlands area formerly used by the Letchworth Village State Mental Institution. Additional surface-water resources include:
   (a) Ambrey Pond Reservoir. A reservoir in this area (Town of Stony Point) has been considered. The drainage area of Ambrey Pond is small—additional water from Cedar Pond Brook (Lake Tiorati outflow) would be diverted to supplement the reservoir.
   (b) Stony Brook watershed impoundment to augment dry-weather flow in the Ramapo River. Retention of springtime or other wet-weather flows in the Stony

Brook watershed in the Town of Ramapo could be used to increase flow in the Ramapo River during dry summer periods, when low flows would curtail withdrawals from the Ramapo Valley well field, which draws water from the river into the alluvial aquifer. Enhanced impoundment in the Pine Meadow area has been considered previously (Quirk, Lawler, and Matusky Engineers, 1970). Much of this 18 mi^2 watershed is state park land.

3. Small-capacity production wells are another potential source of water in the Highlands. For example, the Ambrey Pond area, considered for development as a water-supply reservoir, might also be a favorable location for a production well (in glacial deposits or in combination with bedrock) if the glacial deposits are permeable. Other locations include low areas in the Highlands topography, where permeable stratified glacial deposits are present or along a lineament that might indicate underlying zones of concentrated fracturing in the local topography. Water available from either of these settings would be increased by the presence of lakes in hydraulic connection with these features.
4. Capture of stormflows in retention basins or reservoirs. As areas of impervious surface have increased in Rockland County, recharge to groundwater has decreased and stormflow volume has increased, which results in rapid loss of water downstream and out of the county. An estimated 770 Mgal of potential recharge is lost each year from the main bedrock aquifer area south and west of the Palisades sill because of impervious surfaces (about 12.6 percent). Stormwater retention basins in areas of permeable glacial deposits can provide an opportunity for recharge of stormwater within local watersheds. Alternatively, stormwaters might be impounded and pumped into the Lake DeForest watershed for downstream use at the reservoir. Diversion and impoundment of stormflows from rivers. such as the Ramapo and the Mahwah, has also been considered by Rockland County.
5. Desalinization of Hudson River water. The Hudson River represents a large source of brackish to salty water along the east side of Rockland County. Raw water is, therefore, unpotable, but desalinization of this water is a large potential source of water for the county. This option is currently being pursued by UWNY.
6. Recycled wastewater. Indirect reuse of recycled water is common practice in the United States at locations inland from salt-water bodies. Water is withdrawn for public supply, used, and then sent to wastewater-treatment plants, which discharge the treated water to “receiving water bodies” where biological activity and sunlight can further treat the water before reuse by downstream communities.

   The Village of Suffern recycles wastewater on the western side of the county—water is withdrawn from the alluvial well field, used, and then treated and discharged 0.25 mi downstream into the Ramapo River. A component of the Ramapo River flow at Suffern is in turn derived from upstream treated wastewater discharges at Tuxedo, Harriman, and Kiryas Joel.

   The majority of treated wastewater in Rockland County is discharged by four treatment plants into the brackish water of the Hudson River, where it becomes unavailable to downstream users. In 2005, about 14.1 Ggal of treated wastewater was discharged into the Hudson River. This amount of water exceeds the 2005 estimate of baseline water use that is discharged to the Hudson River by about 5 Ggal (fig. 63). If part of this water could be recycled at a high level of treatment, it could be used to meet downstream streamflow requirements to New Jersey or possibly within-county needs. For example, if treated water was pumped into the wetland area of the Hackensack River valley below Lake DeForest to meet downstream flow requirements in the Hackensack River, perhaps more Lake DeForest water could be used within Rockland County. Alternatively, direct use of recycled water might be a viable major water-supply source in the future. The primary concern with this type of water source is adequate treatment, including the removal of organic wastewater compounds such as pharmaceuticals and personal-care products.

Summary

Concerns over the state of water resources in Rockland County prompted an assessment of current (2005–07) conditions. The investigation included a review of all resources but centered on the Newark basin aquifer, a fractured-bedrock aquifer over which nearly 300,000 people reside.

