DETERMINATION OF THE CONTRIBUTING AREA TO SIX MUNICIPAL GROUND-WATER SUPPLIES IN THE TUG HILL GLACIAL AQUIFER OF NORTHERN NEW YORK, WITH EMPHASIS ON THE LACONA-SANDY CREEK WELL FIELD

By Phillip J. Zarriello

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CONVERSIONS FACTORS AND VERTICAL DATUM

Multiply	*By*	*To Obtain*
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
acre	0.4047	hectare
	Flow	
gallon per minute (gal/min)	0.06309	liter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per day (ft^3/d)	0.02832	cubic foot per day
inch per year (in/yr)	25.4	millimeter per year
	Transmissivity	
cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/d)/ft^2]ft$	0.09290	cubic meter per day per square meter times meter of aquifer thickness
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
	Temperature	
degrees Fahrenheit (°F)	°C = 5/9 (°F-32)	degrees Celsius

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

Determination of the Contributing Area to Six Municipal Ground-Water Supplies in the Tug Hill Glacial Aquifer of Northern New York, with Emphasis on the Lacona-Sandy Creek Well Field

By Phillip J. Zarriello

Abstract

The contributing areas to six municipal ground-water supplies (Adams, Mannsville, Lacona-Sandy Creek, Pulaski, Orwell, and Camden) that tap the Tug Hill aquifer were estimated from surficial geologic maps and potentiometric-surface maps. Contributing areas to the individual water supplies ranged from 0.01 to 1.0 square mile (mi^2) but may include as much as 17 mi^2 of adjacent upland areas that contribute recharge to the aquifer through streambed infiltration and direct runoff. The potential for contamination within the contributing area is low because the region is predominantly rural.

The contributing area to the Lacona-Sandy Creek well field was calculated by several methods for purposes of comparison. A finite-difference ground-water flow model and a post-processing particle-tracking program were used for a range of pumping, recharge, and hydraulic conductivity values. Ground-water budgets computed from steady-state simulation indicate that most of the water pumped by the wells is water that would be lost to springs and as evapotranspiration in the western flank of the aquifer. High pumping rates combined with low recharge rates may induce minor infiltration from Little Sandy Creek. Results of flow-path analysis indicate that (1) the size and shape of the contributing area differs significantly from the area of influence (the surface expression of the cone of depression), (2) flow paths from the eastern edge of the aquifer are less than 1 mile long, and (3) travel times to the supply well are generally between 500 and 1,000 days.

Two modified analytical techniques also were used—the Dupuit uniform-flow method and the Theis nonequilibrium method. Analytical methods are easier to apply than numerical methods but are constrained by limiting assumptions that, if not satisfied, can result in large errors. The Dupuit method, modified for a sloping water table, indicated a contributing area of 0.04 mi^2 for a production well pumped at 200 gallons per minute and a horizontal hydraulic conductivity of 1,200 feet per day. This is smaller than the 0.13-mi^2 contributing area obtained by numerical techniques for similar hydraulic properties, and its position differs also. The Theis method modified for partial penetration of the pumped well, dewatering of the aquifer, and a single linear impermeable boundary indicated a contributing area of 0.12 mi^2, the size and shape of which is similar to the contributing area obtained by the numerical simulation.

The selection of a technique for delineating a contributing area ultimately depends on the resources available for the analysis and the degree of accuracy required. Despite the uncertainties and incomplete information on the factors that affect the size of the contributing area, the four methods used in this study provide a more reliable estimate than the commonly used fixed-radius method.

INTRODUCTION

Ground water is the source of water to 36 percent (2.8 million) of New York's population, excluding Long Island (Waller and Finch, 1982) and in 1985 accounted for 12 percent of the freshwater used in New York State (Snavely, 1988). Detection of chemical compounds in ground-water supplies has resulted in the closure of more than 120 public water-supply wells in New York since 1978 (Rogers, 1986). Contamination of the most productive and heavily used aquifers is a growing concern because many of them are just below land surface and underlie heavily urbanized or intensively farmed areas. Protection of these aquifers from contamination is essential to ensure an adequate and safe water supply for current and future needs.

In 1986, Congress amended the 1974 Safe Drinking Water Act to strengthen the protection of public water-supply wells from contamination. Section 1428 of the amendments established the Well Head Protection Program (WHPP), which is administered through the U.S. Environmental Protection Agency. Specific criteria and implementation of the WHPP are the responsibility of each State. The general goals of the WHPP are to (1) define the contributing area to public water-supply wells, (2) identify within the contributing area potential sources of contamination that may adversely affect the water supply and public health, and (3) identify alternative water supplies for use in the event that the current water supply becomes contaminated.

In New York State, the agency charged with the responsibility for developing a WHPP is the Department of Environmental Conservation (NYSDEC). The draft WHPP submitted by NYSDEC identifies current regulatory and management structures that protect public water supplies and public health. The NYSDEC's goal is to integrate this into a coherent and consistent statewide approach and identify new management or regulatory needs to protect public ground-water supplies. As part of this effort, NYSDEC entered into an agreement with the Temporary Commission on Tug Hill through the Central New York Regional Planning and Development Board to develop a WHPP demonstration project. The Tug Hill glacial aquifer (herein referred to as the Tug Hill aquifer), in northern New York (fig. 1), was selected because (1) the Tug Hill Commission is engaged in promoting public participation, education, and technical assistance to the region, and (2) previous work by the U.S. Geological Survey (Miller and others, 1989) delineated the aquifer boundaries and gave a general appraisal of the ground-water resources. This in turn led to a cooperative agreement between the Tug Hill Commission and the U.S. Geological Survey to identify sources of water to six municipal water supplies from available geohydrologic information and to evaluate methods for delineating the area that contributes water to the well field for the villages of Lacona and Sandy Creek (locations shown in fig. 1).

Purpose and Scope

This report provides information on the ground-water supply to six municipalities (Adams, Mannsville, Lacona-Sandy Creek, Pulaski, Orwell, and Camden) that have developed supplies in the Tug Hill aquifer. It discusses the hydrogeologic conditions of the aquifer and probable sources of recharge to each well field and gives a detailed analysis of the contributing area to Lacona-Sandy Creek well field to demonstrate and evaluate three delineation techniques—two analytical methods and a two-dimensional numerical finite-difference model. Maps depict the estimated contributing area to each water supply.

Physiographic Setting

The Tug Hill aquifer is a 47-mi-long, crescent-shaped sand and gravel deposit along the west and southwest flank of the Tug Hill Plateau in northern New York (fig. 1). The plateau is a remnant of the Allegheny Plateau to the south that was bisected by glacial meltwaters in the Mohawk valley. Flanking the plateau are lowlands of the Black River valley to the north and east and lowlands of the Erie-Ontario plain to the west. The plateau consists of southward dipping sedimentary rocks mantled in most places by 5 to 40 ft of till. Some valleys in the plateau contain as much as 187 ft of unconsolidated deposits consisting of sand and gravel and lacustrine fine sand and silt (Miller and others, 1989).

The Tug Hill area receives between 45 and 55 in/yr of precipitation, one of the highest average rates in New York State. Large amounts of precipitation are caused by relatively cool prevailing west winds that pick up heat and moisture from Lake Ontario predominantly during the fall and winter, which condenses over the Tug Hill Plateau and the western slopes of the Adirondack Mountains. The large amounts of precipitation, low relief, and poor drainage make the plateau swampy in many areas.

The Tug Hill region is predominantly woodlands (41 percent); crop and dairy farming occupy 31 percent of the area, and wetlands occupy 17 percent. Much of the present woodland was once cultivated but has been abandoned because the soils are thin, acidic, and poorly drained, and the climate cool and wet. The remaining 11 percent of the land contains commercial development, residential areas, transportation corridors, and miscellaneous uses. The area is sparsely populated because the climate is cool and wet and the soils generally poor.

Hydrogeologic Setting

The unconsolidated deposits that form the Tug Hill aquifer resulted from the most recent continental glaciation, which ended approximately 12,000 years ago. The distribution of glacial deposits and their relation to the succession of ice-margin advances and retreats is explained in detail by Miller and others (1989). In general, the aquifer consists of two distinct types of ground-water flow systems that reflect the type of depositional processes that formed them.

Glacial History and Water-Bearing Characteristics

In the southern part of the aquifer, south of the West Branch Fish Creek valley (fig. 1), glacial scouring deepened and widened the valleys, which subsequently filled with lacustrine deposits in glacial and proglacial lakes, then recent alluvial deposits. This area also contains many kames, kame terraces, eskers, and outwash deposits that generally yield large quantities of water to wells. These deposits are variable in thickness and permeability and are confined in some places by poorly permeable deposits that formed in proglacial lakes.

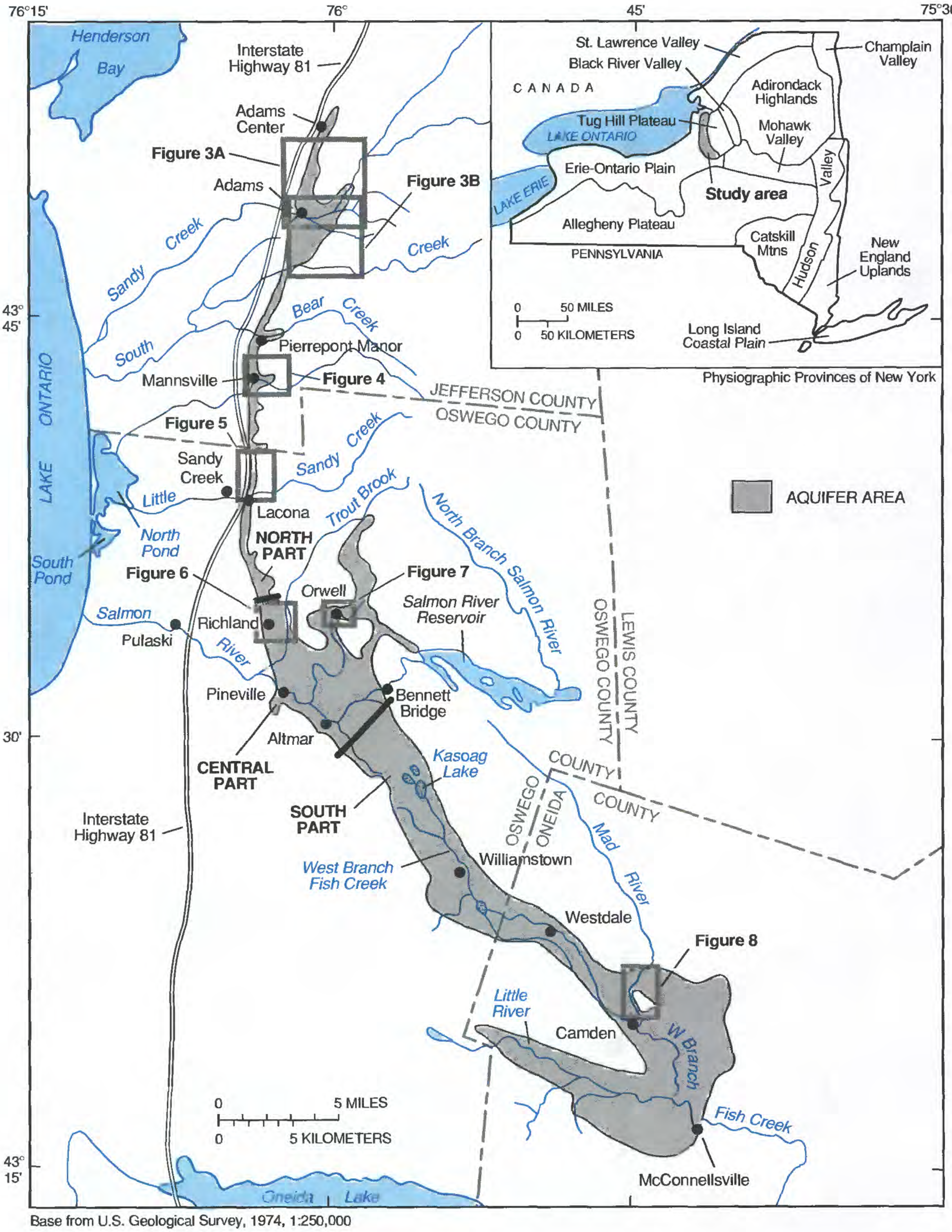


Figure 1.--Location and major geographic features of the Tug Hill aquifer. (Modified from Miller and others, 1989, fig. 1.)

In the northern part of the aquifer, north of Bennett Bridge, wave action along proglacial Lake Iroquois reworked glaciolacustrine till, alluvium, and outwash deposits to form well-sorted deposits of beach sand and gravel and offshore sand bars and deltas. The eastern flank of this part of the aquifer also contains small amounts of outwash and alluvium. These deposits are generally thinner (10 to 50 ft thick) and narrower (0.25 to 0.75 mi) than those that form the southern part.

The central part of the aquifer, between the West Branch of Fish Creek and Bennett Bridge, consists of a mix of the glaciofluvial deposits to the south and glaciolacustrine deposits to the north.

Ground-Water Occurrence and Movement

Precipitation is the source of all ground water. Precipitation in the Tug Hill region ranges between 45 and 55 in/yr, of which more than 60 percent falls during the nongrowing season (Knox and Nordenson, 1955; Dethier, 1966). Not all precipitation is available for ground-water recharge, however; some returns to the atmosphere through evapotranspiration, and some runs off as surface flow to streams and lakes. The remaining water, which is available to recharge the aquifer, is estimated by Miller and others (1989) to be 27 in/yr in the northern and southern parts of the aquifer and 31 in/yr in the central part.

Ground water in the southern part of the aquifer generally flows from the valley walls toward the center of the valley and downvalley toward the south-southeast, where it discharges predominantly into the West Branch Fish Creek and Little River. The direction of ground-water flow may vary locally, however, depending on the composition of the glacial deposits through which it flows.

Ground water in the northern part of the aquifer generally flows westward and originates mainly from precipitation on the aquifer and indirectly from stream runoff from the till-covered uplands that seeps into the aquifer. The aquifer forms a wedge shape that thins to the east and is bordered by the underlying bedrock that slopes upward toward the east and by till and lake deposits on the west. Ground water in this part of the aquifer discharges through numerous springs and wetlands along the west margin of the aquifer.

Acknowledgments

The author thanks Mayor Donald MacVean and Mark Harvey of Sandy Creek for providing information and access to the Lacona-Sandy Creek well field. Special thanks are also extended to Thomas Feeney of the Tug Hill Commission for collecting information on municipal water supplies, and assisting in field work.

CONTRIBUTING AREA TO A WELL

A principal objective of this study was to delineate the sources of water to the municipal groundwater supplies in the Tug Hill aquifer. Because the concepts and terms used to define the sources of water to a well are often interchanged in common usage and may therefore lead to confusion, the principal concepts and terms used in this report are defined below.

Concepts and Definitions

The *contributing area* to a well is the land overlying the *zone of contribution*, which is the geometric volume from which ground-water flow is diverted toward the well (Morrissey, 1987). Areas outside the aquifer that contribute water to wells are collectively referred to as the *upland contributing area.* Sources of water from upland contributing areas include unchanneled overland runoff and streams that drain upland area and lose all or part of their flow into the aquifer.

The *contributing area* is commonly confused with the *cone of depression*, which represents the difference between the water-table or potentiometric-surface altitude before pumping and that which forms after the pumping has begun (Theis, 1938). The *area of influence* is the land area overlying the *cone of depression* (Meinzer, 1923). The *area of influence* is typically limited to that part of the aquifer in which water is perceptibly lowered by the withdrawal. This term commonly is considered synonymous with the contributing area but, in fact, is the same only when the aquifer properties and water-table elevation under prepumping conditions are uniform throughout the system (Morrisey, 1987).

The above concepts and definitions are illustrated in figure 2 in a series of diagrams showing flow nets constructed for a hypothetical aquifer. During non-pumping conditions (fig. 2A), equipotential lines are parallel to the river, and flow is evenly distributed toward the river. Simulated drawdowns resulting

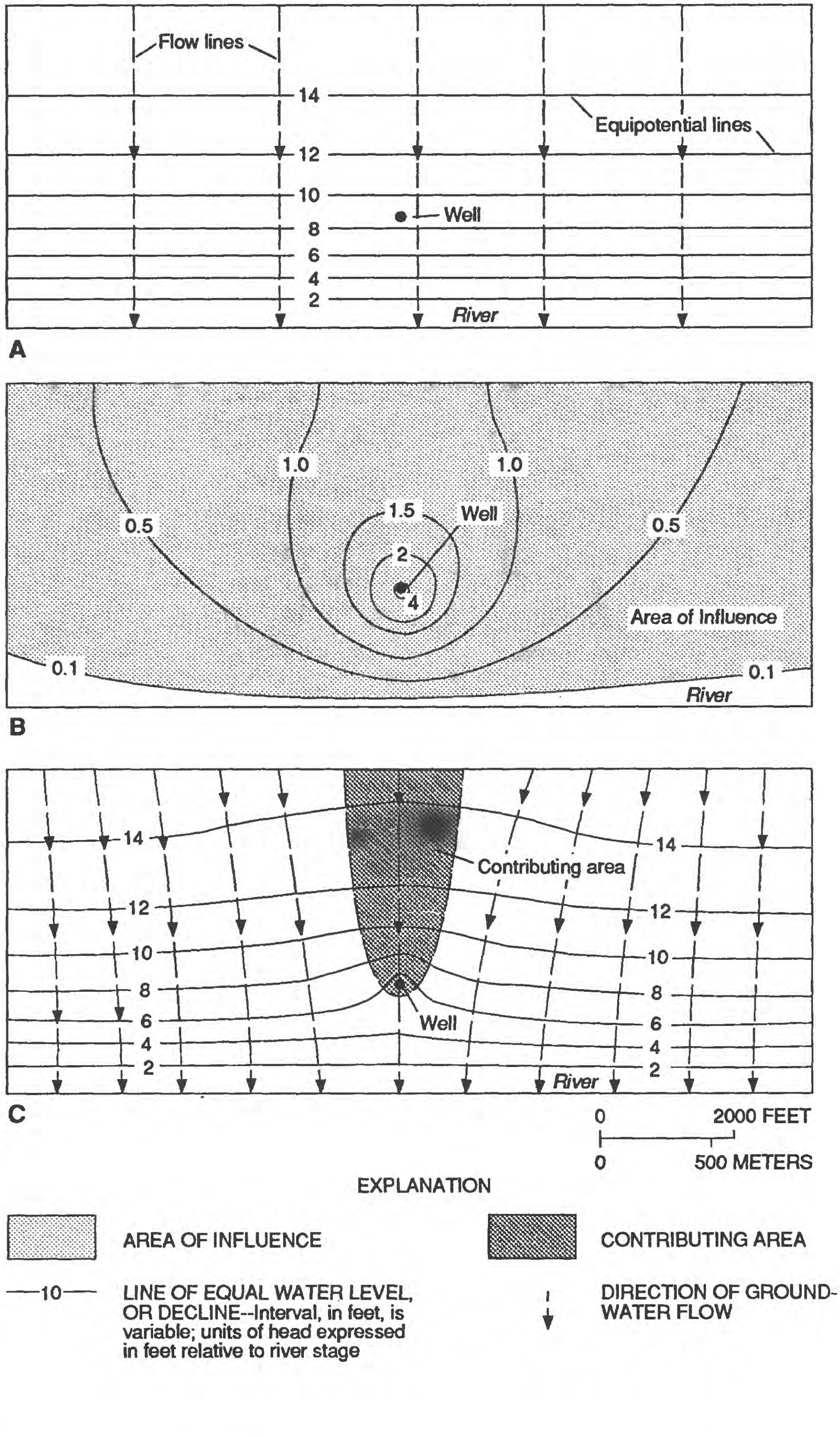


Figure 2.--Plan views of a hypothetical aquifer illustrating (A) prepumping equilibrium water-table configuration. (B) Drawdowns and the area of influence of the pumped well. (C) Contributing area to the well. (From Morrissey, 1987.)

from pumping show the *area of influence* within the 0.1-ft drawdown line (fig. 2B), which is the planimetric view of the *cone of depression.* Superimposing the drawdown depicted in figure 2B onto the prepumping potentiometric surface depicted in figure 2A gives the new potentiometric surface, shown in figure 2C. Flow lines constructed from the resultant potentiometric map show the area in which ground water is diverted to the pumped well. In general, as the natural hydraulic gradient decreases, flow is diverted around the well in an increasingly uniform pattern. If, for example, the water-table surface shown in figure 2A were of uniform elevation, equipotential lines shown in figure 2C would have the same shape as the contours shown in figure 2B. Therefore, flow lines could be drawn directly, and the contributing area would be the same as the area of influence. Conversely, as the natural hydraulic gradient steepens, the distortion of the contributing area upgradient becomes increasingly pronounced. The effect of the natural hydraulic gradient on the contributing area is discussed later in the section on application of the uniform-flow model. The above example illustrates (1) the difference between the area of influence and the contributing area to a well, and (2) how the cone of depression and the natural hydraulic gradient affect the contributing area to a well.

Factors That Affect Contributing Area

The principal factors that control the contributing area to a well, first presented by Theis (1940) are: (1) the distance from the well to the source of recharge and the type and rate of recharge, (2) the distance from the well to the area of natural discharge, and (3) the extent and direction of the cone of depression. In essence, any geohydrologic factor that affects the flow field around a well affects the contributing area. Morrissey (1987) lists eight specific factors that affect the contributing area to a well:

1. Well-discharge rate and duration of pumping.
2. Aquifer transmissivity (a function of aquifer thickness and hydraulic conductivity).
3. Aquifer storage coefficient or specific yield.
4. Proximity of the pumped well to aquifer discharge and recharge boundaries.
5. Spatial and temporal variations in aquifer transmissivity and(or) storage coefficient.
6. Spatial and temporal variations in aquifer recharge.
7. Partial penetration of the pumped well.
8. The presence of extensive confining layers.

All of these reflect one or more of the factors described by Theis. The extent to which these factors influence the contributing area to a supply well depend on the conditions of the site under consideration. The factors that predominate at a given site should be considered when the technique to estimate the contributing area to a well is selected.

In addition to these factors, Theis (1940) emphasizes that to predict how an aquifer will respond to a newly imposed stress requires knowledge of the conditions of equilibrium within the aquifer. Withdrawals from an aquifer previously in a state of dynamic equilibrium must be balanced by (1) an increase in recharge, (2) a decrease in natural discharge, (3) a loss in storage, or (4) a combination of these factors. A new state of dynamic equilibrium is reached when no further losses of storage (drawdown) occur. If the response of an aquifer to pumping can be correctly predicted, the contributing area to the well can be estimated.

DETERMINATION OF THE CONTRIBUTING AREA TO SIX MUNICIPAL WATER-SUPPLY SYSTEMS FROM GEOLOGIC AND POTENTIOMETRIC-SURFACE MAPS

Municipal water-supply systems for the villages of Adams, Mannsville, Lacona-Sandy Creek, Pulaski, Camden, and the Hamlet of Orwell were examined in this study. Adams, Mannsville, and Lacona-Sandy Creek are in the northern part of the Tug Hill aquifer, Camden is in the southern part, and Orwell and Pulaski are in the central part.

The contributing area to each water-supply system was delineated from information on the hydrogeology of the Tug Hill aquifer as reported by Miller and others (1989). The primary sources of information were the maps in that report that show the potentiometric surface and surficial geology of the aquifer. Delineation of the contributing areas involved the construction of flow lines that are drawn perpendicular to lines of equal potentiometric head. Flow lines show the direction of ground-water flow from areas of high head to areas of low head. A sufficient number of flow lines are drawn to distinguish the regional flow field from the flow field to the water supply. Flow lines that separate the regional flow field from the flow to the well define the contributing area to the water supply. This method assumes that the aquifer is isotropic and that all flow in the aquifer is horizontal.