A regional conceptual model of the aquifer framework was needed upon which other regional and local hydrogeologic data could be overlaid to define the regional groundwater flow system. From that point, water-resource questions could be addressed from a regional context.

The framework of the Newark basin aquifer system included characterization of (1) the texture, structure, and fracture occurrence associated with the Newark basin strata, (2) the texture and thickness of overlying glacial and alluvial deposits, (3) the occurrence of the Palisades sill and associated basaltic units on or within the Newark basin strata, and (4) the location of streams that drain the aquifer system. The structure of the aquifer was in part defined by previous mapping and strike and dip measurements of the clastic sedimentary strata that fill the basin, which generally coarsens westward from mudstones and siltstones to conglomeratic sandstones. Borehole geophysical surveys were conducted at 24 wells and provided unprecedented subsurface structural data. Other data that contributed to the conceptual model of the aquifer framework included groundwater-level responses to pumping at production wells and groundwater and surface-water chemistry (particularly chloride concentration data). The strike of the tilted bedding constrains groundwater flow because the most productive water-bearing fractures are subparallel to bedding. The general strike of bedding is north-northeast, and the dip is about 10 degrees to the northwest. The regional groundwater flow system was then delineated by overlaying aquifer-wide groundwater-level data on the bedrock framework (bedding strike). Groundwater divides were identified, including a major southeast to northwest regional divide that partitions groundwater flow northeastward to discharge at the Hackensack River and its tributaries and southwestward towards discharge points in the Mahwah River, Pascack Brook, and Saddle River drainages.

Review of pumping-rate and water-level data from the bedrock aquifer as far back as 1989 suggests that there is not a year-to-year, aquifer-wide downward trend in water levels. Water levels at individual wells have shown declines over periods of several years, and certainly, aquifer levels have declined substantially in response to new stresses as production wells have come on line, especially if they have been used continuously. Once a pumping stress is initiated, water levels move toward a new equilibrium. Groundwater levels in a large area in the west-central (most productive) part of the aquifer have declined due to withdrawals. The greatest depths to groundwater were measured in the same area of the aquifer.

The greatest concern regarding sustainability of groundwater resources is the aquifer response to the annual increase in pumping rates during the growing season (an average increase of 25 percent in 2005). Investigation of pumping rates and water levels during these periods indicates that water levels in most wells decline beyond what is expected under natural conditions and that the effective aquifer yield can decrease as water levels drop or as entrained air from stressed aquifer conditions creates problems in the distribution system. Increases in pumping rates at certain productive well fields during summer result in decline rates that are not sustainable and that represent the greatest stresses on the aquifer. Extrapolation of water-level decline rates under conditions of continuous pumping (a worst-case scenario, although assuming no change in yield over the summer) indicates that between 25 and 35 percent of production wells would not be able to pump through the entire high-use season. In most cases, pumping rates would have to be reduced as aquifer yield declined. This analysis underlines the fragility of the aquifer given the fact that recent years have been relatively wet. Large seasonal water-level fluctuations in the most productive part of the aquifer indicate that recharge during the non-growing season thus far has been enough to replenish the aquifer prior to the next growing season. Streams are also affected by increases in seasonal groundwater pumping; nearly all streams in the productive west-central area of the aquifer went dry during dry periods in the summer of 2005.

Impervious surfaces increase the percentage of stormflow and decrease the percentage of base flow in streams. Analysis of stormflows in watersheds with 11.9 and 17 percent impervious surface increased the percentage of rainfall that becomes stormflow in streams by 7 to 8 percent and 12.5 to 16.5 percent, respectively. An estimated 770 Mgal/yr of potential recharge is lost to the aquifer south of South Mountain because of impervious surfaces in the county.

Recharge was estimated from streamflow data and from groundwater-level data. Estimates from across the county in 1961 ranged from 24.8 in. in the northwest (Highlands) to 14.7 in. in the southeast. In a given location, recharge is largely controlled by the annual amount of precipitation; thus, recharge is probably highest in the Highlands, despite a relatively poor crystalline bedrock aquifer. Across the county, the thickness of glacial deposits on bedrock also appeared to be a major control on the amount of recharge. The distribution of monthly recharge was documented, including substantial recharge during the growing season in 2006.

Water budgets were generated for basins with streamflow data. Recent (1989–94, 2006) groundwater pumpage (public supply) accounts for between 12 to 24 percent of recharge at the Mahwah River near Suffern, NY, gaged watershed. Production-well pumpage as a percentage of recharge in 2006 at the two other currently gaged watersheds (Pascack Brook and Saddle River) was 18 and 21 percent, respectively.

About 12.9 Ggal of water was used in Rockland County in 2005. The majority (63 percent) was for residential use (non-growing season amounts) with about 6 percent of that amount withdrawn from domestic wells. Commercial, industrial, and institutional use make up 10 percent, and growing-season increases account for 18 percent of total use.

Sanitary sewers serve much of Rockland County and the majority of treated wastewater is discharged to the Hudson River, an estuary with brackish water adjacent to Rockland County. Inflow of stormwater and infiltration of groundwater constitute a significant additional contribution of water to the sanitary sewer system (about 36 percent in 2005).

Additional sources of potential water supply for the county were enumerated: (1) small capacity production wells in the Newark basin aquifer and the Highlands, (2) surface water in the Highlands, (3) capture of storm water, (4) desalinization of brackish Hudson River water, and (5) indirect reuse of recycled water.

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Appendixes

Appendix 3. United Water New York production-well data, including groundwater levels, March 2007, Rockland County, New York. Locations depicted in figure 20.

[ft, feet; NAVD 88, North American Vertical Datum of 1988]

Well name	United Water New York well-identification number (prefix "UWNY")	U.S. Geological Survey well-identification number (Prefix "Ro-")	Aquifer (aquifer zone)	Well depth (ft)	Well casing (ft)	Altitude at top of pump foundation (ft above NAVD 88)	2008 airline depth[1] (ft)	Production well usage	March 2007 groundwater-level range			
									Least-stressed water-level altitude (ft above NAVD 88)	Stressed water-level altitude (ft above NAVD 88)	Least-stressed water level (ft below land surface)	Stressed water level (ft below land surface)
Spring Valley	1A	81	Bedrock (C)	520	80	456.3	251	Constant		321.04		135.3
Spring Valley	3	83	Bedrock (C)	500	70	445.4	230	Constant		252.77		192.6
Spring Valley	4	84	Bedrock (C)	500	55	452.3	200	Constant		334.53		117.8
Spring Valley	6	85	Bedrock (C)	502	121	442.6	200	Constant		333.99		108.6
Sparkill	8	87	Bedrock (D.1)	481	62			Not used				
Nanuet	13	90	Bedrock (D)	325	108	262.6	200	Constant	208.45	180.87	54.2	81.7
Nanuet	14	91	Bedrock (D)	375	95	275.5	200	Constant	208.84	151.04	66.7	124.5
Blauvelt	15	92	Bedrock (D.1)	395	60	175.5	240	Constant		96.39		79.1
Tappan	16	8	Bedrock (D.1)	500	118	203.4	245	Nearly constant	101.53	33.24	101.9	170.2
Spring Valley	17	86	Bedrock (C)	506	77	447.3	240	Constant		301.42		145.9
New Hempstead	18	94	Bedrock (C)	300	81	483.0	238	Constant	406.41	393.19	76.6	89.8
Bardonia	19	289	Bedrock (C)	477	50	279.3	274	Not used	5.3	5.3	274.0	274.0
Tappan	20	93	Bedrock (D.1)	555	99	164.9	245	Nearly constant	102.47	58.76	62.4	106.1
Germonds	21	291	Bedrock (C)	601	241	294.8	250	No use	296.08		-1.3	
Pearl River	22	483	Bedrock (D)	655	54	224.0	230	Intermittent use -minor	176.41	161.03	47.6	63.0
New City	23	293	Bedrock (C)	430	53	207.3	250	No usage	200.61		6.7	
New Hempstead	24	295	Bedrock (C)	407	51	471.1	245	Constant	408.87	371.79	62.2	99.3
Tallman	26	294	Bedrock (B)	437	70	434.8	175	Constant		374.8		60.0
River	27	513	Sand & Gravel	119	72	311.1	70	Constant		261.53		49.6
Viola	28	130	Bedrock (B)	215	48	594.7	150	Constant		560.42		34.3
Ramapo	29A	1330	Sand & Gravel	83	61	306.9	55	Broad intermittent periods	302.96	259.3	3.9	47.6
Monsey	30	96	Bedrock (B)	420	100	620.4	204	No pumpage	530.2		90.2	