A more quantitative approach to delineating the contributing area to a well involves the construction of a flow net. A flow net consists of a set of flow lines drawn perpendicular to the equipotential lines but is drawn so that flow is equally divided between adjacent pairs of lines. A properly drawn flow net will not only show the direction of ground-water flow, but will also provide a quantitative estimate of the amount of water flowing through the aquifer. A complete description of flow-net analysis and construction can be found in Freeze and Cherry (1979), Todd (1980), and, in more general terms, in Heath (1983).

The northern part of the Tug Hill aquifer contains many streams that flow across the aquifer; these tend to lose water on the east side and gain water on the west side (Miller and others, 1989). Streams that traverse the contributing area in this area and upland areas that direct runoff onto the contributing area, are likely sources of recharge to the part of the aquifer that supplies water to the well. These areas are indirectly part of the contributing area and have been identified on the maps herein as upland contributing areas.

One of the primary purposes of identifying contributing areas to the water supply is to protect those areas from contamination. In general, the aquifer area is lightly developed and has relatively few potential sources of contamination, but most of the known ones are near water supplies. Common potential contamination sources include leaking petroleum tanks and spills of oil, grease and chemicals used by automotive repair shops, and nonpoint sources that include agricultural chemicals and faulty septic systems. Another potential contamination source may be spills along the railroad that parallels the western edge of the beach deposits in the central and northern part of the aquifer. The railroad is close to and upgradient of the Adams, Lacona-Sandy Creek, and Pulaski water supplies, but whether the materials being transported by rail pose a potential threat to these water supplies is unknown. Application of herbicides to control weed growth along the railroad bed may present a potential contamination source.

The estimated contributing area to the six municipal water supplies is given in the following sections; a detailed descriptión of the supply system, water usage, and hydrogeology of each municipality is also given.

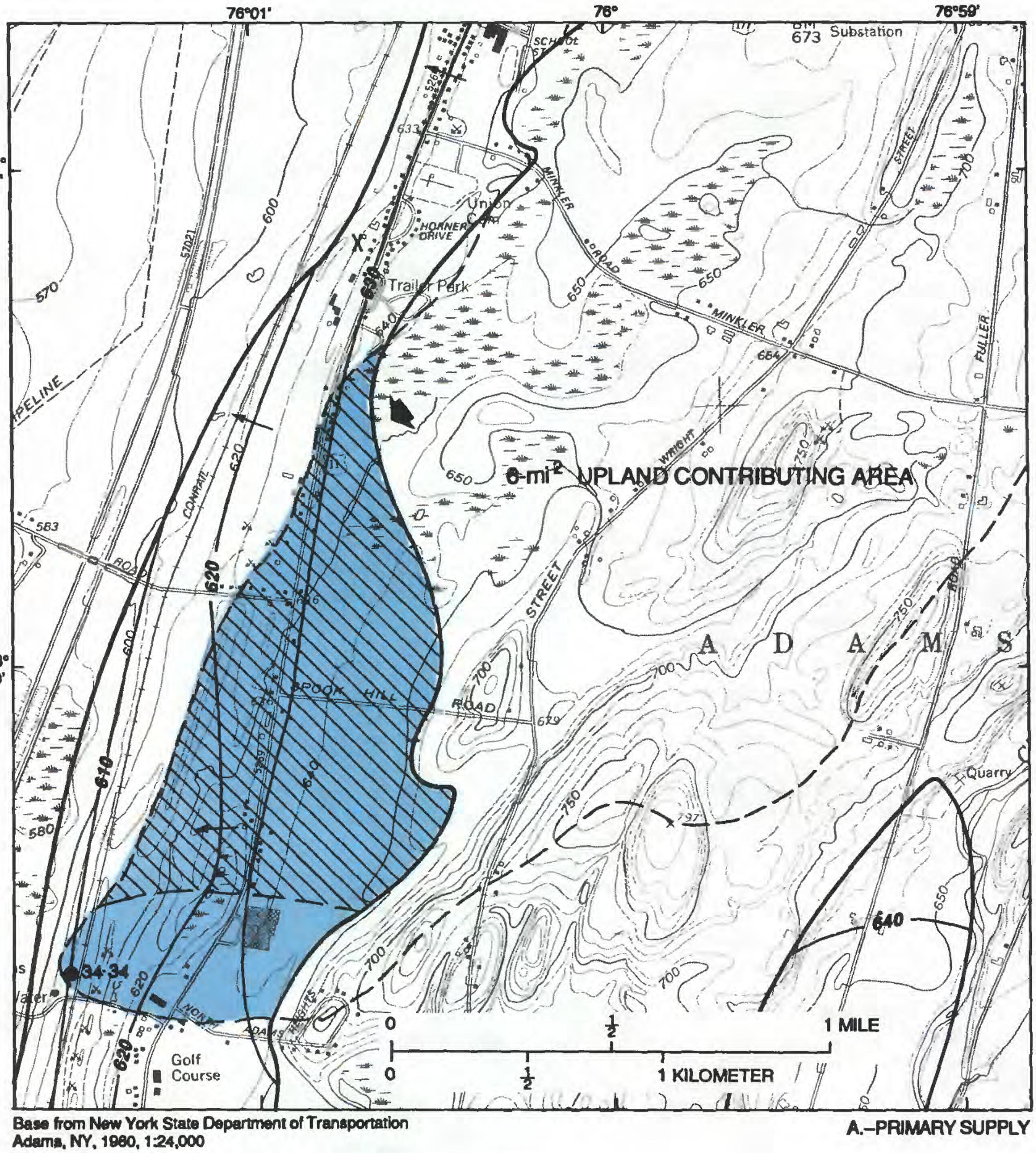
Adams

The Adams water supply serves about 2,900 inhabitants of the village of Adams and the hamlet of Adams Center (fig. 3) and several industrial and commercial facilities. Water use averages 0.75 Mgal/d. Before the fall of 1988, the main water supply consisted of springs that flowed into an open 110,000-gallon reservoir near Interstate Highway 81 and a well with two lateral drains to intercept springs. This system was usually capable of meeting demands except during extended dry periods. During periods of high demand, an auxiliary system consisting of a spring-fed infiltration gallery adjacent to Sandy Creek (fig. 3B), southeast of the village of Adams, is pumped directly into the distribution system. At times, when the springs could not meet the demand, the water supply is augmented by pumping from Sandy Creek.

To meet current and future water needs, a 450-ft-long infiltration gallery was installed to a depth of 10 to 15 ft below land surface in the fall of 1988. The infiltration gallery was expected to meet a future demand of 1 Mgal/d and to improve water quality, but recent yields indicate a much lower capacity than expected. The old system, with the open reservoir, was susceptible to contamination and developed an unpleasant taste, particularly during warm weather as a result of increased microbial activity. The open reservoir and Spring Street supply will be used, if necessary, as an auxiliary supply.

The new infiltration gallery is between the beach-sand and gravel aquifer and the lake-sand and silt deposits that restrict ground-water flow to the west, causing ground water to pool in the permeable beach deposits. The infiltration gallery trends north-south, parallel to the beach deposit, and intercepts ground water that would normally discharge to springs and wetlands along the western margin of the aquifer. Ground water intercepted by the new infiltration gallery will probably decrease ground-water flow to the well and the reservoir, which are west and downgradient of the new infiltration gallery.

The contributing area to the Adams water supply for the new infiltration gallery (fig. 3A) is 0.90 mi^2, which is probably similar in size to the contributing area for the well and open reservoir because they are just downgradient of the new infiltration gallery and because ground-water levels will not change appreciably as a result of the infiltration gallery, except in its immediate vicinity, where they may be lowered. The contributing area includes a 0.75-mi^2 area of surface flow that drains toward the contributing area from other parts of the aquifer through an unnamed tributary just east of the water supply that loses water as it flows southwestward across the aquifer (Miller and others, 1989). Therefore, this tributary is a probable source of recharge to the part of the aquifer that contributes water to the well and is delineated as part of the contributing area, although it differs from the contributing area drawn from flow lines. (This distinction was also made for other water supplies with similar conditions.) In addition, this tributary drains 6 mi^2 of upland area that contains wetlands, forests, and farms near Adams Center. The contributing area to the Spring Street supply (fig. 3B) is 0.2 mi^2 with a small upland contributing area of about 0.1 mi^2.

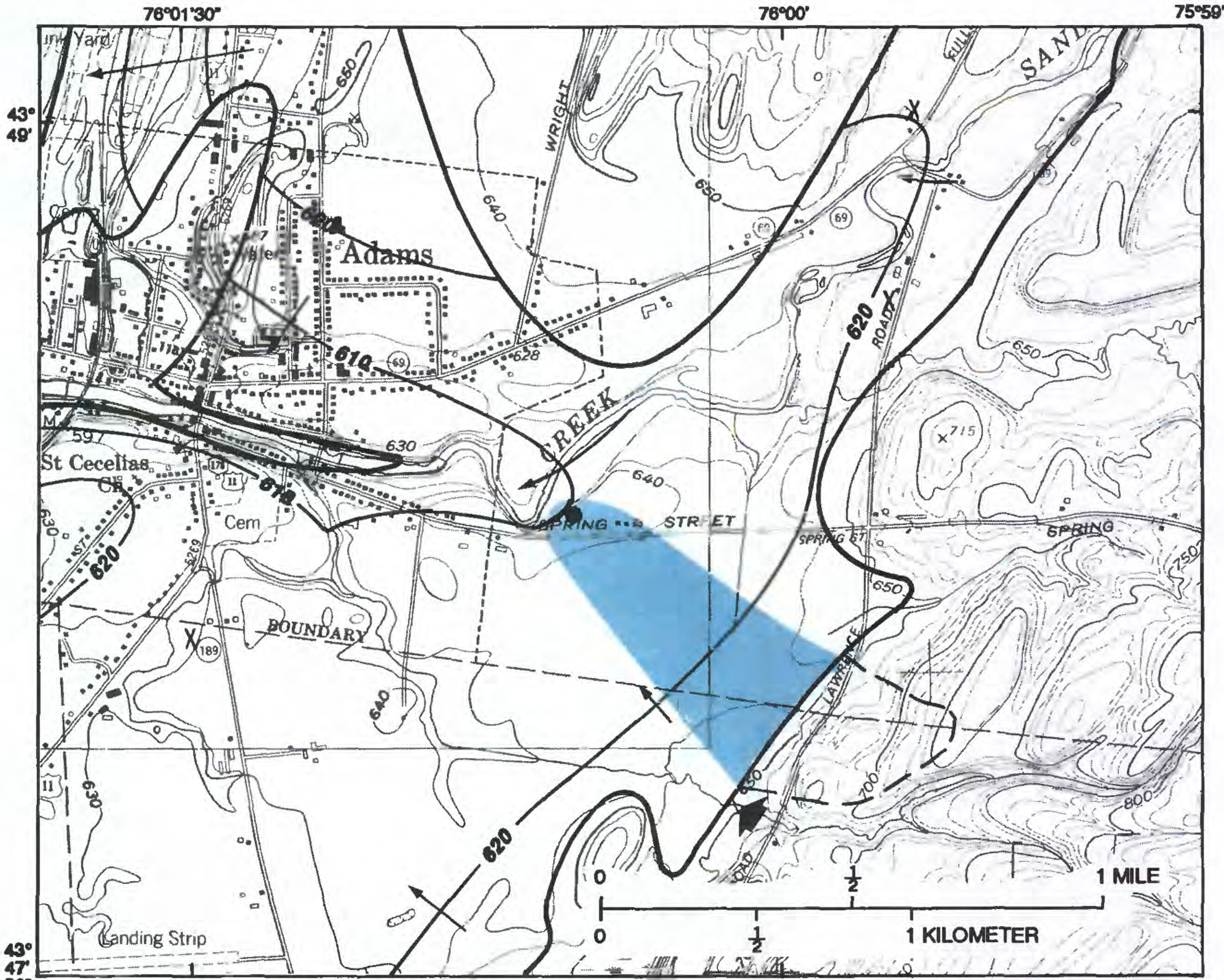


EXPLANATION

CONTRIBUTING AREA–Land-surface expression of the aquifer area that contributes water to a supply well

Area of aquifer where surface water drains toward stream reach that loses water to the aquifer that contributes to a well

Figure 3A.--Contributing area to theAdams main water supply. (Location shown in fig. 1. Modified from Miller and others, 1989, pl. 4D.)



Base from New York State Department of Transportation
Adams, NY, 1980, 1:24,000

B.–SPRING STREET SUPPLY

EXPLANATION (continued)

—610— POTENTIOMETRIC CONTOUR--Line of equal hydraulic head in aquifer based from water level measured in summer 1983 and from measurements made during 1950-86. Datum is sea level. Small arrows indicate direction of ground water flow

——— AQUIFER BOUNDARY--Approximate contact between sand and gravel deposits and till and lacustrine deposits

MAJOR INFLOW TO AQUIFER--Surface-water and ground-water flow along main valleys beyond aquifer

— — — UPLAND CONTRIBUTING AREA--Adjacent upland area that contributes recharge to the contributing area by direct runoff

● 34-34 WATER SUPPLY--springs and infiltration gallery and number

X DATA POINT--Location of water level measurement site

Figure 3B.--Contributing area to the Adams auxiliary water supply. (Location shown in fig. 1. Modified from Miller and others, 1989, pl. 4D.)

Mannsville

The village of Mannsville is about 7 mi south of the village of Adams (fig. 4) and derives its water from a dug well installed in the 1930's and a drilled well installed in the early 1960's. These wells are 17 and 29 ft deep, respectively, and supply 0.04 Mgal/d of water to about 580 residents. The wells tap recent alluvial deposits 0.3 mi east of Mannsville, adjacent to the confluence of two tributary streams to Skinner Creek, and have a contributing area of 0.10 mi^2 within the confines of the narrow alluvial valley (fig. 4). A small reservoir on Skinner Creek about 1,000 ft downgradient of the wells decreases the natural ground-water gradient and thereby decreases the ground-water flow westward and increases the saturated thickness of deposits in the vicinity of the wells. The tributary streams reportedly become dry in low-flow periods in the well vicinity, which may result in part from induced infiltration by pumping. This suggests that the tributary streams are a source of recharge to the aquifer in the well vicinity and that the upland contributing area to the Mannsville wells should probably include the 10-mi^2 watershed of Skinner Creek. Variations in pumpage will probably have only a minimal effect on the size and shape of the contributing area because the wells are close to the stream, which is confined by a narrow valley.

Lacona-Sandy Creek

The well field that supplies water to the villages of Lacona and Sandy Creek is the southernmost municipal supply in the northern part of the Tug Hill aquifer; it was also the well field selected for comparison of analytical and numerical techniques for delineating contributing areas to the wells. Results are discussed further on. Two drilled wells, which are 26 ft deep (No. 1) and 18 ft deep (No. 2), and one dug well 12 ft deep (No. 3) supply 0.33 Mgal/d to about 1,450 residents in the two villages. The wells are finished in beach-sand and gravel deposits near the contact with the less permeable lake deposits and till to the west. The hydrogeologic setting of the Lacona-Sandy Creek well field is similar to the Adams supply in that they both intercept ground water as it moves from sources of recharge in the east to its natural points of discharge (springs and wetlands) to the west.

The contributing area to the well field is 0.30 mi^2, including 0.11 mi^2 that drains toward the contributing area from other parts of the aquifer (fig. 5). The potentiometric surface reported by Miller and others (1989) may not reflect the influence of pumping from the production wells; therefore, the extent of the contributing area may differ from that indicated, depending on the influence of the pumped wells at the time the potentiometric surface was measured. Usually only one well is pumped at any given time. An intermittent tributary stream traverses the aquifer from north to south 0.3 mi east of the well field, but field observations of this stream during the summer and fall of 1988 indicated no flow in the reach east of the well field. This may be partly due to a small manmade berm north of Center Road that impounds water and subjects it to increased evaporation. The hydraulic connection between the tributary and the well field could not be determined because streamflow was zero at the time of field measurements. If a hydraulic connection exists, the upland contributing area would include 0.61 mi^2 of the watershed of the tributary stream south of Center Road and 0.53 mi^2 of the watershed north of Center Road.

Pulaski

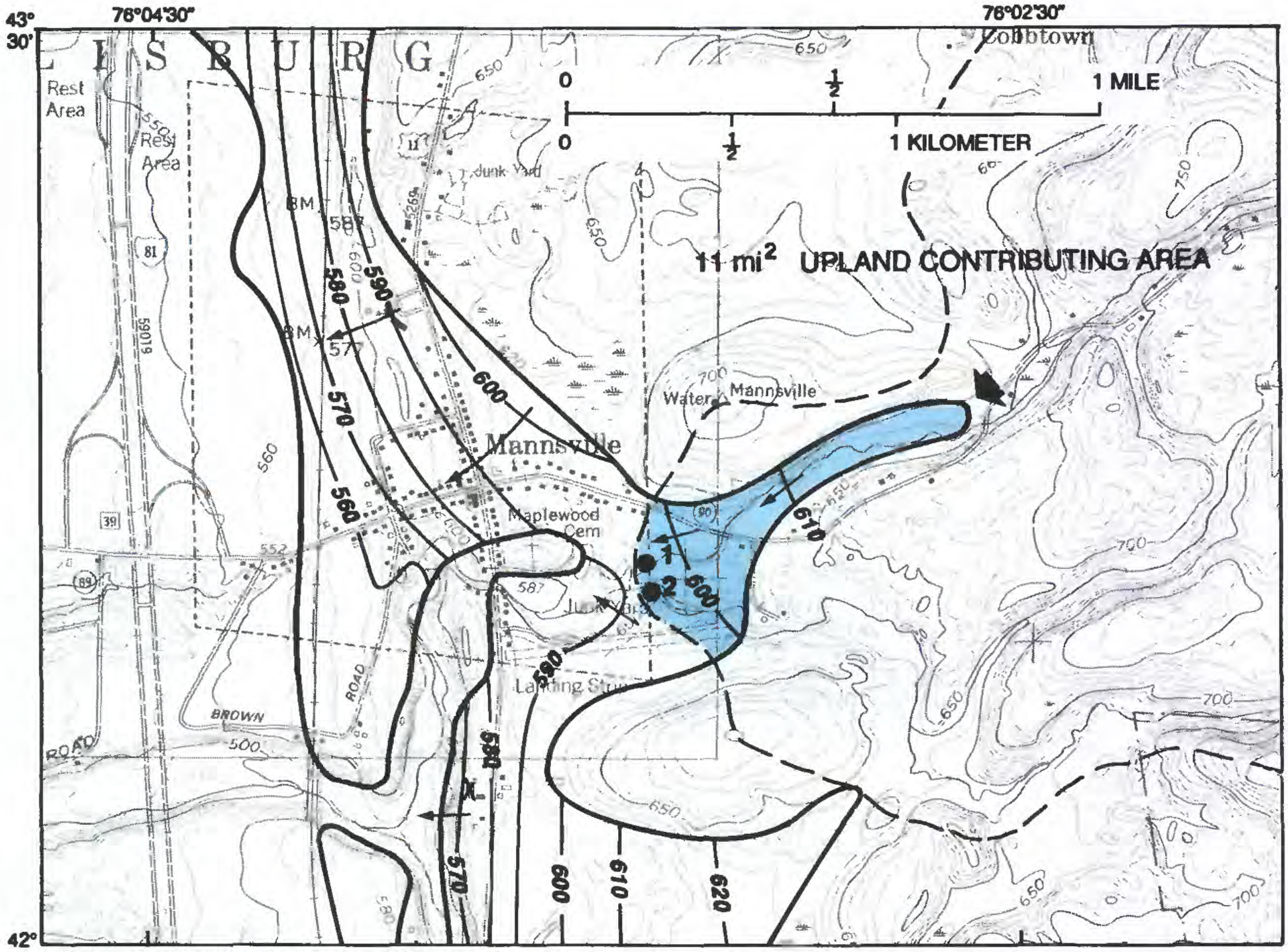
The water-supply system for the village of Pulaski consists of two 6-ft-diameter, 6- and 8-ft-deep spring-fed collection basins that supply 0.25 Mgal/d to 2,500 people. Although this water supply is in the central part of the aquifer, it is hydrogeologically similar to the water supplies of Adams and Lacona-Sandy Creek in that it intercepts ground water near the contact between the beach sand and the fine-grained lacustrine deposits to the west. The contributing area to the springs includes 0.85 mi^2 of the permeable kame and beach sand and gravel deposits (fig. 6).

Pulaski's water supply may also receive recharge from Trout Brook, which loses water as it traverses the aquifer southward about 4,500 ft upgradient (east) of the springs. This recharge may be restricted, however, by a peninsula-shaped deposit of fine eolian sands (Miller and others, 1989, pl. 3B) and lacustrine sand and silt that lies between the water supply and the stream. The effect of this deposit on recharge to the aquifer from Trout Brook is unknown. The watershed area of Trout Brook above the well field would add an upland contributing area of approximately 17 mi^2.

Orwell

The part of the aquifer that supplies water to the hamlet of Orwell is a relatively thin kame complex associated with the Orwell-Bennett Bridge moraine east of the hamlet (Miller and others, 1989). Water is collected in a springhouse, infiltration gallery, and a shallow dug well (9 ft deep). Together these supply 0.02 Mgal/d to 250 residents of the hamlet of Orwell.

The Orwell water supply, unlike the previously discussed water supplies, does not appear to be influenced by surface-water systems, which limits the contributing area to a 0.03-mi^2 area of kame and outwash sand and gravel deposits (fig. 7) that includes a small amount of upland contributing area from unchanneled runoff. The contributing area may be smaller than shown because ground water may be directed more toward the tributary streams to the north and south if ground-water levels parallel the topographic surface in this area.