Appendix 3. United Water New York production-well data, including groundwater levels, March 2007, Rockland County, New York. Locations depicted in figure 20.—Continued

[ft, feet; NAVD 88, North American Vertical Datum of 1988]

Well name	United Water New York well-identification number (prefix "UWNY")	U.S. Geological Survey well-identification number (Prefix "Ro-")	Aquifer (aquifer zone)	Well depth (ft)	Well casing (ft)	Altitude at top of pump foundation (ft above NAVD 88)	2008 airline depth[1] (ft)	March 2007 groundwater-level range				
								Production well usage	Least-stressed water-level altitude (ft above NAVD 88)	Stressed water-level altitude (ft above NAVD 88)	Least-stressed water level (ft below land surface)	Stressed water level (ft below land surface)
Monsey	31A	97	Bedrock (B)	357	50	509.7	200	No pumpage	482.77		26.9	
Wesel	32	544	Bedrock (C)	308	62	308.8	175	Trace usage[1] day	298.97	290.86	9.8	17.9
Pomona	37	545	Bedrock (C)	411	31	410.0	107	Constant		366.23		43.8
Pomona	38	546	Bedrock (C)	399	63	405.0	50	No pumpage through end of april, nearly constant thereafter				
Catamount	42A	566	Sand & Gravel	66	46	399.0	54	Constant		359.53		39.5
Fairmount	44	175	Bedrock (D?)	450	125			Not used				
Garnerville	46	198	Bedrock (D?)	320	32			Not used				
Thiells No.8	50	1331	Sand & Gravel	76.8	63	296 (floor of pump-house)		Not used				
Thiells No.9	51	547	Bedrock (D?)	403	168	310.0	250	Constant		96.7		213.3
Saddle River	53	548	Bedrock (C)	351	51	296.0	197	Constant		160.72		135.3
Catamount	54A	567	Sand & Gravel	107	78	397.0	76	Constant		339.82		57.2
Nottingham	55	549	Bedrock (A/B)	354	71	324.2	200	Intermittent use	319.85	269.54	4.3	54.7
Willow Tree	56	550	Bedrock (B)	350	60	478.0	155	Constant, some var.	448.01	421.67	30.0	56.3
Norge	64	551	Bedrock (C)	352	97	297.3	196	Intermittent use -minor	287.3	262.61	10.0	34.7
Pascack	65	552	Bedrock (C)	404	50	380.7	200	Intermittent use	348.26	332.52	32.4	48.2
Elmwood	66	553	Bedrock (C)	401	79	141.5	85	No pumpage	137.85		3.7	

Appendix 3. United Water New York production-well data, including groundwater levels, March 2007, Rockland County, New York. Locations depicted in figure 20.—Continued

[ft, feet; NAVD 88, North American Vertical Datum of 1988]