Base from New York State Department of Transportation
Sandy Creek, NY, 1980, 1:24,000

EXPLANATION

CONTRIBUTING AREA--Land-surface expression of the aquifer area that contributes water to a supply well

—610— POTENTIOMETRIC CONTOUR--Line of equal hydraulic head in aquifer based from water level measured in summer 1983 and from measurements made during 1950-86. Datum is sea level. Small arrows indicate direction of ground water flow

AQUIFER BOUNDARY--Approximate contact between sand and gravel deposits and till and lacustrine deposits

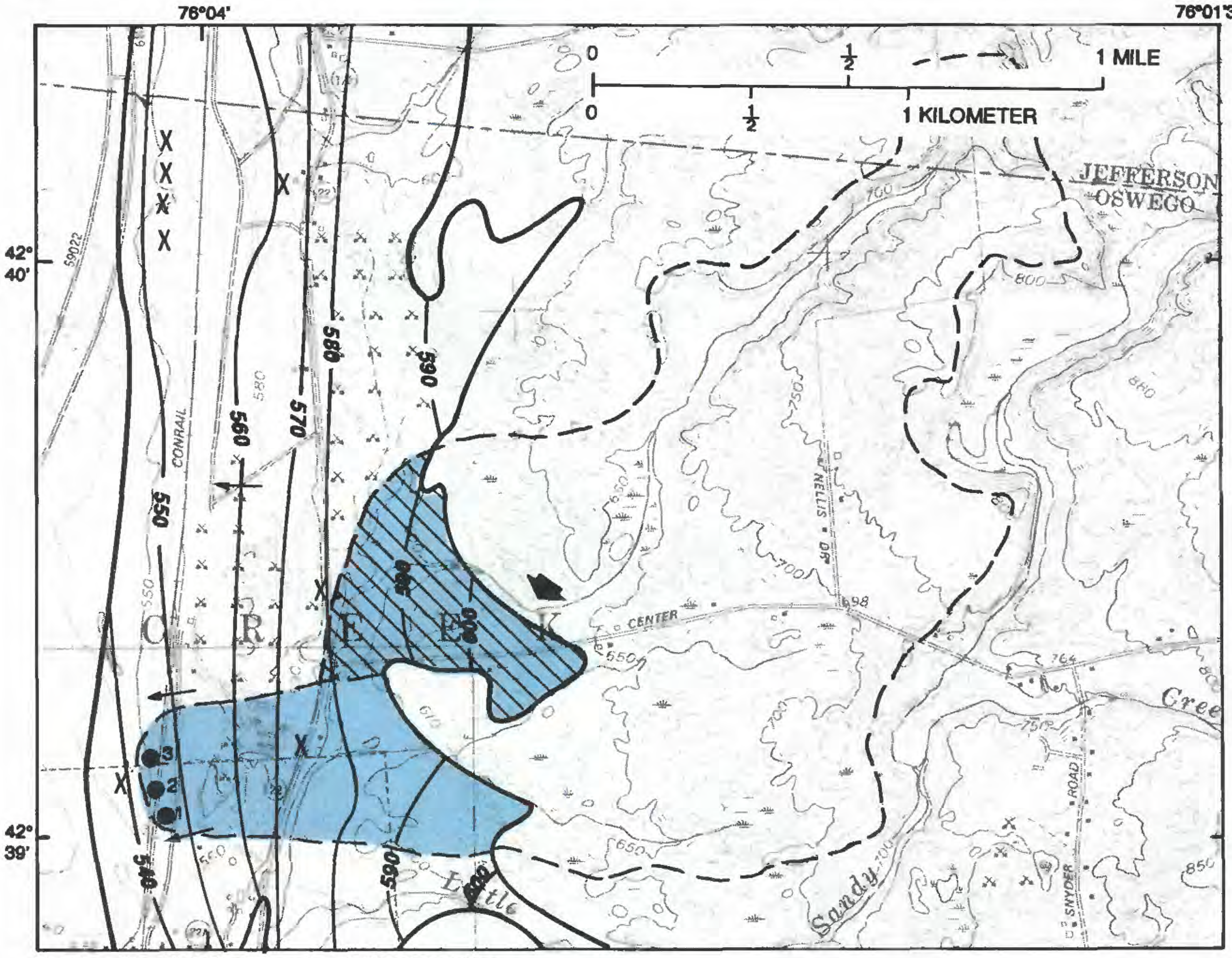
MAJOR INFLOW TO AQUIFER--Surface-water and ground-water flow along main valleys beyond aquifer

— — — UPLAND CONTRIBUTING AREA--Adjacent upland area that contributes recharge to the contributing area by direct runoff

●1 WATER SUPPLY--Dugwell (1) 17 feet deep. Drilled well (2) 29 feet deep

X DATA POINT--Location of water level measurement site

Figure 4.--Contributing area to the Mannsville water supply. (Location shown in fig. 1. Modified from Miller and others, 1989, pl. 4D.)

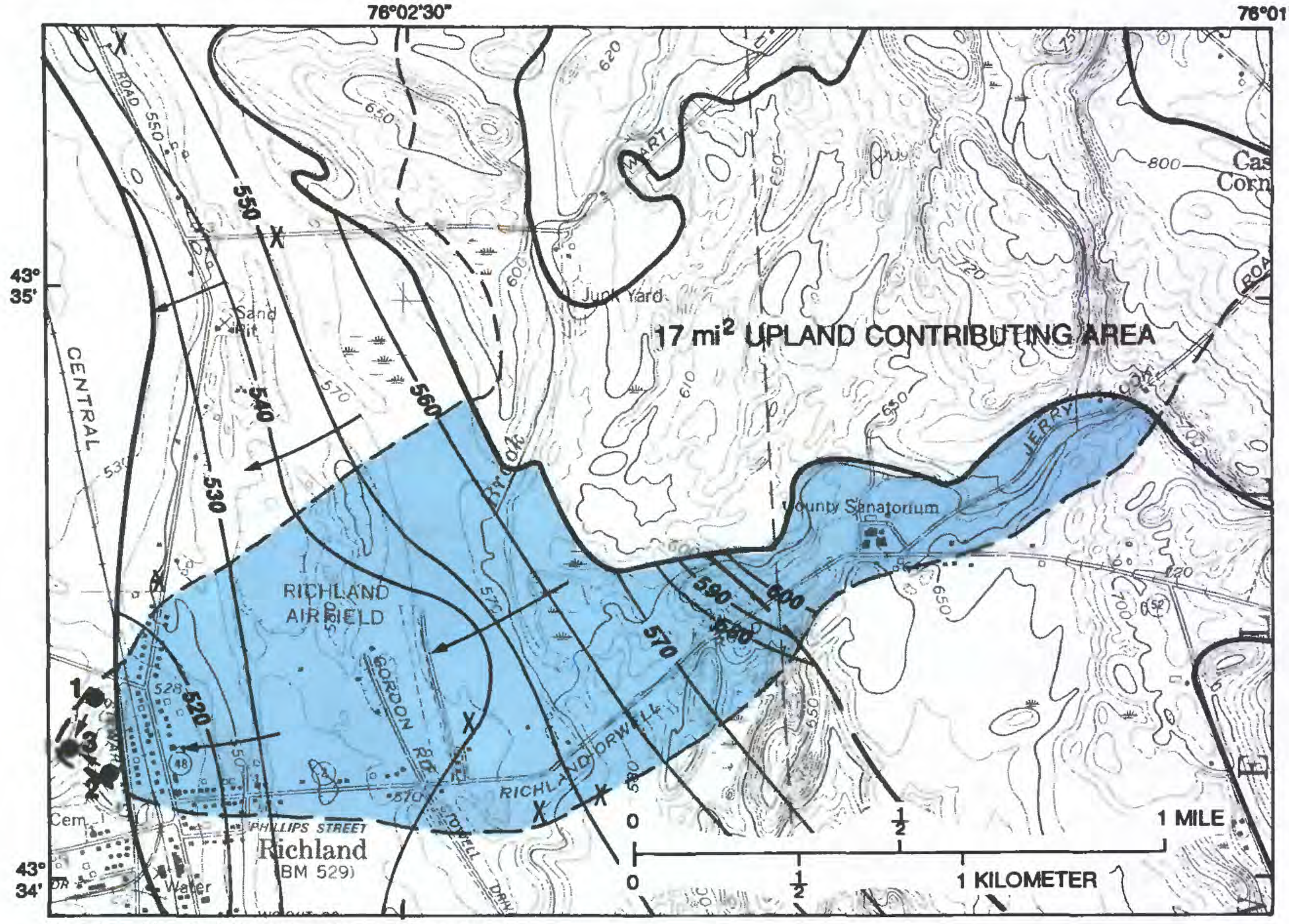


Base from New York State Department of Transportation
Sandy Creek, NY, 1980, 1:24,000

EXPLANATION

- CONTRIBUTING AREA--Land-surface expression of the aquifer area that contributes water to a supply well
- Area of aquifer where surface water drains toward stream reach that loses water to the aquifer that contributes to a well
- —580— POTENTIOMETRIC CONTOUR--Line of equal hydraulic head in aquifer based from water level measured in summer 1983 and from measurements made during 1950-86. Datum is sea level. Small arrows indicate direction of ground water flow
- AQUIFER BOUNDARY--Approximate contact between sand and gravel deposits and till and lacustrine deposits
- MAJOR INFLOW TO AQUIFER--Surface-water and ground-water flow along main valleys beyond aquifer
- UPLAND CONTRIBUTING AREA--Adjacent upland area that contributes recharge to the contributing area by direct runoff
- ●3 WATER SUPPLY--pumped wells (1) 26 feet, (2) 18 feet, and (3) 12 feet
- X DATA POINT--Location of water level measurement site

Figure 5.--Contributing area to the Lacona-Sandy Creek water supply. (Location shown in fig. 1. Modified from Miller and others, 1989, pl. 3D.)



Base from New York State Department of Transportation
Richland, NY, 1980, 1:24,000

EXPLANATION

CONTRIBUTING AREA--Land-surface expression of the aquifer area that contributes water to a supply well

—600— POTENTIOMETRIC CONTOUR--Line of equal hydraulic head in aquifer based from water level measured in summer 1983 and from measurements made during 1950-86. Datum is sea level. Small arrows indicate direction of ground water flow

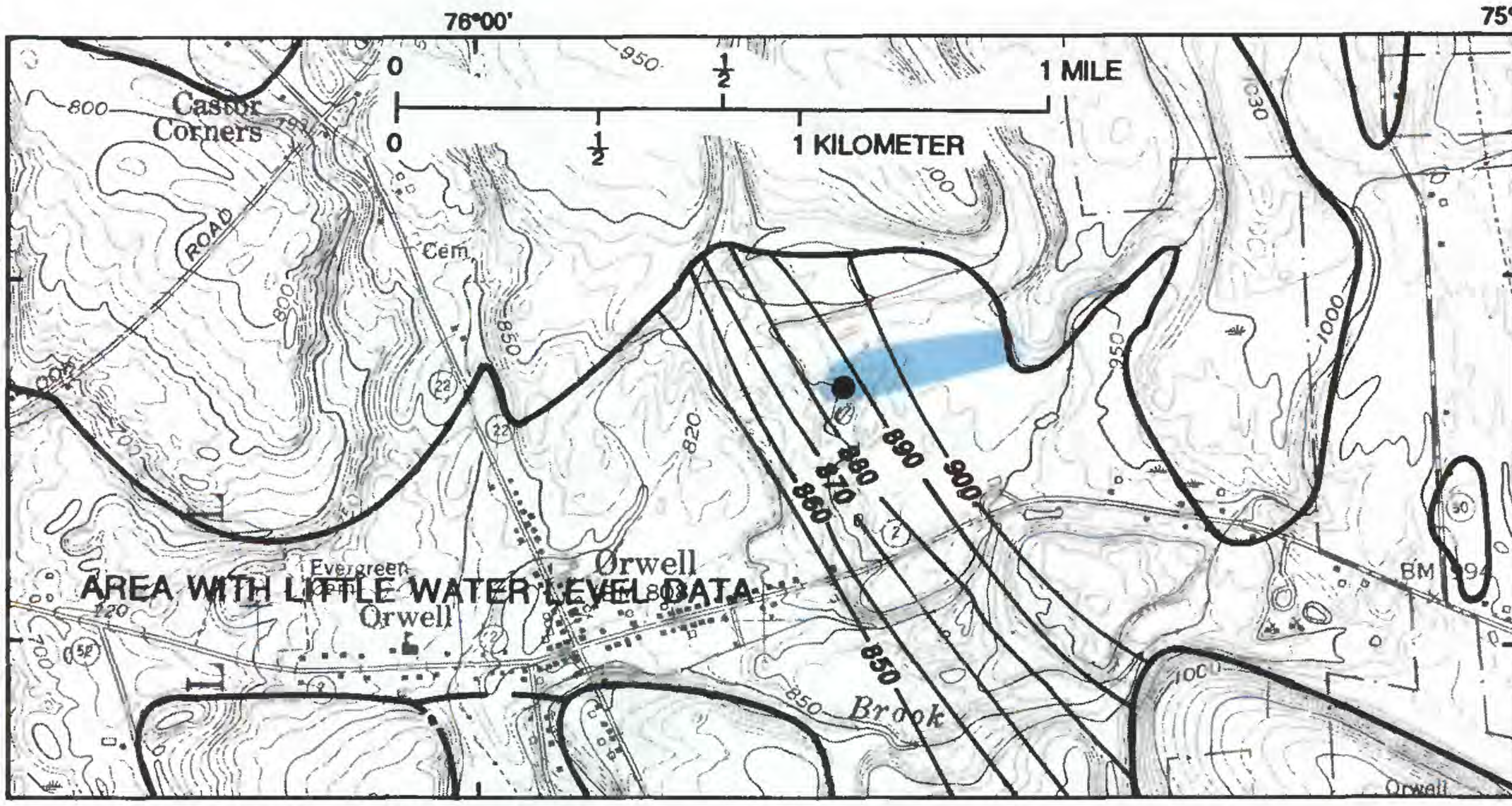
AQUIFER BOUNDARY--Approximate contact between sand and gravel deposits and till and lacustrine deposits

UPLAND CONTRIBUTING AREA--Adjacent upland area that contributes recharge to the contributing area by direct runoff

● 1 WATER SUPPLY--spring fed dug wells, (1) 6 feet and (2) 8 feet gravity fed into (3)

X DATA POINT--Location of water level measurement point

Figure 6.--Contributing area to the Pulaski water supply. (Location shown in fig. 1. Modified from Miller and others, 1989, pl. 3D.)



Base from New York State Department of Transportation
Orwell, NY, 1975, 1:24,000

EXPLANATION

CONTRIBUTING AREA--Land-surface expression of the aquifer area that contributes water to a supply well

—880— POTENTIOMETRIC CONTOUR--Line of equal hydraulic head in aquifer based from water level measured in summer 1983 and from measurements made during 1950-86. Datum is sea level. Small arrows indicate direction of ground water flow

AQUIFER BOUNDARY--Approximate contact between sand and gravel deposits and till and lacustrine deposits

UPLAND CONTRIBUTING AREA--Adjacent upland area that contributes recharge to the contributing area by direct runoff

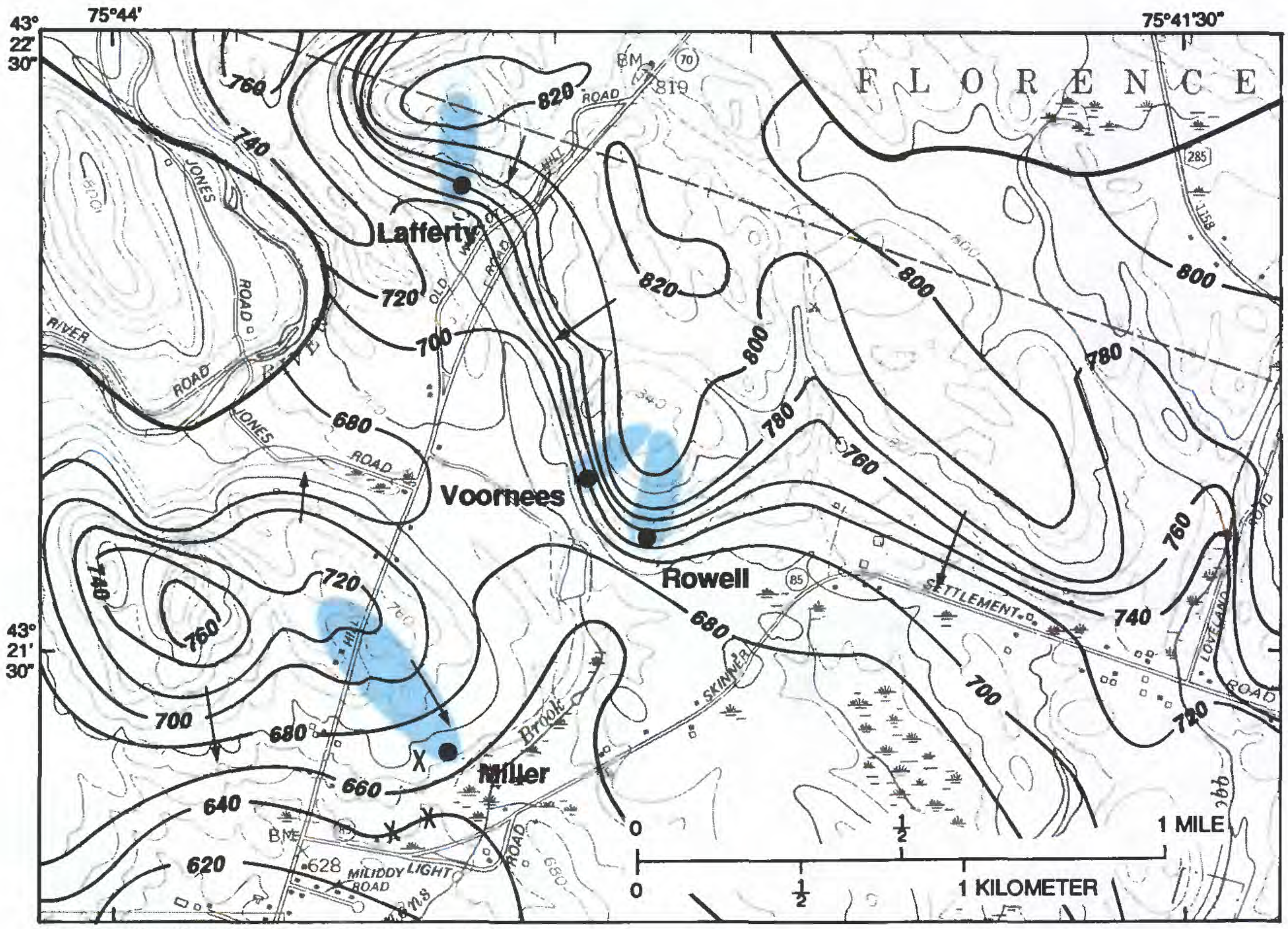
WATER SUPPLY--spring fed dug wells and infitration gallery

Figure 7.--Contributing area to the Orwell water supply. (Location shown in fig. 1. Modified from Miller and others, 1989, pl. 3D.)

Camden

The village of Camden water supply consists of 10 spring-fed, dug wells installed in the contact between the valley outwash deposits and the kame deposits. The wells are grouped at three sites in two clusters of four (Rowell and Lafferty wells) and a cluster of two (Voorhees wells) northeast of the village (fig. 8). The present water use is 0.60 Mgal/d, which supplies 2,940 residents of Camden and some light industry. Catchment areas to the dug wells range from 0.01 to 0.02 mi^2 (fig. 8).

A reservoir on Emmons Brook, below the Voorhees and Rowell wells, is occasionally used as an emergency supply, but this is expected to be phased out with a recently installed (1988) 94-ft drilled well (Miller well) near the contact between the outwash and kame on the west side of the Emmons Brook valley. Approximately 5 ft of the well is screened in sand and gravel at a depth of 51 to 56 ft just above bedrock. Flow to the well is likely more regional than the other shallow supply wells because the sand and gravel is semiconfined and because some water may



Base from New York State Department of Transportation
Camden East, NY, 1978, 1:24,000

EXPLANATION

CONTRIBUTING AREA--Land-surface expression of the aquifer area that contributes water to a supply well

—700— POTENTIOMETRIC CONTOUR--Line of equal hydraulic head in aquifer based from water level measured in summer 1983 and from measurements made during 1950-86. Datum is sea level. Small arrows indicate direction of ground water flow

AQUIFER BOUNDARY--Approximate contact between sand and gravel deposits and till and lacustrine deposits

UPLAND CONTRIBUTING AREA--Adjacent upland area that contributes recharge to the contributing area by direct runoff

WATER SUPPLY--spring fed dug wells (Lafferty, Rowell, Voorhees), and drilled well(Miller)

Figure 8.--Contributing area to the Camden water supply. (Location shown in fig. 1. Modified from Miller and others, 1989, pl. 1D.)

be derived from fractured bedrock flow. Also, no information is available to determine whether pumping the drilled well will induce infiltration from Emmons Brook, although this reach does not appear to lose water during nonpumping periods (T. S. Miller, U.S. Geological Survey, written commun., 1988). The village of Camden owns all the land surrounding the drilled and dug wells. As a result, land use within the estimated contributing areas is protected and consist of woodlands.

DETERMINATION OF THE CONTRIBUTING AREA TO THE LACONA-SANDY CREEK WELL FIELD BY NUMERICAL AND ANALYTICAL METHODS

The contributing area to the Lacona-Sandy Creek well field was calculated by a numerical ground-water flow model and two analytical flow models—the Dupuit uniform flow model and the Theis nonequilibrium method for purpose of comparison. Use of analytical and numerical techniques to delineate a well's contributing area requires more information on aquifer characteristics than would normally be needed to delineate solely from hydrogeologic information. The following section describes the hydrogeologic setting from which the models were constructed and the extent, thickness, and hydraulic properties of the aquifer.

Hydrogeology

The sand and gravel that forms the aquifer in the Lacona-Sandy Creek area was deposited during glacial retreat in proglacial Lake Iroquois, which inundated the lowlands for about 200 years. The well field is completed in beach deposits of proglacial Lake Iroquois that are parallel to the present-day Lake Ontario.

The sequence of events that formed the deposits in this area is depicted in figure 9. As ice retreated, meltwater streams draining the Tug Hill Plateau deposited coarse sand and gravel in channels that formed between the ice lobe and the plateau, and, as the ice lobe retreated westward, proglacial Lake Iroquois filled the lowland between the ice lobe and the plateau. During this period, wave action reworked the till and outwash to form extensive beach deposits along the lakeshore. Further ice recession exposed successively lower outlet channels to the north through the present-day St. Lawrence River, which caused the lake level to drop to what is now known as Lake Ontario. Till and lake silt and clay flank the west side of the beach deposits. The wave-washed deposits consist of sorted sand and gravel that forms the aquifer from which the villages of Lacona and Sandy Creek obtain water.

Aquifer Extent and Saturated Thickness

The extent of the sand and gravel deposits that form the aquifer is shown in figure 10. Generally, these deposits form a relatively narrow band about 1/2 mile wide that represents the proglacial Lake Iroquois beach. These deposits typically range from 10 to 50 ft thick and pinch out to the east and west. The stratigraphy of the aquifer area is shown in geologic sections A-A′ and B-B′ (fig. 11), which also indicate the distribution and thickness of the outwash.

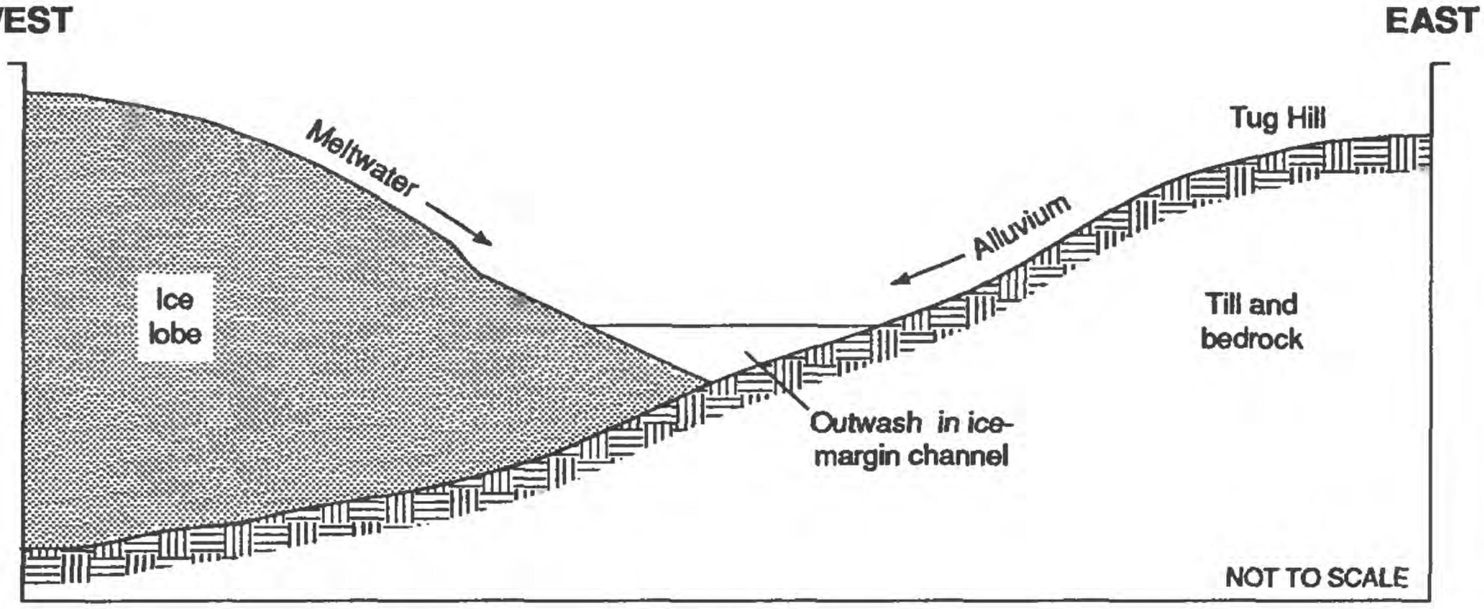
Sand and gravel mining has altered the surface and thickness of the beach deposits. Section B-B′ (fig. 11) illustrates that more than 20 ft of sand and gravel has been excavated from this area, as indicated by the difference between the estimated position of the previous land surface and present land surface. Ground-water flow paths may have been altered as a result of the mining. Excavation immediately west of the Lacona-Orwell Road creates a seepage face during periods of high water table, as evidenced by the intermittent stream at the base of the excavation (section B-B′, fig. 11). As a result, the hydraulic gradient probably steepens at the seepage face, and thereby decreases the saturated thickness to some extent.

The saturated thickness (about 20 ft) during nonpumping conditions is greatest in the vicinity of the pumped wells but decreases rapidly to the west, where it pinches out at the edge of the lake deposits and till. The saturated thickness of the outwash sand and gravel and till deposits east of the Lacona-Orwell Road is unknown but is estimated to be 10 ft or less.

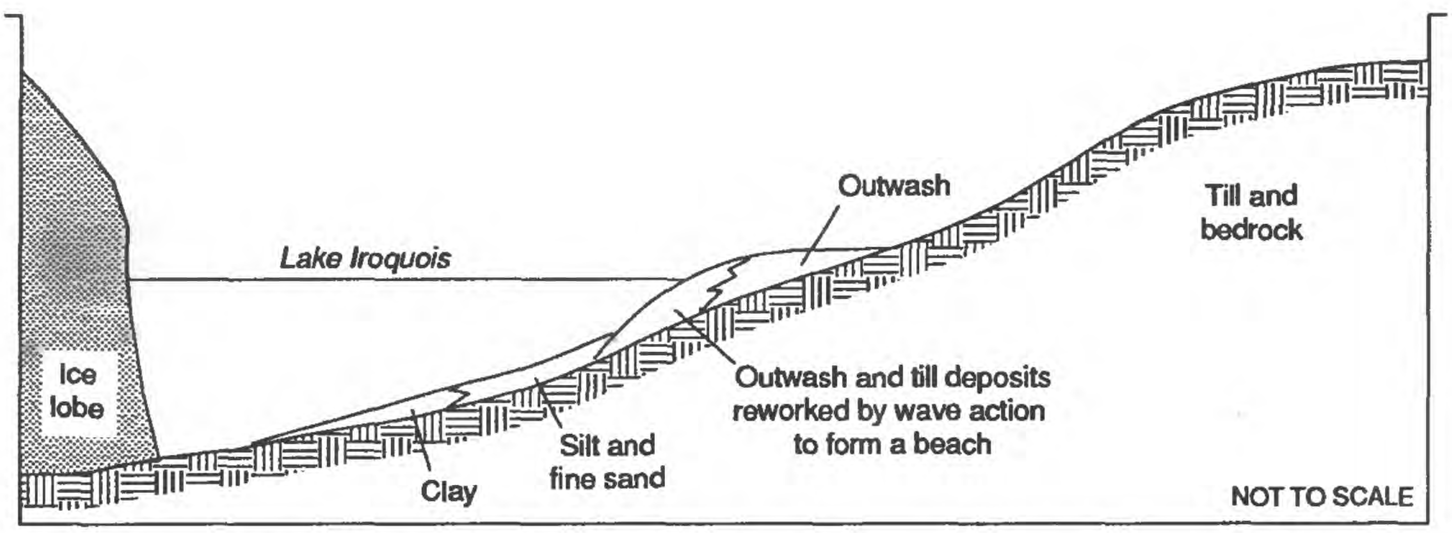
Hydraulic Properties

Aquifer test. Initial values of horizontal hydraulic conductivity used in the numerical simulation model were derived from analysis of drawdown and recovery data recorded during an aquifer test in November 1988. The aquifer test consisted of pumping production well 2 at 196 gal/min over a 24-hour period while recording water-level changes in three fully screened and two partially screened observation wells (LA-1 through LA-5), and in production well 3. (Locations are shown in fig. 12; well logs are shown in fig. 13.) Before the test, pumping at the production wells was discontinued for 24 hours or more, and ground-water levels were monitored to ensure that the aquifer system had recovered to static levels before the test began. (Water levels are indicated on the well logs in fig. 13). Ground-water levels were continually monitored with a Cambell[1] CR10 data logger and Geokon vibrating wire transducers at observation wells LA-1, LA-2, LA-3, and LA-4. The pumped well was also continuously monitored with a Telog data logger and a Druck pressure transducer. Periodic measurements were made at each well during the test by steel tape to verify the transducer measurements. These measurements matched the transducer measurements to within 0.03 ft during the first 7 hours of the test and to within 0.20 ft at the end of 24 hours of pumping. The increased discrepancy between measurements in the later part of the test was probably caused by changes

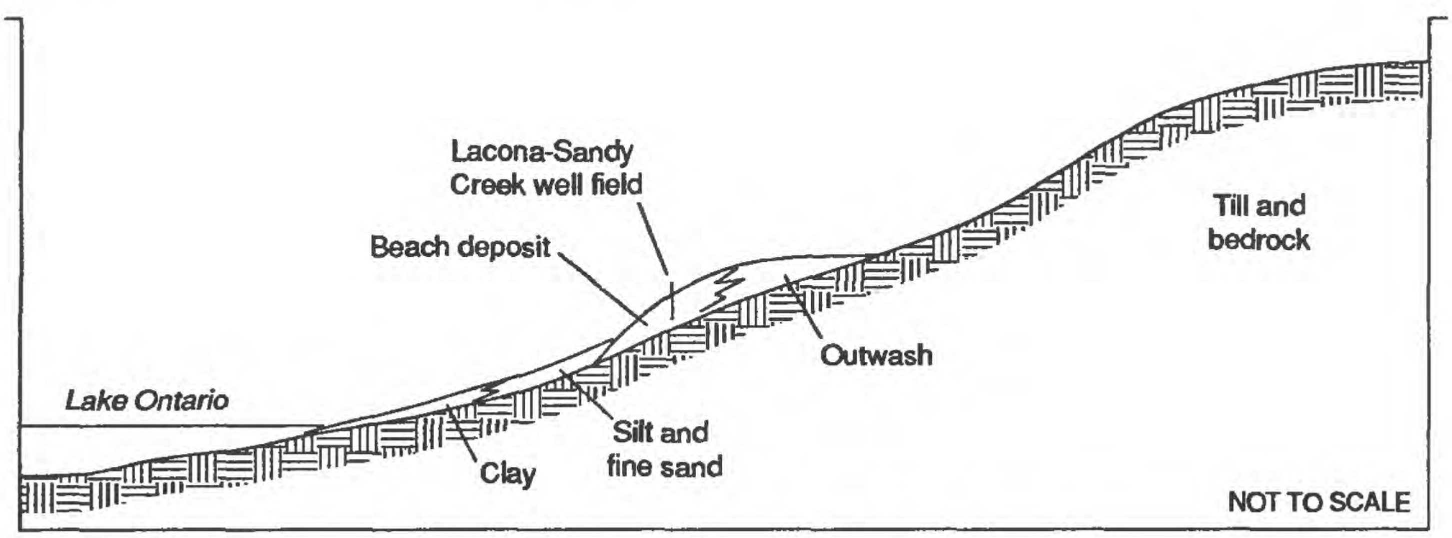
[1]Use of brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.



A. As ice retreated, outwash was deposited in the ice-margin channels between the ice lobe and the Tug Hill Plateau.



B. Meltwaters from retreating ice formed proglacial Lake Iroquois whose wave action reworked till and outwash deposits. Lacustrine sediments that were deposited in the lake, flank the beach deposits.



C. Preglacial Lake Iroquois drained and Lake Ontario formed. Beach deposits are flanked on west by lake deposits and till, and on the east by till and bedrock.

Figure 9.--Generalized sequence of glacial and proglacial processes that formed the aquifer from which Lacona-Sandy Creek derives its water.

EXPLANATION
(to figure 10)

Al	Alluvial silt, sand, and gravel; stream deposits of postglacial time; unconsolidated and generally permeable
As	Eolian sand; wind-deposited sand that forms ridges or mounds; fine to medium grained; oxidized and moderately permeable
Bsg	Beach sand and gravel; coarse sand and gravel deposited near or at shore of proglacial lakes; well sorted, unconsolidated and highly permeable
Lss	Lake silt and fine sand; offshore deposits in proglacial or postglacial lakes, thin bedded to massive; low to moderate permeability
Osg	Outwash sand and gravel; coarse sand to cobble gravel deposited by streams flowing from former ice sheets; stratified; well sorted; highly permeable
At	Ablation till; mixture of clay, silt, sand, and boulders deposited from drift laid down after ice melted beneath it; unconsolidated; noncompact and generally slightly coarser than lodgment till; variable permeability. Typically, ablation till overlies lodgment till
Lt	Lodgment till; mixture of clay, silt, sand, and boulders deposited at base of glacier; poorly sorted; compact and impermeable
Br	Bedrock; sedimentary rocks
(hatched box)	AREA OF TILL WITHIN AQUIFER
—— — —	AQUIFER BOUNDARY--Dashed where valley aquifer is adjacent to permeable material on uplands and valley walls for which there are little data to determine whether deposits are saturated year round
A —— A'	LINE OF HYDROGEOLOGIC SECTION
● 06-10	Well used to draw hydrogeologic section and identification number

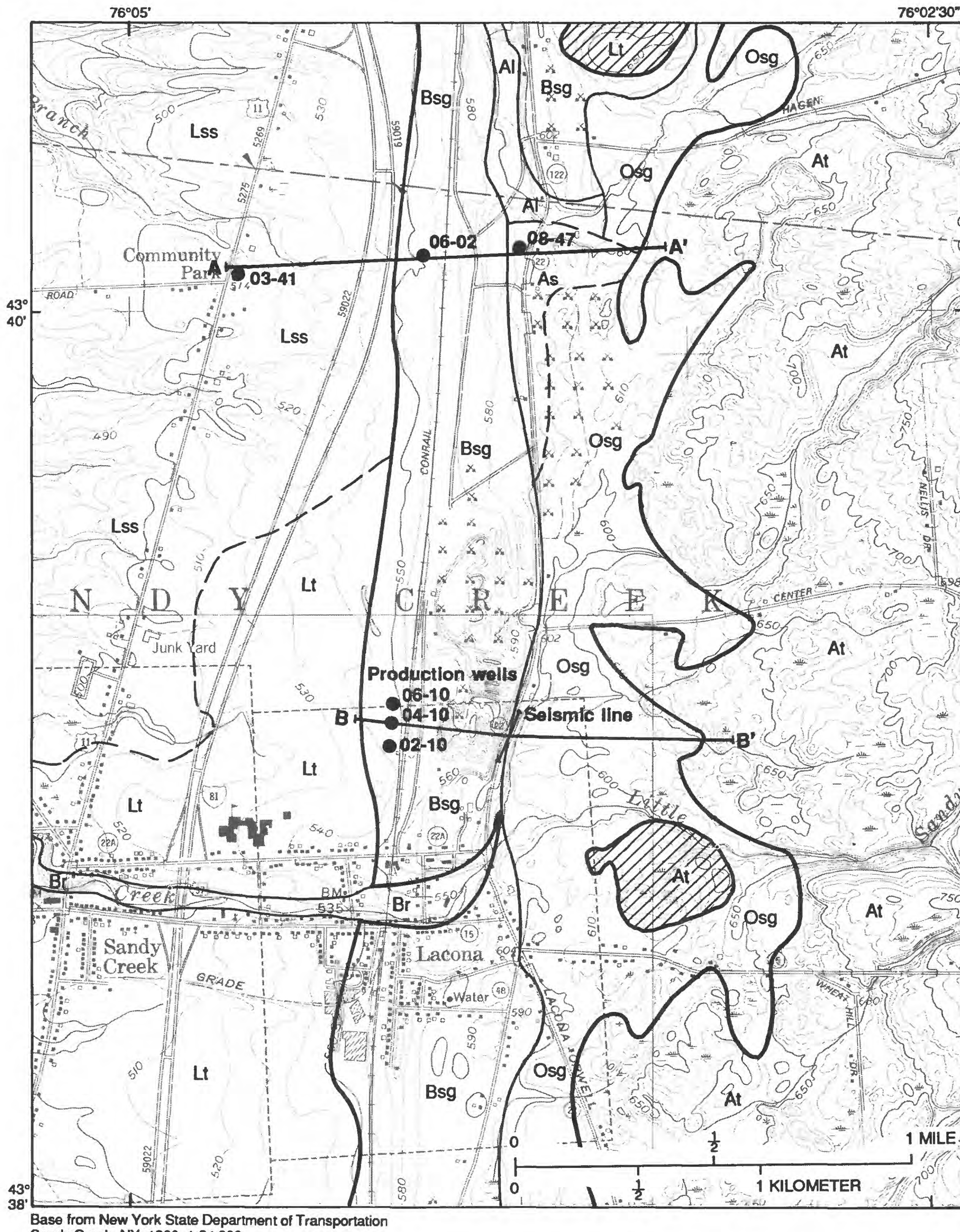


Figure 10.--Surficial geology of the Lacona-Sandy Creek area. (Modified from Miller and others, 1989, pl. 4B. Geologic sections A-A′ and B-B′ shown in fig. 11.)

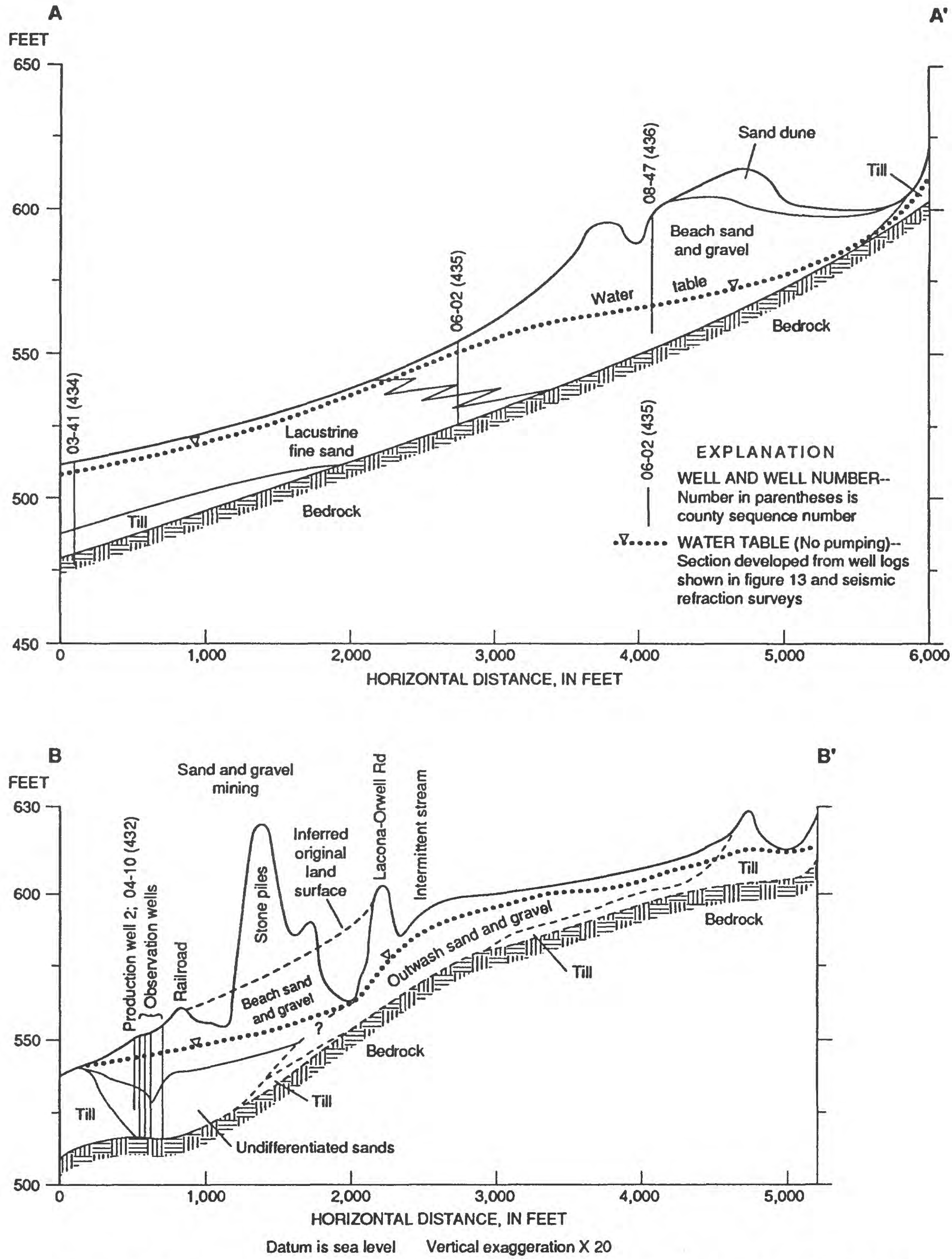


Figure 11.--Hydrogeologic cross sections A-A' and B-B' near the Lacona-Sandy Creek well field. (Location shown in fig. 10. Section A-A' modified from Miller and others, 1989. Section E-E', pl. 4B.)

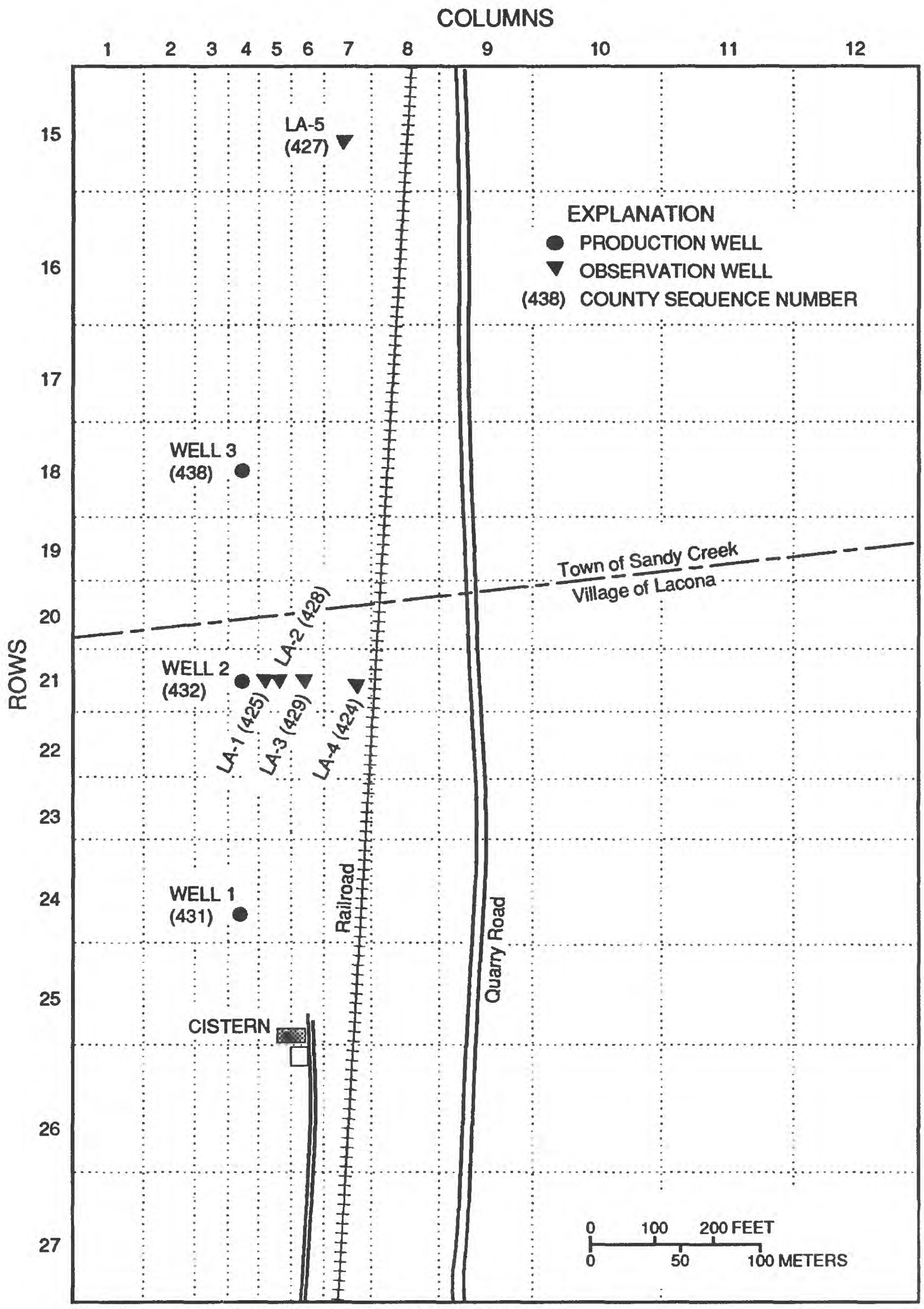


Figure 12.--Detail of model grid showing location of pumped wells and observation wells near the Lacona-Sandy Creek well field. (Location is shown in fig. 10.)

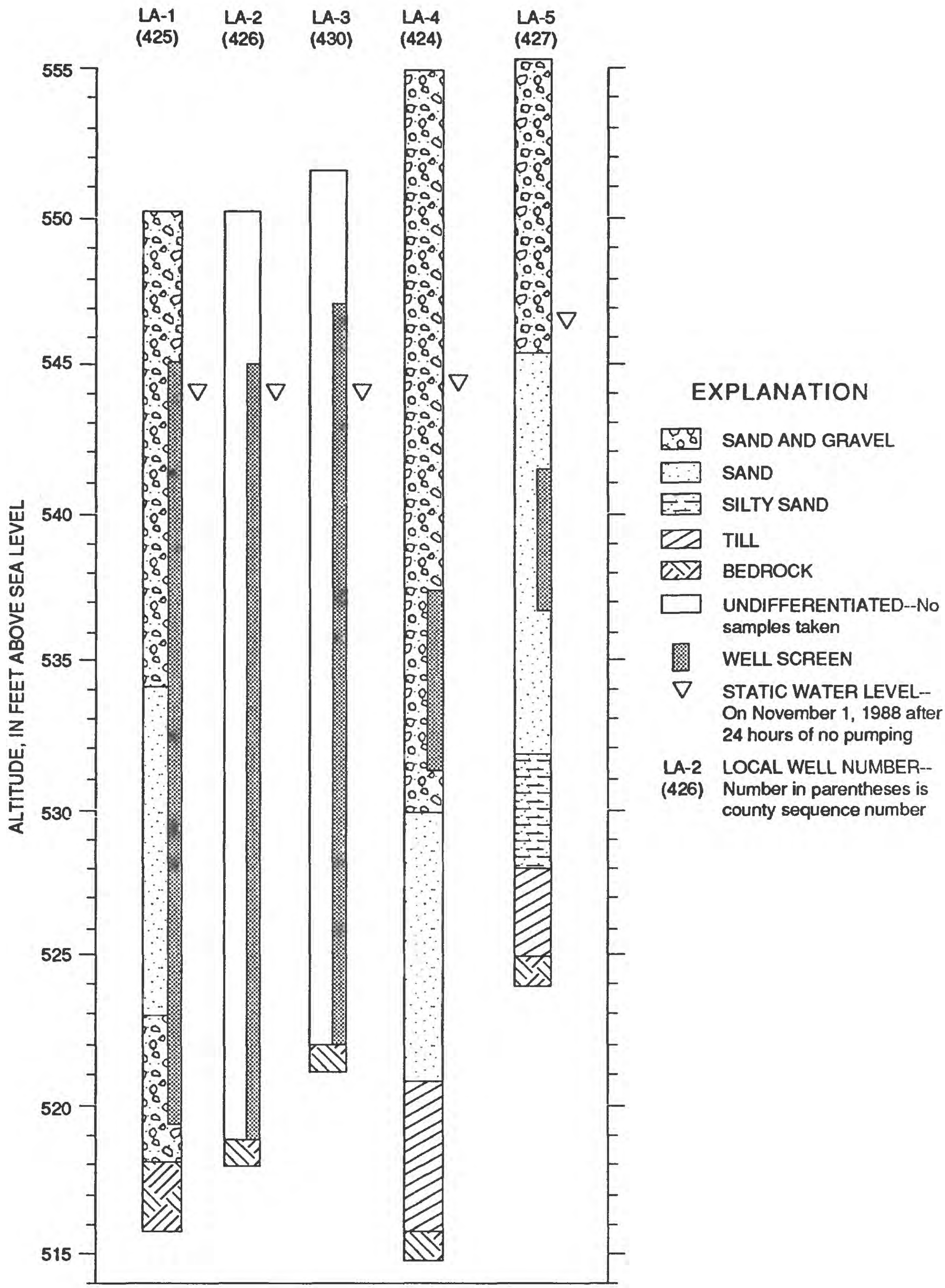


Figure 13.--Logs of observed wells LA-1 through LA-5. (Location is shown in fig. 12.)

in atmospheric pressure because the vibrating wire transducers are a sealed gage and sensitive to changes in atmospheric pressure.