Well name	United Water New York well-identification number (prefix "UWNY")	U.S. Geological Survey well-identification number (Prefix "Ro-")	Aquifer (aquifer zone)	Well depth (ft)	Well casing (ft)	Altitude at top of pump foundation (ft above NAVD 88)	2008 airline depth[1] (ft)	March 2007 groundwater-level range				
								Production well usage	Least-stressed water-level altitude (ft above NAVD 88)	Stressed water-level altitude (ft above NAVD 88)	Least-stressed water level (ft below land surface)	Stressed water level (ft below land surface)
Grandview	67	554	Bedrock (A/B)	435	16	390.5	250	No recorded pumpage, missing data	140.5	140.5	250.0	250.0
Cherry	68	555	Bedrock (B)	455	26	378.8	150	Intermittent use	375.94	315.64	2.9	63.2
Pinebrook	69	556	Bedrock (C)	402	35	360.8	195	Intermittent use	355.08	291.16	5.7	69.6
Birchwood	70	557	Bedrock (C)	450	37	344.3	150	No pumpage	333.37		10.9	
Eckerson 1	71	558	Bedrock (C)	406	55	448.8	200	Broad intermittent periods	248.8	248.8	200.0	200.0
Rustic	72	559	Bedrock (B)	401	100	419.3	203	Broad intermittent periods	404.84	310.7	14.5	108.6
Lake Shore.	73	560	Bedrock	363	65	303.2	150	Intermittent use -minor	303.03	264.62	0.2	38.6
Grandview	78	561	Bedrock (A/B)	452	51	398.3	266	No pumpage	385.69		12.6	
West Gate	79	562	Bedrock (D)	400	51	132.3	250	Nearly constant	102.53	-69.53	29.8	201.8
Eckerson 2	82	563	Bedrock (B)	454	76	472.3	214	Intermittent use	439	425.89	33.3	46.4
Grotke	83	564	Bedrock (C)	500	66	285.3	200	Nearly constant	262.78	161.55	22.6	123.8
Viola (new)	106	565	Bedrock (B)	440	50	599.0	183	Constant		558.97		40.0
							46			38	30	

[1]2008 Leggette, Brashears & Graham, Inc., written commmun., 2008.

Appendix 6. $^{3}H/^{3}He$ ages of groundwater samples, Rockland County, New York. Analyses by Lamont-Doherty Earth Observatory, Palisades, New York.

[Samples in red contain radiogenic ^{4}He, ages were corrected accordingly (using $2e^{-8}$ as radiogenic $^{3}H/^{4}He$ ratio), STP (standard temperature and pressure), 0 degrees celsius and 1 atmosphere of pressure]

Well identification number	Sampled interval (feet below land surface)	Sample date	Tritium concentration (tritium units)[1]	Error +/-	$d^{3}He$ (percent)[2]	Error +/-	^{4}He ccSTPg[3]	Error +/-	Ne ccSTPg[4]	Error +/-	Age (years before sample date)	Error +/-
UWNY 56	entire well	10/24/2006	5.4	0.7	7.8	1.0	0.000	0.000	0.000	0.000	7.9	0.8
Ro-1277	entire well	10/19/2006	4.7	0.6	-18.4	1.0	0.000	0.000	0.000	0.000	18.7	2.0
UWNY 78	entire well	10/24/2006	2.5	0.5	2.1	1.0	0.000	0.000	0.000	0.000	23.0	2.6
Ro-1289	335–495	07/19/2006	0.10	0.02	-6.2	0.3	0.000	0.000	0.000	0.000	≥48	3.4
Ro-1289	50–150	07/20/2006	10.39	0.13	66.0	0.3	0.000	0.000	0.000	0.000	22.9	0.3
Ro-1221	entire well	10/24/2006	3.8	0.6								

[1] Tritium units (TU), 1 TU = $^{3}H/^{1}H$ ratio of 10^{-18}.

[2] $d^{3}He$ is the percent deviation of the measured $^{3}He/^{4}He$ ratio from the atmospheric value.

[3] ^{4}He ccSTPg, Helium 4, in cm^{3}/g at STP.

[4] Ne ccSTPg, Neon, in cm^{3}/g at STP.

Appendix 7. Organic wastewater compound analyses of streams and production wells, Rockland County, New York. Analyses by USGS National Water Quality Laboratory, Denver, Colorado.