The electronic measurement and recording of water levels at short time intervals (initially 3 seconds) enabled measurement during the early part of drawdown, which corresponds to the instantaneous release of water from storage by expansion of the water and compaction of the aquifer material (Neuman, 1974; Freeze and Cherry, 1979, p. 325). Thus, the early time-vs-drawdown curves could be matched with the dimensionless time-vs-drawdown curves developed by Theis (1935) to solve for transmissivity (T) and storage coefficient (S). The curves for observation wells LA-1 through LA-4, corrected for dewatering of the aquifer (Walton, 1970, p. 224), are shown in figure 14; results of the aquifer test are summarized in table 1.

The early drawdown data (within the first 10 minutes of the aquifer test) proved to be the most useful because later data were probably influenced by the nearby boundary of till and lake deposit west of the pumped well. Discharges to springs and wetlands along the western toe of the aquifer may also influence drawdown data, but these were considered small in relation to the effect of the till and lake deposit boundary. Normally drawdowns in an unconfined aquifer of infinite lateral extent show a delayed yield in response to pumping (Neuman, 1975), whereby drawdowns are less than those predicted by the Theis curve because the water reaching the well is derived from dewatering of the aquifer. The Lacona-Sandy Creek drawdown data show just the opposite response, in which the drawdown is greater than indicated by the Theis curve because the poorly permeable boundary limits the volume of aquifer contributing to the well. The proximity of this boundary limits the use of the drawdown data to that part that is unaffected by the boundary (Freeze and Cherry, 1979; Lohman, 1972). The later drawdown data can be used to determine the location of the boundary through application of well images (Walton, 1970; Freeze and Cherry, 1979; Lohman, 1972).

Table 1.--Estimated hydraulic values from analysis of 1988 aquifer-test data through methods of Theis (1935) and Stallman (1963).

[ft, feet; ft^2/d, feet squared per day]

A. Method of Theis (1935)

Well number	Distance to pumping well (ft)	Saturated thickness (b) (ft)	Trans-missivity (T) (ft^2/d)	Horizontal hydraulic conductivity (K) (ft/d)	Storage coefficient (S) (dimensionless)
LA-1	22.5	25.7	30,000	1,200	0.0478
LA-2	53.5	23.6	50,000	2,100	0.0335
LA-3	100	23.0	79,000	3,400	0.0230
LA-4*	180	23.0	18,000	780	0.0030
		Log mean	38,000	1,600	0.0182

B. Method of Stallman (1963)

Well number	Trans-missivity (T) (ft^2/d)	Horizontal hydraulic conductivity (K) (ft/d)	Storage coefficient (S) (dimensionless)	Constant of propor-tionality** (kp)
LA-1	33,000	1,300	0.0667	5
LA-2	61,000	2,600	0.0293	3.5
LA-3	97,000	4,200	0.0264	2.5
LA-4	11,000	480	0.0187	2.5
Log mean	38,000	1,600	0.0315	

*Partial screen observation well (17.3 to 22.3 ft below land surface).

**Kp constant of proportionality equal to ratio of radial distance of the image well to the radial distance of the observation well from the pumped well. (See fig. 14.)

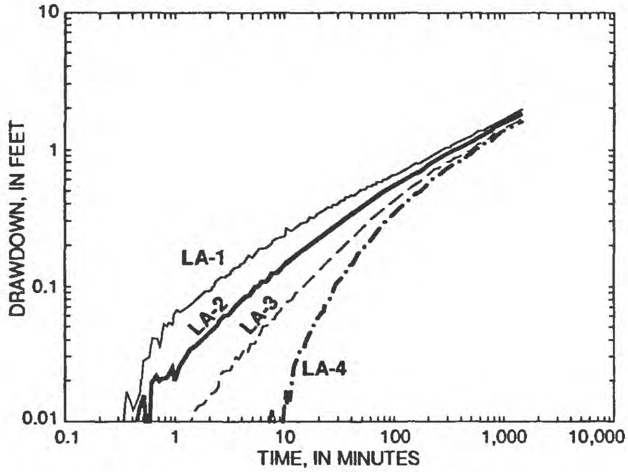


Figure 14.--Drawdowns over time in observation wells LA-1 through LA-4 during an aquifer test at production well 2. (Location is shown in fig. 12.)

Estimating distance to a boundary by image wells. "Image wells" mathematically duplicate the hydraulic effect of an impermeable boundary by placing an imaginary discharging well the same distance from the pumped well as the boundary, but on the opposite sides. The drawdown produced by the image well is added to the drawdown produced by the pumped well (principle of superposition, Reilly and others, 1984) to determine the resultant cone of depression in the observation well. The aquifer is assumed to respond linearly to stress, but application of this technique to an unconfined aquifer (nonlinear system) is generally acceptable when the drawdown is small, 10 percent or less than the saturated thickness (Reilly and others, 1984). The drawdown (2.3 ft) relative to the saturated thickness (25 ft) in this aquifer is near the limits of acceptable error that results from changes in transmissivity; thus, the estimated location of the boundary may be affected by the nonlinearity of the system.

In application, the departure of the drawdown curve from the Theis curve is used to determine the distance to the boundary (fig. 15) from the equation (Heath, 1983):

$$\frac{r_r^2}{t_r} = \frac{r_i^2}{t_i} ,$$

where r_r = distance from observation well to pumped well;

r_i = distance from observation well to image well;

t_r = time at which drawdown (Si) is caused by real well; and

t_i = time at which an equivalent drawdown (Si) is caused by image well.

The distance to the image well (aquifer boundary) from the observation well is then:

$$r_i = r_r \sqrt{\frac{t_i}{t_r}}$$

The distances from the pumped well to the impermeable boundary calculated from time-vs-drawdown curves for wells LA-1 through LA-4 by this method were 32 ft, 38 ft, 52 ft, and 152 ft, respectively. These values generally correspond to the field estimates, which place the distance to the till contact between 50 and 160 ft from the production well.

Lohman (1972) reports a simpler method by Stallman (1963), who developed a family of type curves for determining transmissivity of aquifers influenced by a single boundary. Values of transmissivity and storage coefficient (calculated from the match of the Stallman type curve) along with the constant of proportionality are summarized in part B of table 1. The distance to the boundary from production well 2, is calculated from the following equation:

$$r_i = k_p - r_r ,$$

where r_i = distance to image well (boundary) from the observation well;

k_p = constant of proportionality equal to the ratio of the radial distance of the image well to the radial distance of the observation well from the pumped well. Values of k_p are determined by matching the Stallman type curve with the measured type drawdown curve; and

r_r = distance to the real well from the observation well.

The proportionality constants were obtained by matching the Stallman type curve with drawdown data from observation wells LA-1 through LA-4. The distances to the boundary from production well 2, as determined from the respective curve matches, were 45 ft, 67 ft, 75 ft, and 135 ft. This method shows less variation in the distance to the boundary than the previous method but more variation in the transmissivity and storage coefficient.

Analytical solutions for calculating aquifer properties are rigorously applicable only in situations where the underlying assumptions in the method are satisfied (horizontal radial flow in a homogeneous aquifer of infinite lateral extent and the pumped well fully penetrates the entire saturated thickness of the aquifer). These conditions are not completely met in the aquifer in the Lacona-Sandy Creek well field. In addition, the proximity of the less permeable boundary to the pumped well limits the estimation of

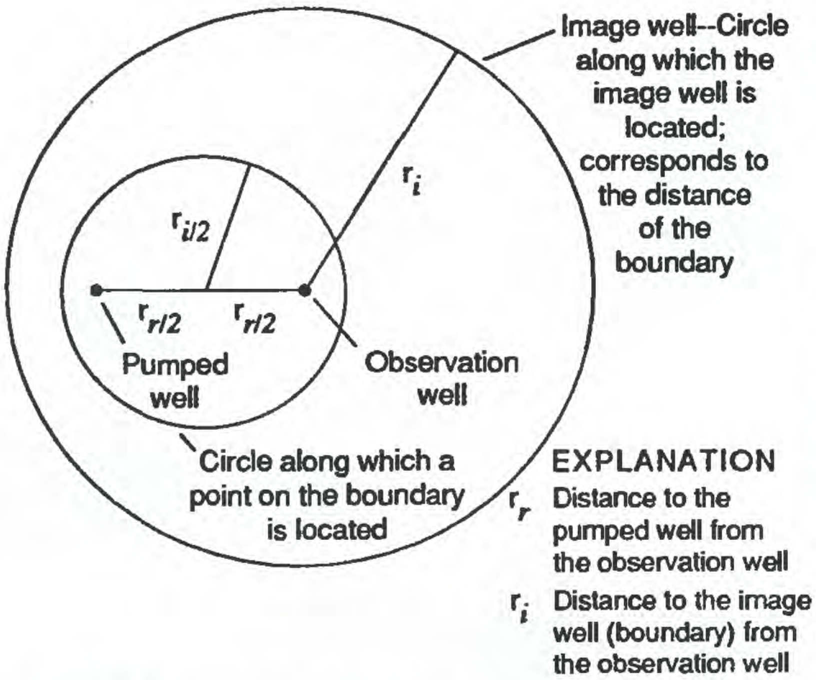


Figure 15.--Use of an image well to duplicate the effect of a boundary system in an infinite aquifer. (Modified from Heath, 1983, p. 49.)

hydraulic values by the Theis solution to the early drawdown data (those unaffected by the boundary), which were obtained within the first 10 minutes of the test, with drawdowns of less than 0.20 ft.

The Stallman type curves for aquifers affected by a single boundary enables use of the first 100 minutes of the drawdown data for the curve-matching process. The hydraulic conductivity values computed by this method were similar to those obtained by the Theis method and provided identical results for the log-transformed mean hydraulic conductivity of the four observation wells. The estimates for hydraulic properties of the aquifer are affected by generalizations and assumptions inherent in these methods, particularly in the selection of the curve-match point, in addition to the accuracy limits of the transducers for the small changes in head.

Two-Dimensional Numerical Model Analysis

The U.S. Geological Survey's three-dimensional, modular, finite-difference ground-water flow model developed by McDonald and Harbaugh (1988) was selected to simulate ground-water flow in the vicinity of the Lacona-Sandy Creek well field. A two-dimensional numerical analysis was used because (1) data were insufficient to support a three-dimensional model, and (2) the predominant flow path is probably horizontal with a vertical flow component limited mainly to the immediate area around the pumped well. The assumption of two-dimensional flow is generally considered valid in stratified-drift aquifers in the Northeast because they are relatively thin (Morrissey, 1987). Contributing areas to the well field were then calculated through MODPATH, a semianalytical particle-tracking program that uses heads and fluxes predicted through steady-state simulation by the ground-water model to trace the flow lines in the aquifer (Pollock, 1989).

The principal advantage of numerical models over analytical models is the ability to simulate a wide range of hydrogeologic conditions that may affect the contributing area to a well. Analytical techniques require several simplifying assumptions that are often unrealistic for the aquifer in question. Numerical methods can incorporate a variety of hydrogeologic features into the model design but require more time and resources for development and use.

Model Description and Design

The McDonald-Harbaugh model (1988) uses a finite-difference approximation of the partial differential equation that describes the movement of ground-water through an aquifer. For two-dimensional steady-state analysis used in this study, the governing differential equation is:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) = 0 ,$$

where x,y = cartesian coordinates aligned along major axes of hydraulic conductivity, K_{xx}, and K_{yy}; and
h = hydraulic head (L).

The model uses finite-difference techniques to solve a set of algebraic equations that approximate the governing differential equation. Algebraic equations are formulated by representing the aquifer as a grid of homogeneous blocks or cells with a specifying set of hydraulic values. Boundary conditions are specified for the entire model to solve the set of algebraic equations for the specific conditions of the aquifer. The following sections discuss the development of the grid used in the Lacona-Sandy Creek model, the specification of boundary conditions for the model, and the assignment of hydraulic values to each grid cell.

Model grid. In finite-difference models, the number of rows and columns chosen to represent the aquifer is selected to minimize the computation time while maintaining a grid fine enough to accurately represent the aquifer geometry. Several other factors influence the selection of the grid; these include (1) accuracy of measured values against which the model is calculated, (2) level of accuracy in defining stresses on the system, and (3) suitability of the grid spacing for the application of the particle-tracking program.

The grid chosen to represent the Tug Hill aquifer in the vicinity of the Lacona-Sandy Creek well field contains 34 rows and 25 columns (fig. 16). The active

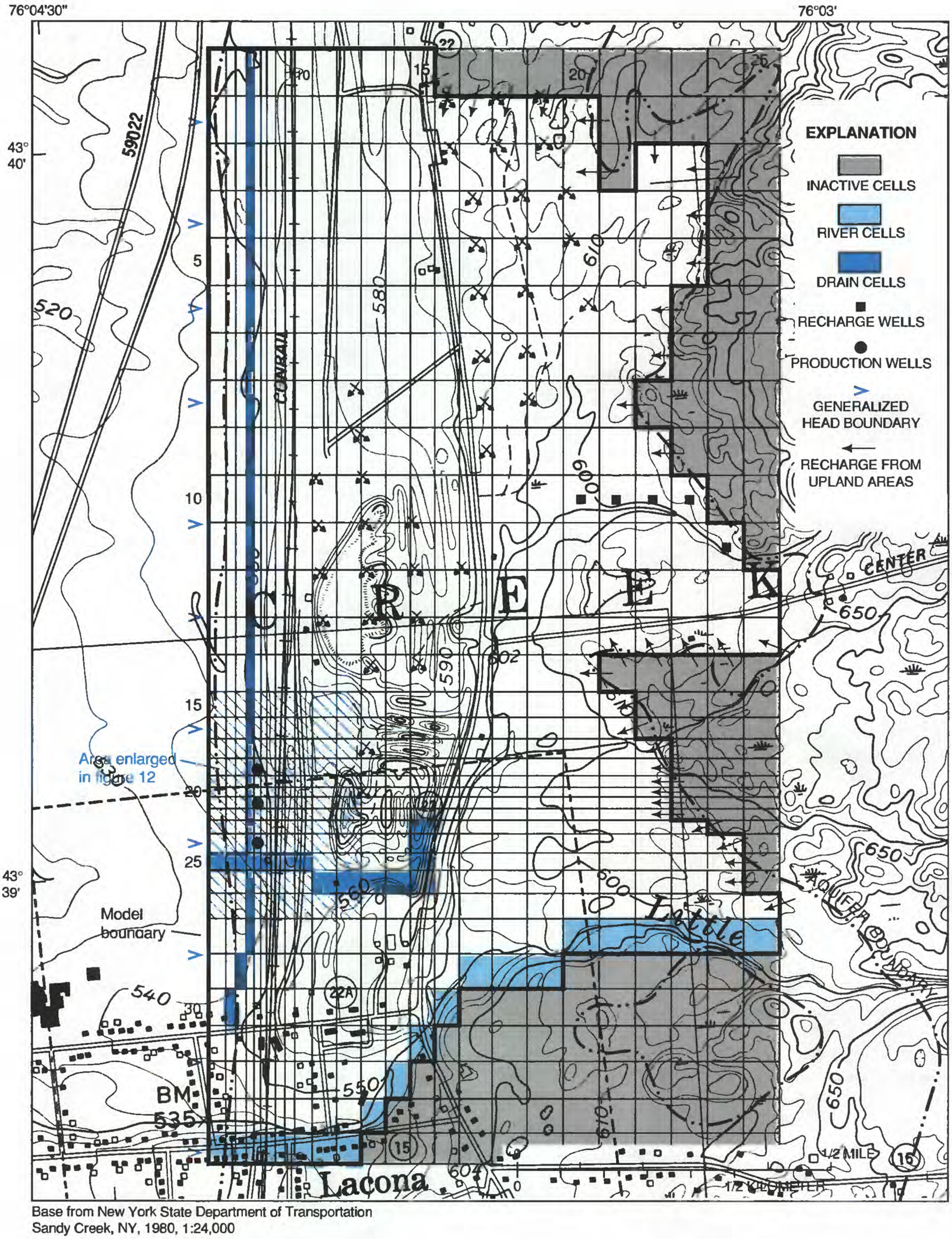


Figure 16.--Finite-difference grid and model boundaries. (Location is shown in fig. 12.)

part of the model represents a 1.19-mi^2 area that contains the major water-yielding outwash and beach sand and gravel deposits. The inactive part of the model is the upland till deposits, which were estimated to be several orders of magnitude less permeable than the outwash and beach deposits and therefore were eliminated from the model computations.

The model grid is oriented such that the columns are aligned with the north-south axis of the aquifer in this area. The cell size in the vicinity of the well field is relatively small (50 by 100 ft) to (1) permit the pumped wells to be accurately simulated in the center of a cell, (2) allow sufficient detail to postulate a range of pumping rates, and (3) accommodate the close spacing of the observation wells in that area. Cells beyond the well field are larger because that amount of detail is not needed and because data are insufficient to support a finer grid spacing.

Boundary conditions. Boundaries are specified in the model to represent the sources and rates of inflow and outflow of water to the active part of the model. The model boundaries used are shown in plan view in figure 16 and in an idealized east-west section in figure 17.

Aquifer boundaries. Ground-water flow between aquifer and the upland till and the underlying till and bedrock was assumed to be negligible compared to the rate of ground-water flow within the aquifer; therefore these areas are represented in the model by assigning a value of zero hydraulic conductivity, which results in no flow into or out of the model area. This type of boundary is referred to as a no-flow boundary, although in reality, a small amount of flow probably does occur between the aquifer and these units.

Not all of the model boundaries correspond to natural boundaries of the aquifer. For example, the aquifer extends beyond the modeled area to the north and south, and a no-flow boundary was specified as the northern boundary because it approximated a flow line in the aquifer that, by definition, does not allow water to cross its path. Artificial boundaries such as this are placed far enough from the pumped wells that they do not affect the heads and flows produced by pumping, and the pumping does not change the head distribution such that the boundary is no longer a flow line. The southern boundary, which is formed by Little Sandy Creek, is discussed in the section on the influence of streams, further on.

The till and lake deposits that flank the western part of the model were treated as a head-dependent boundary to prevent excessive head buildup along the western edge of the aquifer. The underflow through these deposits was simulated by a general-head boundary that establishes the flow between the active model and the area external to the model as the difference between the head and hydraulic conductivity values of the model cell and those of the area outside the model. The head in the outside area was assumed to be at land surface and was assigned a value based on elevations obtained from U.S. Geological Survey 1:24,000-scale topographic maps. The hydraulic conductivity between the outside area and the model cell was established during the model calibration.

Areal recharge. Areal recharge to the aquifer is the difference between the amount of precipitation minus losses due to evapotranspiration and surface runoff. Recharge is a specified flux to a free-surface boundary (water table) and represents the volume of water that enters the saturated ground-water system per unit area per unit time. Surface runoff from the aquifer was assumed to be minor, from reports that flow in

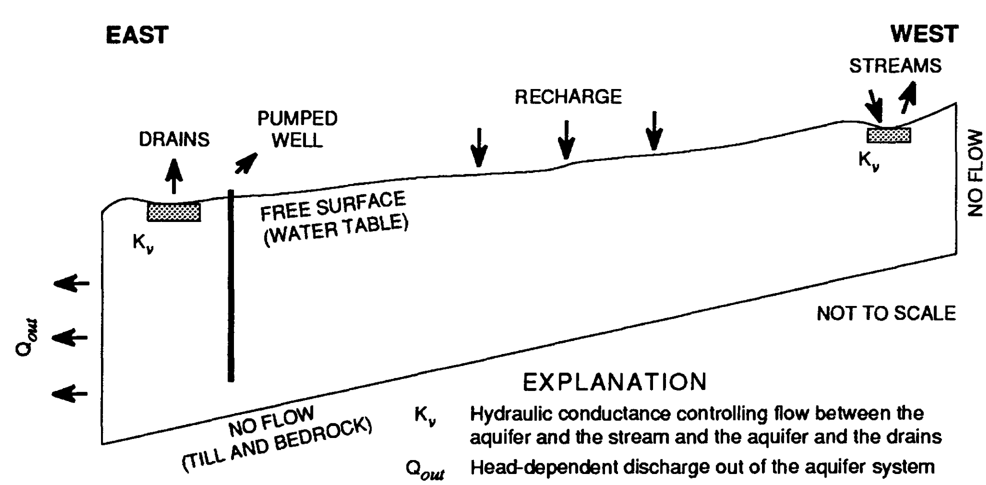


Figure 17.--Idealized vertical section illustrating boundary conditions and hydraulic properties that control flow within the aquifer system.

gullies occurs only during periods of extreme precipitation and snowmelt (D. MacVean, Lacona, Mayor, oral commun., 1988). Miller and others (1989) calculated the average annual recharge in this area to be 27 in/yr, from regional precipitation and average annual evapotranspiration losses reported by Weist and Giese (1969) and Knox and Nordenson (1955).

Infiltration from streams. Typically, streams that originate in the till uplands lose water as they traverse the permeable sand and gravel and are reported to be a significant source of recharge to the Tug Hill aquifer (Miller and others, 1989). In the modeled area, Little Sandy Creek is the only major stream, and forms a natural ground-water divide along its western reach in the aquifer where it has exposed till and bedrock. The stream was assumed to form a local ground-water divide representing the southern extent of the modified aquifer area.

The rate at which water moves between stream and aquifer is dependent on the head difference between the two, as well as the vertical conductance of the streambed material. Flow between the aquifer and the stream is referred to as a head-dependent flux and is governed by the following equation (McDonald and Harbaugh, 1988):

$$Q = C(H-h) ,$$

where Q = flow between the aquifer and stream (L^3t^{-1});
C = conductance of the streambed material (L^2t^{-1});
H = head in the stream (L); and
h = head in the aquifer (L).

The streambed-conductance term is defined as the hydraulic conductivity of the streambed material times the streambed area (channel length times width) divided by the streambed thickness. For each stream cell, values of streambed conductance and head in the stream are specified, and the flux between the stream and the aquifer is computed from simulated head in the aquifer at that cell. The equation states that infiltration from the stream to the aquifer occurs when $H > h$, and discharge from the aquifer to the stream occurs when $H < h$. Both conditions were shown to occur in the Tug Hill aquifer by Miller and others (1989), who reported that streams in the northern part of the aquifer lose water at the eastern side of the aquifer and gain water on the western side of the aquifer.

Initial estimates of streambed conductance were made from the reported vertical hydraulic conductivity of 0.2 ft/d calculated from piezometer tests of the streambed in the Susquehanna River by Yager (1986) and visual observations of the streambed geometry. The streambed was assumed to be 2 ft thick and of varying width, depending on the location. The reach west of the Lacona-Orwell Road, where Little Sandy Creek flows on bedrock, was assigned a width of 1 ft to simulate the leakage through unconsolidated deposits along the streambank. The reach east of Lacona-Orwell Road was assigned a width of 10 ft. The length of each reach was measured from U.S. Geological Survey 1:24,000-scale topographic maps. Head in the creek was assumed to be 1 ft greater than the streambed elevation, which was obtained from 1:24,000-scale topographic maps.