[laboratory remark code for all samples is E, (estimated); NY, New York; MRL, Minimum reporting limit; MDL, Minimum detection limit]

Station Name	Sample Date	Sample Time	Result (ug/L)	MRL and MDL (ug/L)	Parameter
Streams					
Pascack Brook Tributary at Spring Valley, NY	9/27/2006	1055	0.003	0.5	anthracene
Pascack Brook Tributary at Spring Valley, NY	9/27/2006	1055	0.004	0.5	fluoranthene
Pascack Brook Tributary at Spring Valley, NY	9/27/2006	1055	0.003	0.5	phenanthrene
Pascack Brook Tributary at Spring Valley, NY	9/27/2006	1055	0.005	0.5	pyrene
Pascack Brook Tributary at Spring Valley, NY	9/27/2006	1055	0.031	0.5	caffeine
Pascack Brook Tributary at Spring Valley, NY	9/27/2006	1055	0.011	0.5	acetyl-hexamethyl-tetrahydro-naphthalene (ahtn)
Pascack Brook Tributary at Spring Valley, NY	9/27/2006	1055	0.015	0.5	anthraquinone
Pascack Brook Tributary at Spring Valley, NY	9/27/2006	1055	0.007	0.5	camphor
Pascack Brook Tributary at Spring Valley, NY	9/27/2006	1055	0.277	2	cholesterol
Pascack Brook Tributary at Spring Valley, NY	9/27/2006	1055	0.038	0.5	tri(2-chloroethyl) phosphate
Pascack Brook Tributary at Spring Valley, NY	9/27/2006	1055	0.018	0.5	tri(dichloroisopropyl) phosphate
Pascack Brook Tributary at Spring Valley, NY	9/27/2006	1055	0.092	0.5	tri(2-butoxyethyl) phosphate
New City Brook near New City, NY	9/27/2006	0900	0.004	0.5	fluoranthene
New City Brook near New City, NY	9/27/2006	0900	0.014	0.5	isophorone
New City Brook near New City, NY	9/27/2006	0900	0.004	0.5	phenanthrene
New City Brook near New City, NY	9/27/2006	0900	0.003	0.5	pyrene
New City Brook near New City, NY	9/27/2006	0900	0.006	0.5	tetrachloroethylene
New City Brook near New City, NY	9/27/2006	0900	0.029	0.5	caffeine
New City Brook near New City, NY	9/27/2006	0900	0.008	1	3-methyl-1h-indole (skatol)
New City Brook near New City, NY	9/27/2006	0900	0.008	0.5	acetyl hexamethyl tetrahydro naphthalene (AHTN)
New City Brook near New City, NY	9/27/2006	0900	0.044	0.5	benzophenone
New City Brook near New City, NY	9/27/2006	0900	0.011	0.5	camphor
New City Brook near New City, NY	9/27/2006	0900	0.055	1	p-cresol
Saddle River near Spring Valley	9/27/2006	1345	0.003	0.5	anthracene
Saddle River near Spring Valley	9/27/2006	1345	0.014	0.5	fluoranthene
Saddle River near Spring Valley	9/27/2006	1345	0.014	0.5	phenanthrene
Saddle River near Spring Valley	9/27/2006	1345	0.070	0.5	phenol
Saddle River near Spring Valley	9/27/2006	1345	0.006	0.5	pyrene
Saddle River near Spring Valley	9/27/2006	1345	0.008	1	3-methyl-1H-indole (skatol)
Saddle River near Spring Valley	9/27/2006	1345	0.038	0.5	camphor

Appendix 7. Organic wastewater compound analyses of streams and production wells, Rockland County, New York. Analyses by USGS National Water Quality Laboratory, Denver, Colorado.—Continued

[laboratory remark code for all samples is E, (estimated); NY, New York; MRL, Minimum reporting limit; MDL, Minimum detection limit]

Station Name	Sample Date	Sample Time	Result (ug/L)	MRL and MDL (ug/L)	Parameter
Saddle River near Spring Valley	9/27/2006	1345	0.004	0.5	carbazole
Saddle River near Spring Valley	9/27/2006	1345	0.005	0.5	indole
Saddle River near Spring Valley	9/27/2006	1345	0.282	1	p-cresol
Nauraushaun Brook at Nauraushaun, NY	9/27/2006	1145	0.018	0.5	caffeine
Nauraushaun Brook at Nauraushaun, NY	9/27/2006	1145	0.062	0.5	tris(dichloroisopropyl) phosphate
Nauraushaun Brook at Nauraushaun, NY	9/27/2006	1145	0.706	0.5	tris(2-butoxyethyl) phosphate
Nauraushaun Brook at Nauraushaun, NY	9/27/2006	1146	0.687	0.5	tris(2-butoxyethyl) phosphate
United Water New York (UWNY) Wells					
UWNY 1A (Spring Valley wellfield)	9/6/2006	1115	0.847	0.5	tetrachloroethylene
UWNY 28 (no detections)	9/6/2006	1230			
UWNY 83 (no detections)	9/6/2006	0950			
UWNY 37	9/6/2006	1415	0.014	0.5	isophorone

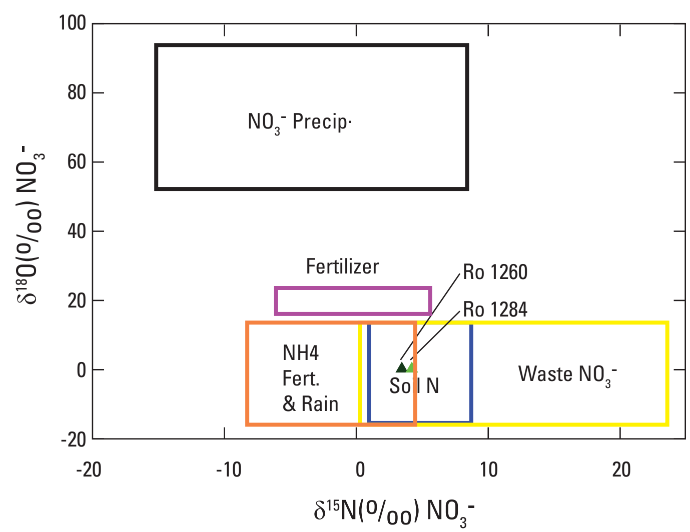
Explanation of compounds

Compound	Use / Source
anthracene	hydrocarbon
fluoranthene	hydrocarbon
phenanthrene	hydrocarbon
pyrene	hydrocarbon
caffeine	stimulant
acetyl-hexamethyl-tetrahydro-naphthalene (ahtn)	fragrance
anthraquinone	geese repellent, pesticide
camphor	insecticide, fungicide, microbiocide
cholesterol	fecal sterol
tri(2-chloroethyl) phosphate	fire retardant
tri(dichloroisopropyl) phosphate	fire retardant
tri(2-butoxyethyl) phosphate	plasticizer, floor polish, fire retardant
isophorone	solvent for inks (can remain in water for ~20 days)
3-methyl-1h-indole (skatol)	constituent of human feces
benzophenone	fragrance, photosensitizer, UV protection cream
p-cresol	tar, wood, vehicle exhaust, wood smoke, household sanitizer
tetrachloroethylene	solvent, volatile organic compound (VOC)
carbazole	poly aromatic hydrocarbon (PAH)
indole	coal tar (PAH)

Appendix 8. Analyses of nitrogen and oxygen isotopes in nitrate, Rockland County, New York. Analysis by U.S. Geological Survey Reston Stable Isotope Laboratory (RSIL), Reston, Virginia.

USGS well identification number (Ro-)	Sample date	Sample time	Nitrate concentration (mg/L as N)	Nitrate concentration (mg/L as N)	Nitrate concentration (mg/L as N)	Average nitrate concentration (mg/L as N)	Standard deviation nitrate concentration (mg/L as N)	d ^{15}N (per mil NO_3^-)	d ^{18}O (per mil NO_3^-)
			run 1	run 2	run 3	(from RSIL)			
1260	7/25/2007	1205	5.22	5.19	5.26	5.22	0.03	3.53	2.82
1284	7/25/2007	0915	6.28	6.20	6.27	6.25	0.04	4.23	2.84

(Plot from Kendall and others, 2007)



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