Recharge from intermittent streams and unchanneled runoff. Additional recharge enters at the eastern edge of the aquifer as runoff from intermittent streams and unchanneled flow from till-covered hills. To account for this recharge, cells bordering areas outside the active model boundary were assigned additional recharge in proportion to the upland drainage area contributing to the cell. During the calibration procedure, the rate of recharge was reduced in some cells with relatively large upland contributing drainage areas.

A tributary stream in the model area just north of Center Road (fig. 10) was observed to be flowing during base-flow conditions in August 1988. This tributary enters the aquifer in the center of the east side of the modeled area and flows to where a small manmade earthen berm ponds the water and overflows only during extreme runoff (D. McVean, Mayor of Lacona, oral commun., 1988). To simulate recharge from this stream, a constant flow was specified at five cells along the channel to the pooled area.

Seepage from this stream to the aquifer was calculated from discharge measurements made in the stream during August and October 1988 and by regional lake-evaporation and unit-area runoff data collected at Sandy Creek at Adams. Average annual runoff reported for 30 years of record at Sandy Creek near Adams (Firda and others, 1988), approximately 12 mi north of the study area, is 29 in/yr. Weist and Giese (1969) report annual lake evaporation to be 23 in/yr, which was also used to estimate water loss from the ponded area. The remaining 6 in/yr (18,400 ft^3/d) was assumed to recharge the aquifer and was distributed among five cells along the east part of the aquifer (fig. 17) at rates proportional to the seepage rates measured during August and October.

Discharge from springs and evapotranspiration. Ground-water discharge to springs and wetlands along the western part of the model and along the southeastern part of the sand and gravel quarry were simulated by drains (fig. 16). Drains are head-dependent flow boundaries similar to the stream boundaries except that they allow water only to discharge from the aquifer. The head in the drain cells were determined from land-surface elevations given in U.S. Geological Survey 1:24,000-scale topographic maps. The hydraulic conductivity of the drain cell was established during the calibration process.

Model Calibration

The ground-water flow model was calibrated through both transient and steady-state simulations. Transient-state simulations of the well-field area were made to compare the hydraulic conductivity values obtained from analytical methods by duplicating drawdowns observed in the 1988 aquifer test discussed previously. Steady-state simulations were used to (1) calibrate the model area beyond the well field, and (2) simulate the hydraulic head and flows that result from pumping to delineate the well-field contributing area, as described in the next section.

Transient-state simulations. Transient-state simulations of the well field area were made through use of a 800-ft by 800-ft subset of the model area. This area was discretized into 40 equally spaced rows and columns (20 ft x 20 ft grid spacing) to obtain a grid resolution to accurately depict drawdowns around the pumped well. Initially, simulations were made by applying principles of superposition (Reilly and others, 1984), whereby the aquifer was treated as a confined system. This technique was used because the starting heads are not needed for the problem solution and because the model was sensitive to changes in hydraulic conductivity. To simulate a confined system, transmissivity values were calculated from the computed saturated thickness of the aquifer (difference between the estimated head distribution and the bottom elevation of the aquifer), multiplied by selected values of hydraulic conductivity.

The simulated drawdowns that most closely matched observed drawdowns were those that resulted from a hydraulic conductivity of 1,200 ft/d and a storage coefficient of 0.025. These values match fairly well those calculated by analytical methods given in table 1. Figure 18 shows the drawdown curves for selected values of hydraulic conductivity and storage in relation to drawdowns observed during the aquifer test. Predicted drawdowns were within 0.13 ft of those observed at the observation wells in six time steps ranging from 1.15 to 24 hours.

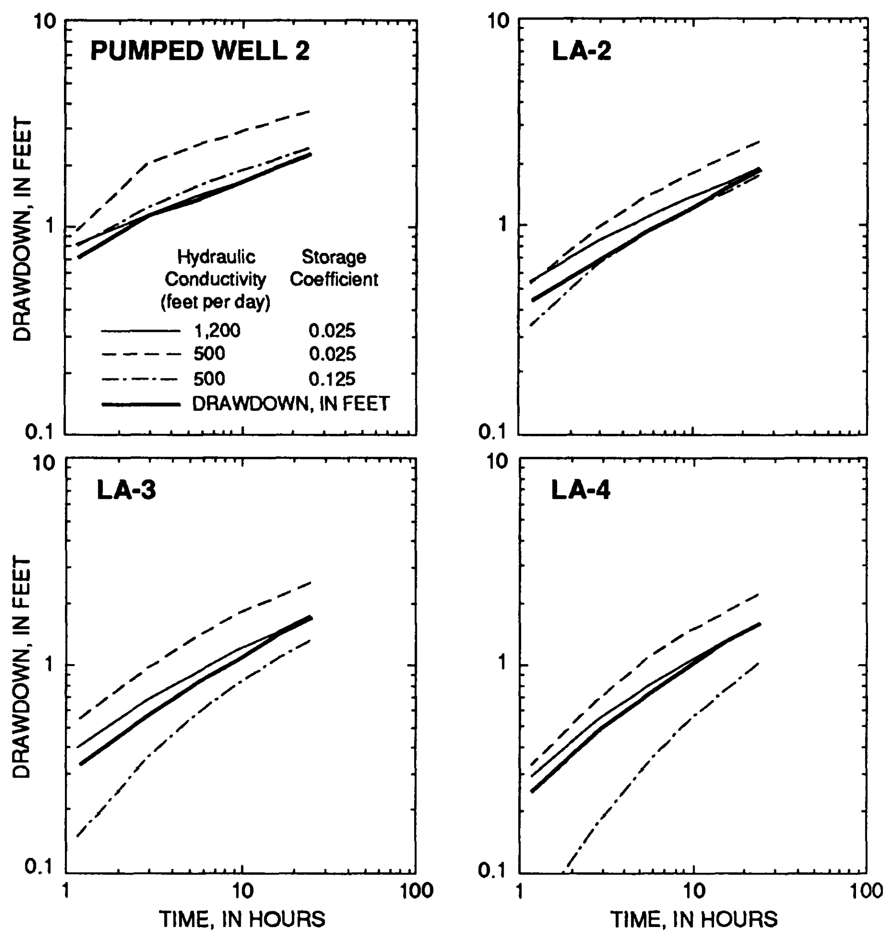


Figure 18.--Predicted drawdowns at pumped well 2 and observation wells LA-2, LA-3, and LA-4 for transient-state simulations of aquifer test. (Location is shown in fig. 12.)

In unconfined systems, transmissivity is a function of saturated thickness, which is in turn a function of head. Therefore, to correctly duplicate drawdowns measured in the field, simulations were run for an unconfined system in which hydraulic conductivity values derived from superposition simulations were used as initial estimates. These simulated drawdowns were within 0.11 ft of the observed drawdowns for the first 10 hours of the aquifer test, but the difference varied by as much as 0.45 ft in later parts of the test. Hydraulic conductivity values between 500 ft/d and 1,200 ft/d gave a better match for later drawdown data than did the early drawdown data. Therefore, horizontal hydraulic conductivities of 1,200 ft/d to 500 ft/d were used to compute the contributing area to the well field.

Steady-state simulations. The water-surface elevations used for the steady-state model calibration were those reported by Miller and others (1989) and those measured in the five observation wells installed during this study. The relatively steep east-west profile of the land surface and shallow depth to the till and bedrock underlying the aquifer (fig. 19) facilitated adjustment of hydraulic conductivity values during calibration The resultant steep hydraulic gradient and thinness of permeable deposits limited the range of acceptable hydraulic conductivity values for a given rate of recharge that would not produce heads greater than land surface or cause dewatering of cells. This calibration method assumes that the average rate of recharge estimated for this area is correct and is sufficient to maintain water in all parts of the aquifer. The simulated hydraulic head for the calibrated steady-state model along row 21 of the model grid is shown in cross section in figure 19.

The distribution of hydraulic conductivity (fig. 20) was estimated from surficial geologic interpretations by Miller and others (1989), analysis of an aquifer test, a transient-state simulation of the aquifer test, and the steady-state simulations discussed in the following sections. The aquifer was assumed to be isotropic along rows and columns even though the bedding planes reported for beach deposits (Davis, 1987) may create preferential flow paths that result in horizontal anisotropy. This could not be verified without further field investigations, however.

The area that was most sensitive to changes in hydraulic conductivity was the outwash deposits that form the eastern part of the aquifer because these are the thinnest sand and gravel deposits in the aquifer. Hydraulic conductivity of these deposits was estimated to be 180 ft/d. Changes in hydraulic conductivity of ± 20 percent would either cause cells to become dry or hydraulic heads to rise above land surface.

Three values of hydraulic conductivity for the beach sand and gravel deposits were assigned—one for a crescent-shaped area surrounding the well field (1,200 ft/d), the quarried area north and east of the well field (80 ft/d), and the remaining undisturbed beach deposits mainly north of the well field (500 ft/d) (fig. 20). The value for the crescent-shaped (1,200 ft/d) was calculated from the aquifer test and transient-state simulations. The crescent-shaped area was delineated from the Oswego County Soil Survey (Rapparlie, 1981) and from the percentage of sand in relation to the sand and gravel in well LA-5 (location shown in fig. 12, well log in fig. 13).

Sand and gravel mining has removed much of the beach-deposit material in the Lacona-Sandy Creek area, as mentioned previously, and, in some areas, has removed the sand and gravel to a depth reaching or nearly reaching the till deposits (B. Reid, Manager, General Crush Stone, oral commun., 1988). Although the effect of this mining on the natural flow system is uncertain, it probably removed the more permeable beach deposits (the higher deposits more subject to washing by wave action) and decreased the permeability of the remaining deposits by compaction from heavy earth-moving equipment. A similar condition was reported by Yager (1986) for a mined area near a well field in the Susquehanna River valley near Kirkwood, N.Y. Simulations that used a hydraulic conductivity of 80 ft/d appear to best represent the water table in this area. Sensitivity tests that indicated a +100 percent and -80 percent change in hydraulic conductivity of the mined area would result in a maximum head change of about 2 ft in this area, with only minor changes in head outside the mined area.

The remaining beach sand and gravel deposits were assigned a hydraulic conductivity of 500 ft/d. Sensitivity analysis of the hydraulic conductivity of these deposits indicated that a change of +100 percent and -80 percent would result in a head change of only 0.2 ft. The head in this area is controlled mainly by the elevation and hydraulic conductance of the drains that were used to simulate discharge to springs and wetlands.

Other deposits include a small area of eolian sand in the northern part of the modeled area and the lake and till deposits bordering the aquifer on the west. The model is sensitive to changes in hydraulic conductivity of the eolian deposits because they are thin and border the till deposits (no-flow boundary) along the eastern flank of the aquifer. A hydraulic conductivity of 25 ft/d was used to represent these deposits. The fine lake sand, silt, and till bordering the aquifer on the west restrict flow from the more permeable beach deposits and were assigned a hydraulic conductivity of 1.0 ft/d and 0.5 ft/d, respectively.

The simulated water budget to the aquifer is summarized in table 2. Under nonpumping conditions, the simulated loss from Little Sandy Creek to the aquifer above Lacona-Orwell Road is 6,000 ft^3/d or approximately 11 (gal/d)/ft of stream reach. This loss, which represents 2 percent of the recharge to the

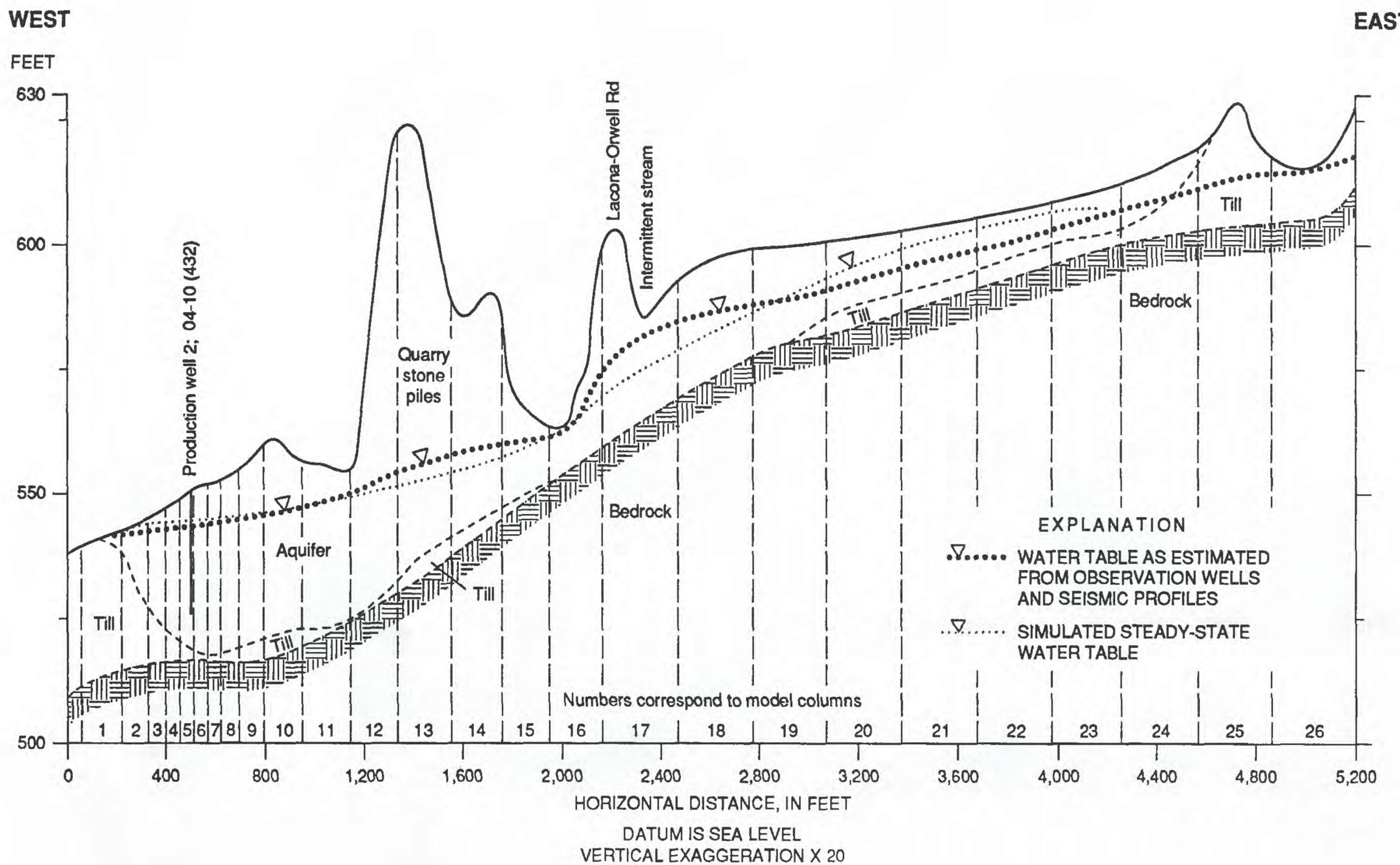
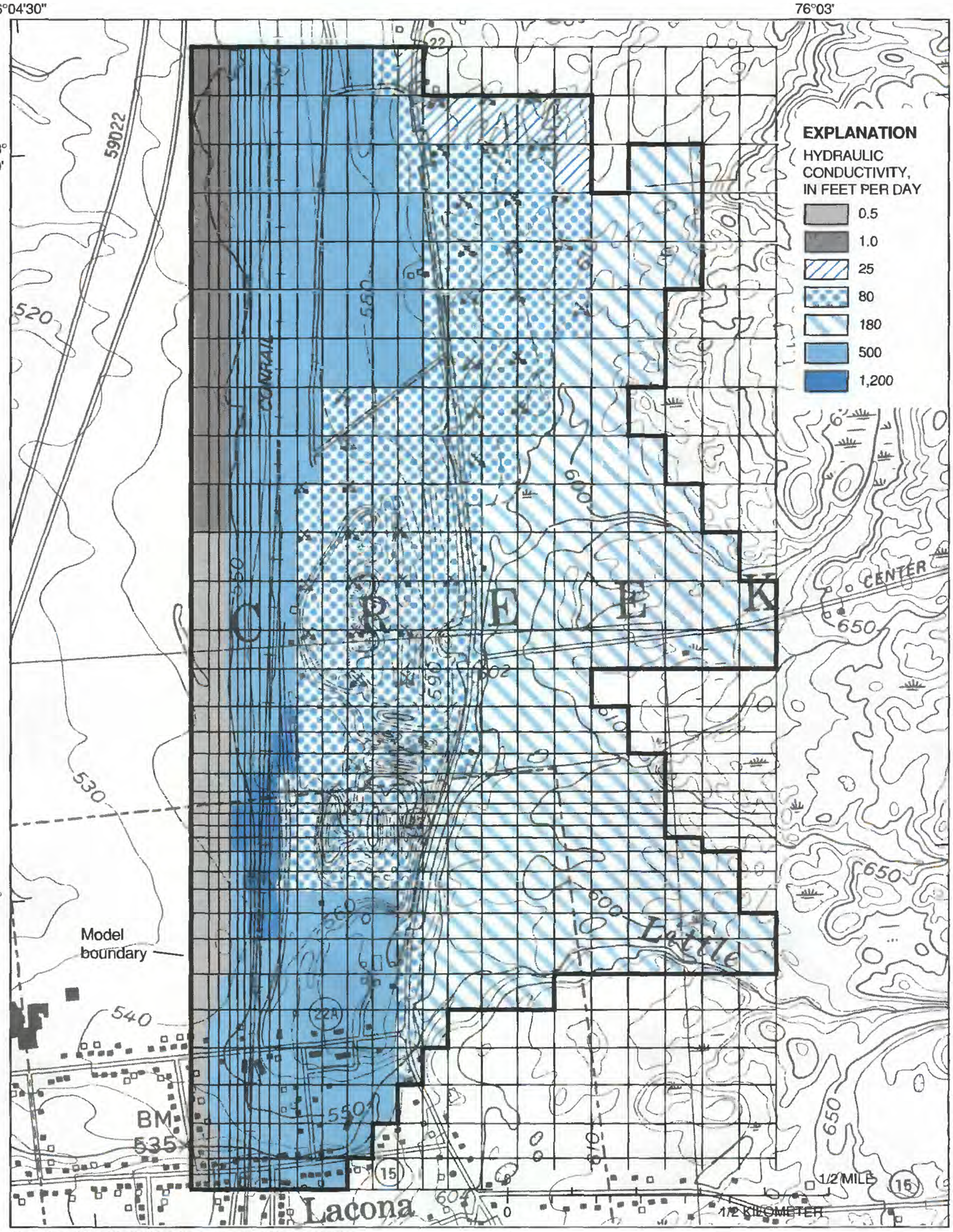


Figure 19.--Hydrologic section of aquifer along row 21 of the ground-water model showing water-table configuration as calculated from water-level measurements and seismic profiles, and as simulated by the steady-state flow model. (Location is shown in fig. 16.)



Base from New York State Department of Transportation
Sandy Creek, NY, 1980, 1:24,000

Figure 20.--Distribution of hydraulic-conductivity values in the modeled area.

Table 2.--Simulated volumetric recharge and discharge to the model area.

[Amounts are in cubic feet per day.]

Recharge			Discharge		
Source	Amount	Percentage of total	Location	Amount	Percentage of total
Precipitation and unchanneled runoff	293,300	92	Spring and evapotrans-piration	287,600	90
Intermittent stream	18,400	6	Till and lake deposits	17,600	6
Little Sandy Creek	6,000	2	Little Sandy Creek	12,500	4
Total	317,700	100	Total	317,700	100

model area, compares closely to the 10 to 260 (gal/d)/ft stream loss reported by Miller and others (1989) for streams traversing the northern section of the Tug Hill aquifer. South of Lacona-Orwell Road, Little Sandy Creek gains 12,500 ft^3/d or 52 (gal/d)/ft of stream reach, which represents 4 percent of the discharge from the model area. Another simulated source of recharge is the tributary stream north of Center Road, which accounts for 6 percent of the recharge to the model area. The remaining 92 percent of water entering the aquifer is from areal recharge and unchanneled runoff from till uplands to the east. Flow to springs and wetlands along the western edge of the aquifer account for 90 percent of the water discharged from the model area. Ground-water flow to the till and lake deposits along the western boundary of the aquifer accounts for 6 percent of the discharge from the model area.

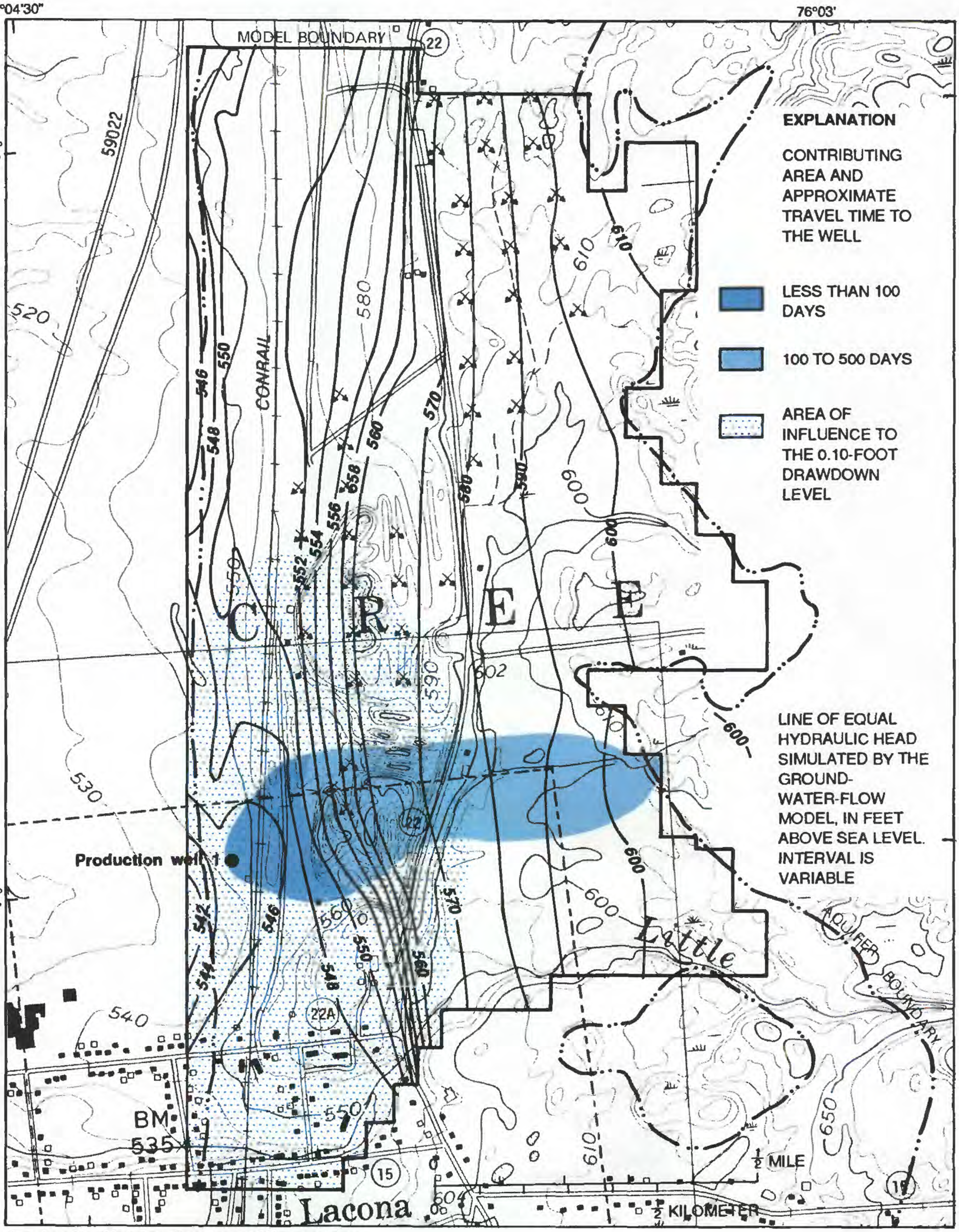
Simulation of Ground-Water Withdrawals and Determination of Contributing Area

The contributing area to the three production wells that supply water to the villages of Lacona and Sandy Creek was estimated from steady-state simulations and a post-processing particle-tracking program developed by Pollock (1989). The particle-tracking program is designed to use output from the modular, three-dimensional, finite-difference ground-water flow model of McDonald and Harbaugh (1988) for steady-state simulations. The algorithm for tracking particles is based on the conservation of mass. Ground-water flow into and out of each cell face computed by the finite-difference model is used to compute the principal velocity components within each cell, which are then used to determine path lines of particles. This ensured that path lines distribute water throughout the flow field in a way that is consistent with the movement of water in the aquifer as predicted by the ground-water flow model.

The particle-tracking program uses a semi-analytical particle-tracking scheme. The method is based on the assumption that each directional velocity component varies linearly within the grid cell in its own coordinate direction. This assumption allows an analytical expression to be obtained that describes the flow path within a grid cell. Given the initial position of particle anywhere in a cell, the coordinates in space and time of any other point along its path within the cell can be computed directly. By this approach, particles are moved from cell to cell. This process produces a series of positions and time coordinates that trace the path of a particle through a flow field as a function of time. In this fashion, particles can be traced forward to areas of discharge or backward toward areas of recharge. A complete description of the particle-tracking algorithm is given by Pollock (1989).

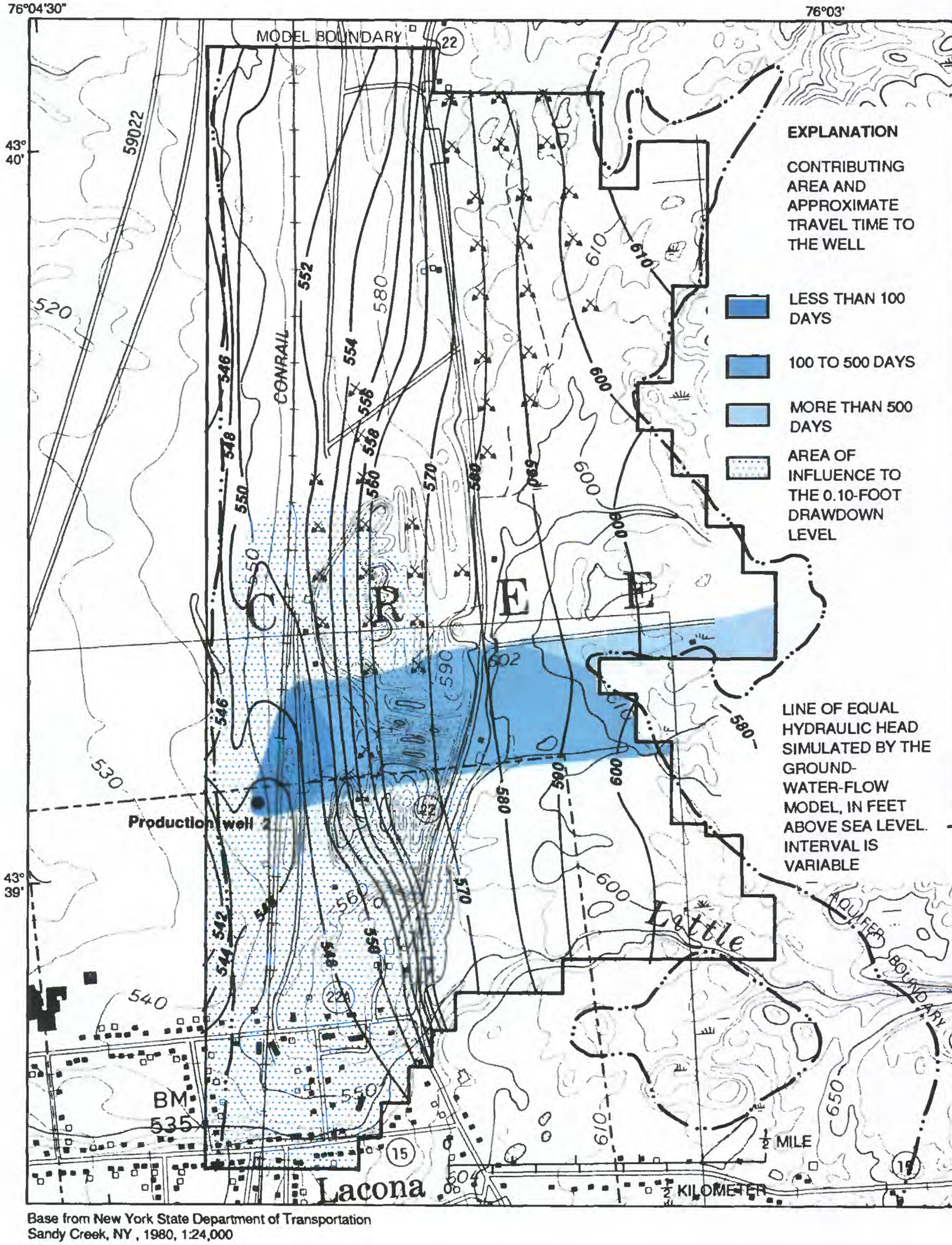
The sources of recharge to the Lacona-Sandy Creek well field were examined (1) in the forward direction (toward areas of discharge) by simulating particles at the top face of all cells within the model and flagging those that discharge to the pumped wells, and (2) in the reverse direction (toward area of recharge) by simulating particles in the four vertical faces of the cells containing the pumped well(s). Particles tracked in the reverse direction were used to trace particle paths as a function of time. Figures 21A through 21D show the contributing areas for various pumping rates at the three production wells and a recharge rate of 27 in/yr. The figures also illustrate time-related contributing area and how the contributing area to a well differs from the area of influence. Travel time is calculated from the velocity vectors and the effective porosity of the aquifer. The effective porosity was assumed to be 0.30, but can vary and inversely affect travel times in proportion to changes in porosity.

Steady-state simulations. The size of the contributing areas (steady state) to production wells 1 and 2, each pumping at 200 gal/min (0.446 ft^3/s), are similar, 0.11 mi^2 and 0.13 mi^2, respectively (fig. 21A, 21B), but the areas differ in shape and position. The estimated captured recharge from these areas contributes 0.467 ft^3/s to well 1, which is 5 percent greater than



Base from New York State Department of Transportation
Sandy Creek, NY, 1980, 1:24,000

Figure 21A.--Contributing area to Lacona-Sandy Creek well field with production well 1 pumping at a simulated rate of 200 gallons per minute, with an annual recharge rate of 27 inches per year and a porosity of 0.30.



Base from New York State Department of Transportation
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Figure 21B.--Contributing area to Lacona-Sandy Creek well field with production well 2 pumping at a simulated rate of 200 gallons per minute, with an annual recharge rate of 27 inches per year and a porosity of 0.30.

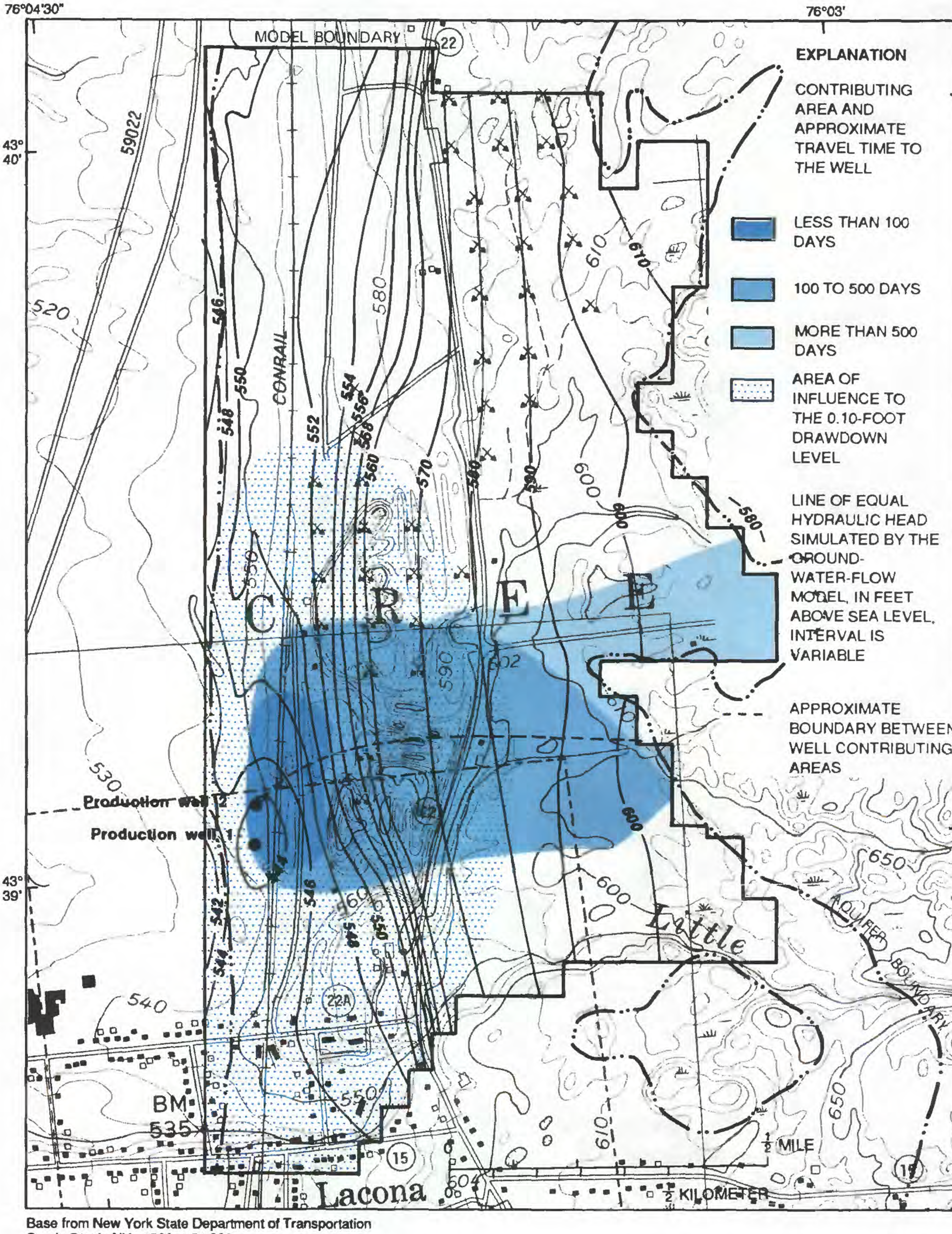
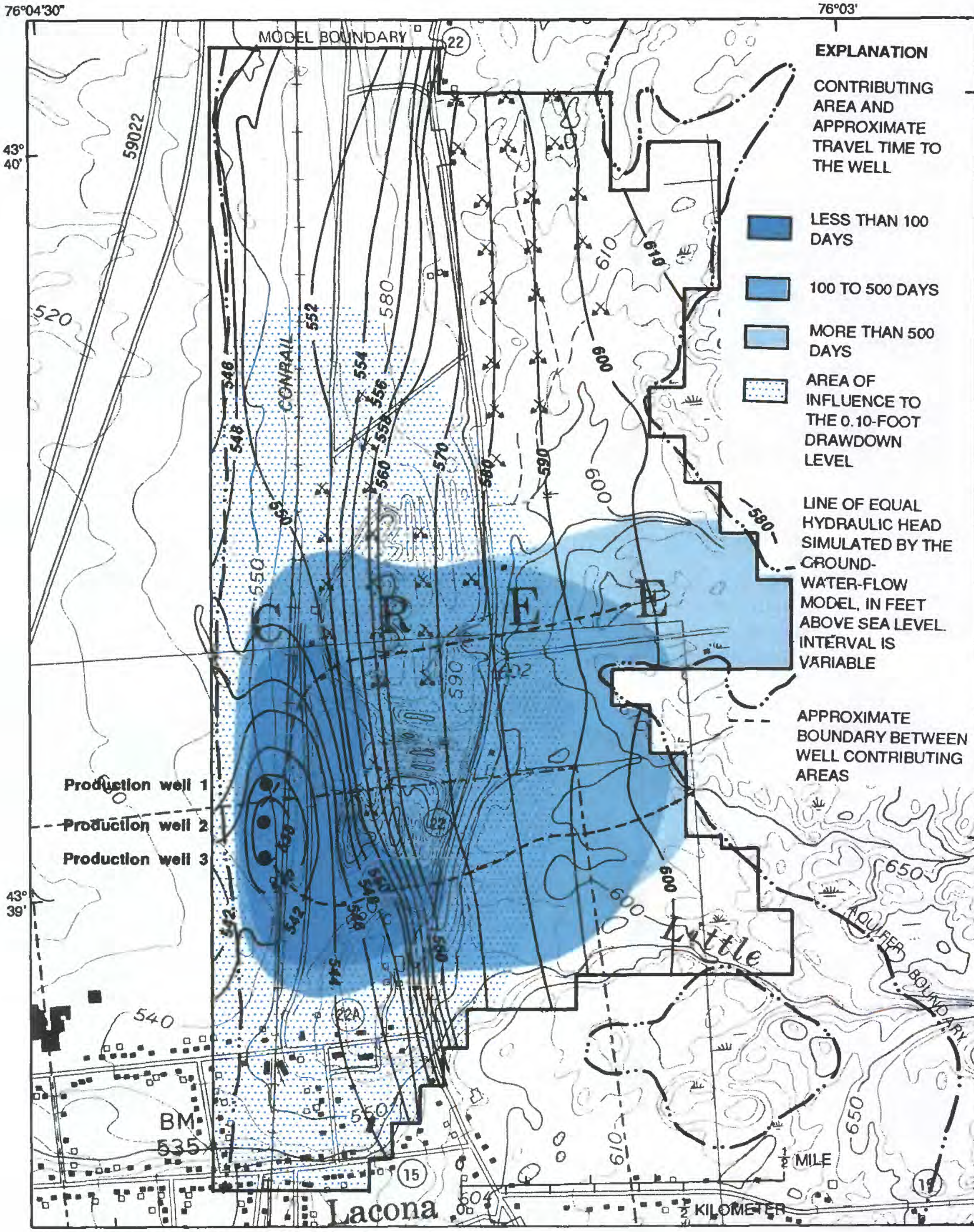


Figure 21C.--Contributing area to Lacona-Sandy Creek well field with production wells 1 and 2 each pumping at a simulated rate of 200 gallons per minute, with an annual recharge rate of 27 inches per year and a porosity of 0.30.



Base from New York State Department of Transportation
Sandy Creek, NY, 1980, 1:24,000

Figure 21D.--Contributing area to Lacona-Sandy Creek well field with production wells 1, 2, and 3 each pumping at a simulated rate of 200, 400, and 125 gallons per minute, respectively, with an annual recharge rate of 27 inches per year and a porosity of 0.30.

its pumpage and 0.560 ft^3/s to well 2, which is 26 percent greater than its pumpage. These estimates of captured recharge exceed the pumpage rates at these wells because the recharge from upland till to cells bordering the contributing area is probably overestimated. In these cells, recharge was assigned a value in proportion to the upland drainage area, but not all recharge may be directed toward the well.

Flow lines indicate that the source of water is predominantly the part of the aquifer that receives runoff from the watershed of the two tributary streams that join at the eastern edge of the aquifer just south of Center Road. Observations of this tributary stream during August and October 1988, a drought year, showed no flow in the reach just east of Lacona-Orwell Road. Flow lines to well 2 indicate a small amount of recharge from the area north of Center Road. Hydrologic budgets for these pumping conditions indicate that 99 percent of the water reaching these wells would have discharged to springs and wetlands under nonpumping conditions and a minor amount of flow (less than 1 percent) is diverted from Little Sandy Creek.

Simulations of the combined pumping effect of wells 1 and 2 (fig. 21C), each discharging at a rate of 200 gal/min (0.691 ft^3/s), indicate a contributing area of 0.29 mi^2. The estimated captured recharge from this area contributes 1.06 ft^3/s, which is 19 percent greater than the combined pumpage from these wells.

The contributing area is broader to the north and south than the contributing area of each well pumping separately (figs. 21A, 21B) and includes some contribution from the tributary stream north of Center Road. The contributing area also widens to the south toward Little Sandy Creek, but flow lines indicate that the major recharge area is still the tributary watershed south of Center Road. Hydrologic budgets for this pumping combination also indicates most of the water reaching the wells is water that would be lost through springs and wetlands along the western flank of the aquifer and slightly more flow is diverted from Little Sandy Creek.

The most pronounced change in the size and shape of the contributing area occurs when all three production wells are run simultaneously at maximum pumping capacity (fig. 21D)—well 1 at 200 gal/min, well 2 at 400 gal/min, and well 3 at 125 gal/min. The estimated captured recharge from this area contributes 1.45 ft^3/s, which is 24 percent greater than the combined pumpage from these wells.

This pumping scenario is only hypothetical, though, because the drawdown exceeds the depth of the wells. The contributing area to the well field increases to 0.48 mi^2 and continues to broaden to the north and south (fig. 21D). Flow lines show that infiltration from Little Sandy Creek enters well 1, but hydrologic budgets computed by the model indicate this to be only a minor amount. Pumping diverts about 0.03 ft^3/s of ground water from the creek, but the primary source of water to the wells is water diverted from springs and wetlands. This simulation of maximum pumpage also suggests that higher rates of withdrawal may be sustained if the wells fully penetrate the aquifer.

The major features of the flow-path analysis indicate that the contributing area differs significantly in both size and shape from the area of influence, and that the flow paths and traveltimes are relatively short. Flow paths are less than a mile long, and traveltimes along the flow path generally require between 500 and 1,000 days to move from the eastern aquifer boundary to the pumped well. These traveltimes are based on an assumed porosity of 0.30, which may not be valid in the entire aquifer.

Sensitivity of contributing area to hydraulic conductivity and recharge rate. Hydraulic conductivity and recharge rates in the model were varied within probable ranges to test the sensitivity of the contributing area to each. A constant pumping rate of 200 gal/min at wells 1 and 2 was maintained while recharge and hydraulic conductivity were varied.

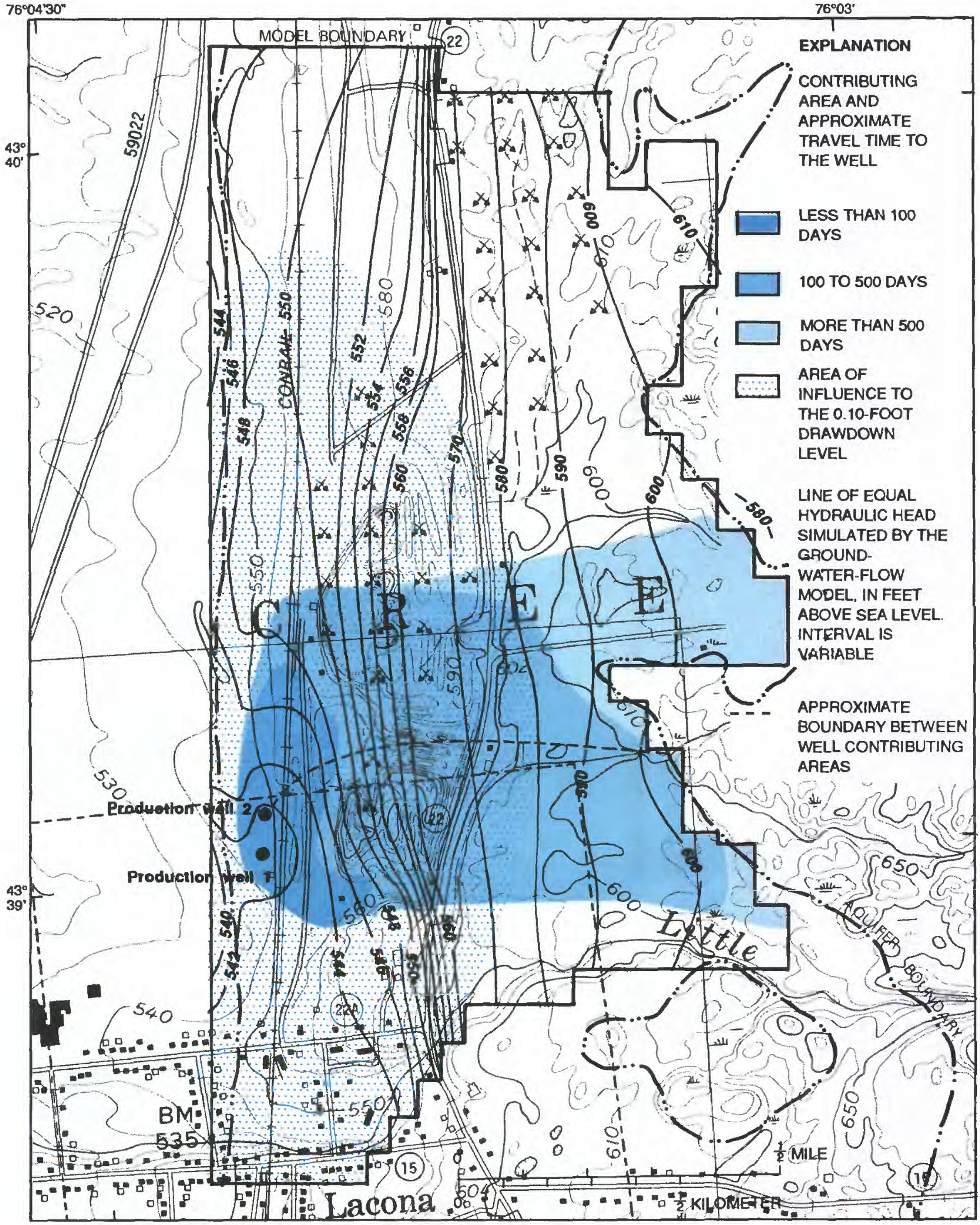
Hydraulic conductivity. As previously discussed, hydraulic conductivity of the outwash deposit indicated a narrow range of acceptable values for a recharge rate of 27 in/yr and therefore was not changed. Beach deposits were less sensitive to changes in hydraulic conductivity, however, so a range of values was tested to determine their effect on the size and shape of the contributing area. Flow lines calculated for the various hydraulic conductivity values tested indicated little change in the size or shape of the contributing area.

Recharge. The rate of recharge was decreased while hydraulic conductivity was held constant to examine the effect of drought on the size and shape of the contributing area. Recharge rates were decreased by 35 percent to 18 in/yr, the lowest rate that could be sustained before model cells dried. Flow lines indicate the contributing area to become 44 percent larger (total area 0.42 mi^2) than the original contributing area during an average year of precipitation (fig. 22). The estimated captured recharge contributes 1.17 ft^3/s, which is 31 percent greater than the combined discharge from wells 1 and 2.

Further decreases in the amount of recharge resulted in unsaturated flow conditions (dewatering of model cells), which prohibited the use of the particle-tracking program. One can infer, however, that the size of the contributing area will increase in response to a decrease in recharge to make up the water deficit.

Model Limitations

The numerical simulations of the Tug Hill aquifer offer a means of examining hydrogeologic features that affect ground-water flow and the contributing



Base from New York State Department of Transportation
Sandy Creek, NY, 1980, 1:24,000

Figure 22.--Contributing area to Lacona-Sandy Creek well field with production wells 1 and 2 each pumping at a simulated rate of 200 gallons per minute, with an annual recharge rate of 18 inches per year and a porosity of 0.30.

area to pumped wells in the Lacona-Sandy Creek area. To appraise the reliability of these simulations requires additional field data to refine the calibration and verify the model, however. Specifically, more wells would be needed to obtain head information in the aquifer for model calibration, and additional aquifer tests would be needed to estimate hydraulic properties and to determine the extent and saturated thickness of sand and gravel deposits.

The use of this model as a quantitative predictive tool would be inappropriate without further data acquisition and calibration. The model at its present stage should be considered useful for estimating the general effects of changes in hydraulic values and boundary conditions on the size and shape of the contributing area. The accuracy of the flow lines generated by the particle-tracking program will largely depend on how realistically the flow model represents the system; flow lines also will be influenced by the grid size used to represent the hydrologic system. A grid that is too coarse may not adequately describe the flow pattern near discharge points if the discharge point does not consume all the water entering the cell (weak sink), or where the discharge point is not adequately represented by a uniform discharge throughout the cell. In cells with weak sinks, a particle that is discharged cannot be distinguished from one that passes through it. The movement of water through these areas is somewhat ambiguous and can be defined only by refining the grid spacing. The limitations inherent in modeling due to uncertainty of parameter values and boundary conditions, as well as the limitations associated with discretization in particle tracking, must be recognized if the model is to be used effectively.

One-Dimensional Analytical Model Analysis

Analytical models are one of the most widely used methods for calculating the contributing area to a well because they are easy to apply. These methods lack the flexibility of numerical models, however, and are truly applicable only in situations where the simplifying assumptions are met or closely approached by field conditions. Assumptions inherent in these types of analyses are that:

1. The aquifer is homogeneous, isotropic, of uniform thickness, and of infinite lateral extent.
2. The well penetrates the full thickness of the aquifer, and all flow to the well is horizontal.
3. Withdrawals are constant.
4. Drawdown is less than 10 percent of the saturated thickness.

Analytical methods are typically used to calculate drawdowns from hydrogeologic properties that generally include hydraulic conductivity and saturated thickness. The resultant water-table configuration in the vicinity of the wells is then calculated through superposition (Reilly and others, 1984) by subtracting the drawdowns from the prepumping water level. The validity of this procedure requires that the aquifer system be described by a set of linear partial differential equations, which although true only in a confined aquifer, give reasonably acceptable results for an unconfined aquifer when the drawdown is less then 10 percent of the saturated thickness (Reilly and others, 1984).

The limitations associated with the use of analytical models can result in considerable error if the underlying assumptions are not satisfied. Thus, analytical models will not be applicable in every situation but can provide a reasonable estimate of head distribution and flow patterns if the effects of the assumptions are taken into account. In this study, two analytical models were chosen for comparison, one based on the Dupuit uniform flow equation and the other on the Theis non-equilibrium equation.

Uniform-Flow Method

The U.S. Environmental Protection Agency Guidelines for Delineation of Wellhead Protection Areas (U.S. Environmental Protection Agency, 1987) provide the uniform-flow equation of Todd (1980) for defining contributing areas for wells in an area of sloping water table. The guidelines list this method as moderately sophisticated in that it incorporates only some aquifer characteristics but still provides a fairly quantitative analysis.

Todd's method (1980, p. 122) calculates the steady-state contributing area to a well that fully penetrates an aquifer with a sloping hydraulic gradient by applying the Dupuit solution for radial one-dimensional flow and superimposing the prepumping hydraulic gradient. The region of the aquifer that contributes water to the well is shown in figure 23 and defined by:

$$-\frac{y}{x} = tan\left(\frac{2\pi Kbi}{Q}\ y\right),$$

where x,y = rectangular coordinates, in feet (see fig. 23); x = distance to the stagnation point, and y = distance to the limiting flow line of ground water entering well;

K = hydraulic conductivity, in feet per day;

b = saturated thickness of aquifer, in feet;

i = hydraulic gradient, dimensionless; and

Q = discharge of the well, in cubic feet per day.

From this equation, the distance to the stagnation point (a local ground-water divide caused by pumping) downgradient can be determined by:

$$x = -\frac{Q}{2\pi Kbi}$$

The width of the contributing area as the distance from the well upgradient approaches infinity asymptotically approaches the limits defined by.

$$y = \pm\frac{Q}{2Kbi}$$

The resulting parabola-shaped curve defines the contributing area. Because the assumptions previously mentioned that are inherent in this calculation are not completely satisfied in the Lacona-Sandy Creek well field, application of this method may lead to erroneous results. Therefore, the method is presented here for comparative purposes only.

The values of horizontal hydraulic conductivity that were used to calculate the analytical solution were obtained from the 1988 aquifer test discussed previously. Well inventories by Miller and others (1989) and data from test holes and seismic-refraction surveys provided information on saturated thickness and hydraulic gradients. Substituting values of 1,200 ft/d for hydraulic conductivity, 24 ft for average saturated thickness, 4.545×10^{-3} for the hydraulic gradient in the vicinity of the well field, and a pumping rate of 38,500 ft^3/d (200 gal/min) yields a stagnation point 50 ft downgradient of the well and a maximum contributing-area width of 300 ft. Figures 24A and 24B show the contributing area calculated by the uniform flow method for production wells 1 and 2, respectively. Included for comparative purposes are the contributing areas obtained by the numerical techniques discussed previously.

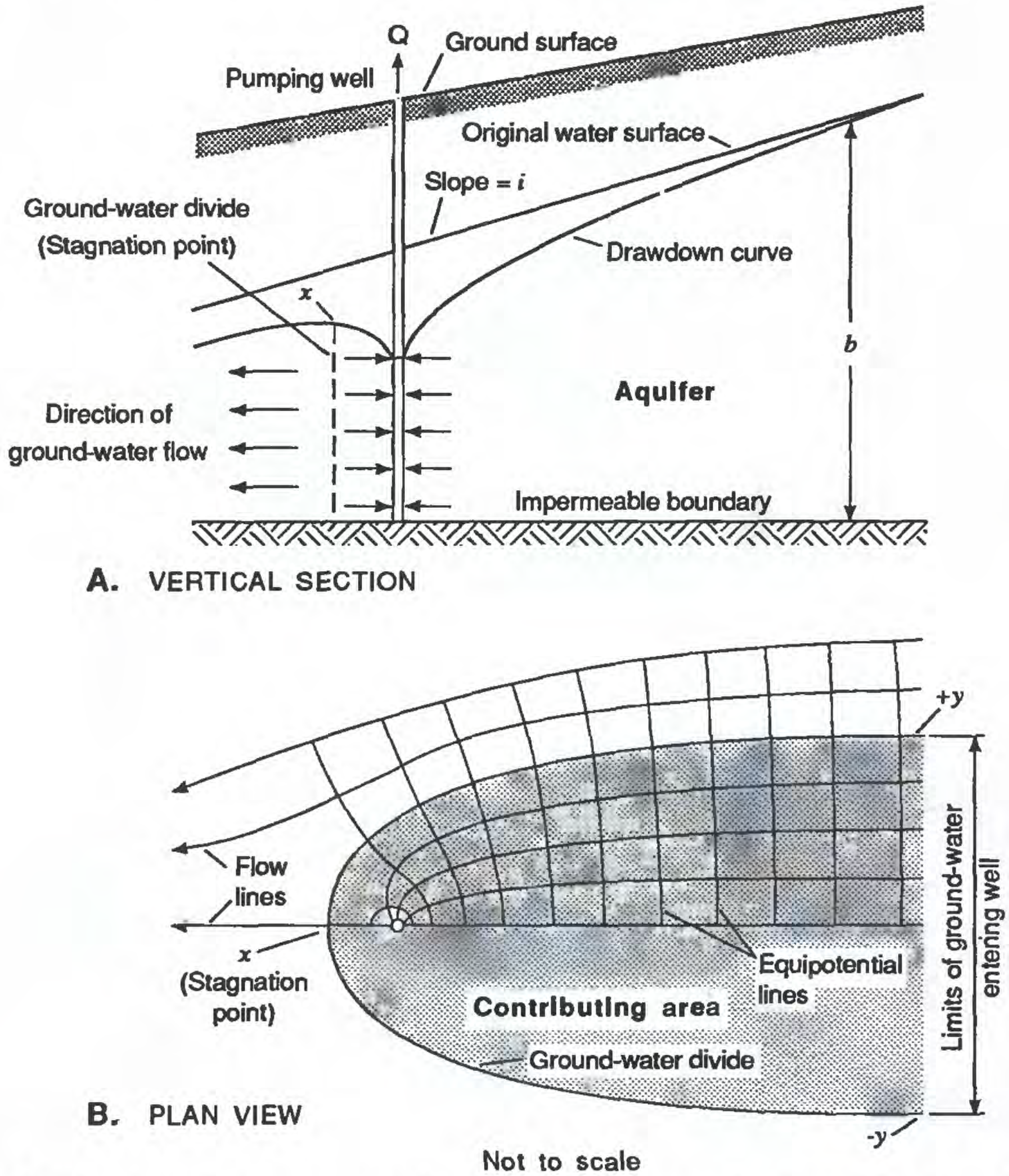
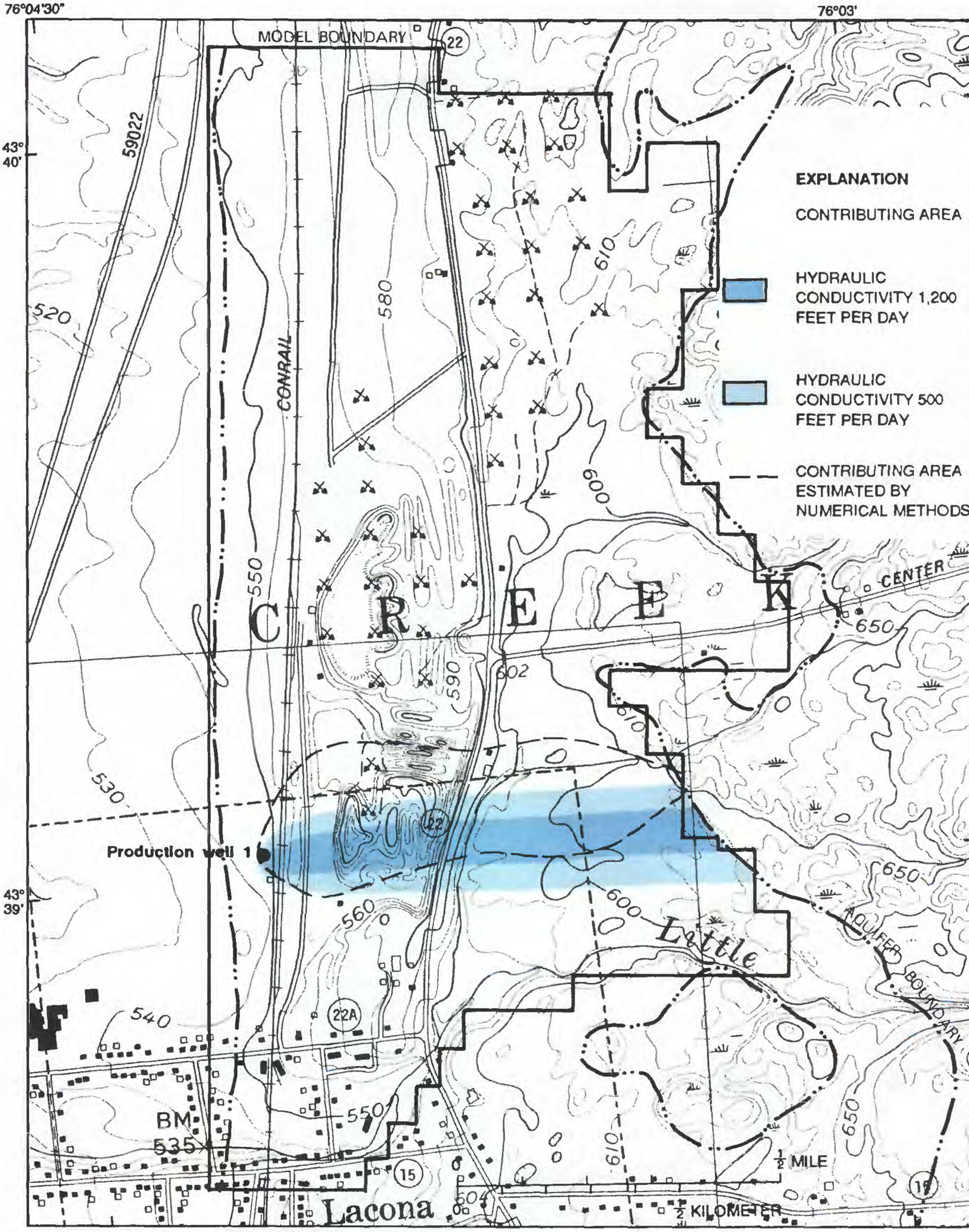
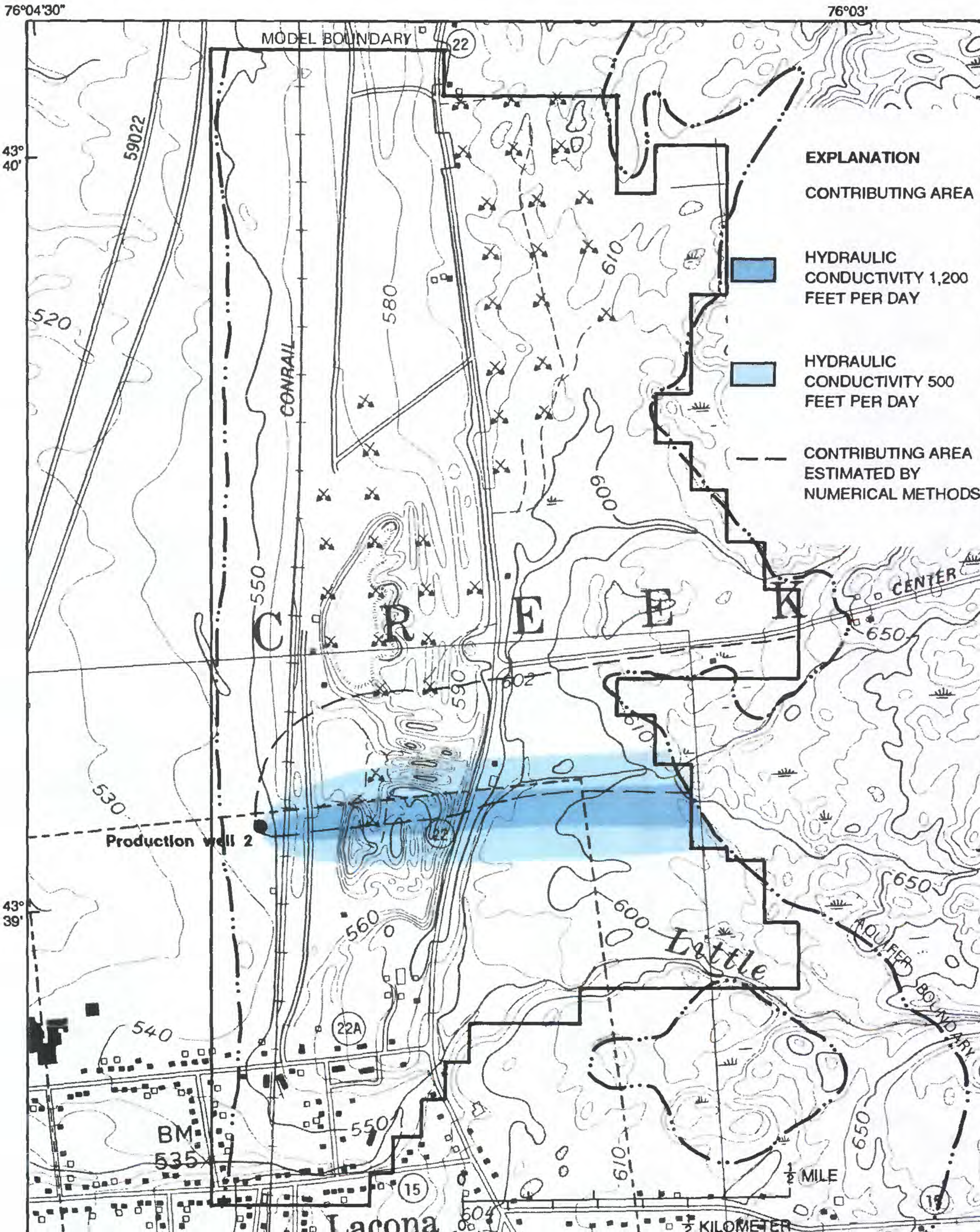


Figure 23.--Contributing area to a well penetrating an unconfined aquifer with a sloping potentiometric surface by the modified uniform flow method. A. Vertical section. B. Plan view. (Modified from Todd, 1980, p. 22.)



Base from New York State Department of Transportation
Sandy Creek, NY , 1980, 1:24,000

Figure 24A.--Contributing area to the Lacona-Sandy Creek well field with production well 1 pumping at 200 gallons per minute as calculated by the modified uniform flow method for hydraulic conductivity values of 1,200 and 500 feet per day.



Base from New York State Department of Transportation
Sandy Creek, NY, 1980, 1:24,000

Figure 24B.--Contributing area to the Lacona-Sandy Creek well field with production well 2 pumping at 200 gallons per minute as calculated by the modified uniform flow method for hydraulic conductivity values of 1,200 and 500 feet per day.

The effect of hydraulic conductivity on the width of the predicted contributing area for wells 1 and 2 is illustrated in figures 24A and 24B. Deposits with low hydraulic conductivity result in wider contributing area and greater distance to the stagnation point than those with high hydraulic conductivity. The contributing area obtained for a hydraulic conductivity of 500 ft/d was 0.10 mi^2, approximately twice as wide as that obtained for a hydraulic conductivity of 1,200 ft/d (0.64 mi^2).

The width of the contributing area and distance to the stagnation point is also inversely proportional to the hydraulic gradient. Steep gradients result in narrow contributing areas and short distances to the stagnation points. The choice of gradient is therefore an important consideration in the application of this method. Hydraulic gradients can vary seasonally and locally. For example, if the hydraulic gradient were based on data from the steep, eastern part of the aquifer (see aquifer cross section in fig. 19), the contributing area's width would be 120 ft and the stagnation point 24 ft for a pumping rate of 200 gal/min and a hydraulic conductivity of 1,200 ft/d.

Nonequilibrium Method

The second analytical method is based on the Theis nonequilibrium formula for unsteady flow (Theis, 1935). The Theis solution expresses the cone of depression in an ideal homogenous and isotropic aquifer as:

$$s = \frac{Q}{4\pi T} \int_{r^2 S/4Tt}^{\infty} \frac{e^{-u}\,du}{u} \quad ,$$

where s = drawdown at any point, in feet;
Q = rate of discharge of the well, in gal/min;
T = coefficient of transmissivity in (gal/d)/ft;
r = distance between pumped well and point of observation in feet;
S = coefficient of storage, dimensionless;
t = time the well has been discharging, in days; and
u = a dimensionless quantity varying between the limits given.

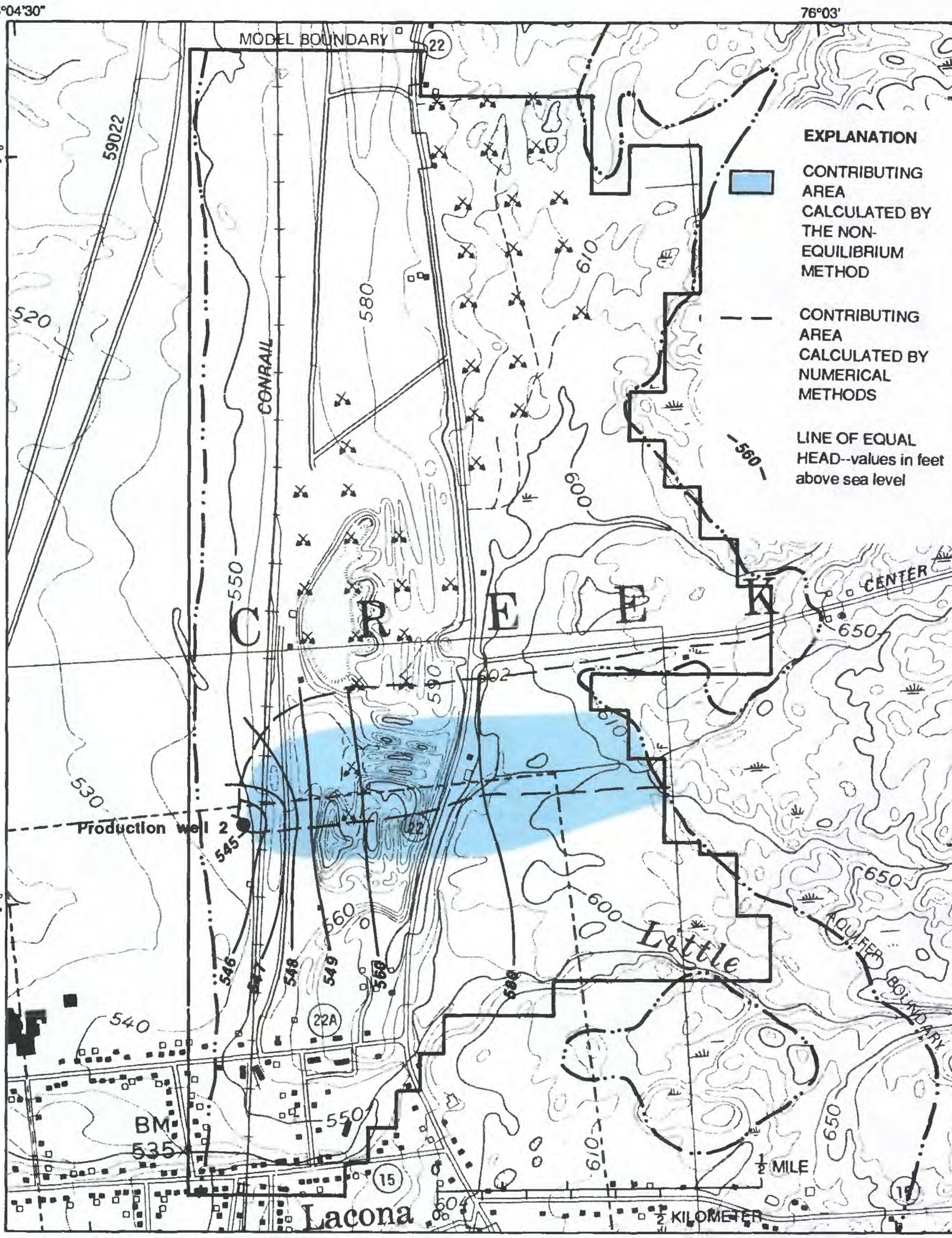
Drawdowns were calculated through this equation and were corrected for (1) linear boundary conditions to coincide with the contact between the aquifer and the till and lake deposits by the method of Ferris and others (1962); (2) for penetration of the pumped well by the method of Jacob (1963); and (3) for dewatering due to unconfined conditions by the method of Heath (1983). Although some of the simplifying assumptions governing analytical methods are relaxed by these modifications, the method still requires the aquifer to be idealized as a homogeneous block with boundary conditions treated as a simple line source or sink. Because this computation requires more site-specific hydrogeologic information than the uniform-flow model, this method is considered somewhat more sophisticated.

The Theis solution entails many computations, especially when adjustments are made for boundary conditions. Although these calculations can be performed on a hand calculator, they are cumbersome and time consuming. To facilitate the process, a computer code for solving the equations was developed by D. Mazzaferro (U.S. Geological Survey, Hartford, Conn., written comm., 1989).

To facilitate comparison, hydraulic properties used for the calculations were the same as those used in the uniform flow solution except that a linear impermeable boundary was placed 50 ft from the pumped well, and the pumped well was simulated as penetrating 40 percent of the saturated thickness of the aquifer to reflect field conditions. A total of 42 observation wells were simulated in a matrix at 0-, 100-, 200-, 300-, 400-, 500-, and 1,000-ft intervals parallel to the axis of the impermeable boundary and 0, 100, 300, 500, 1,000, and 2,000 ft from the pumped well perpendicular to the axis of the impermeable boundary. Because drawdowns are mirrored in the opposite direction, this is equivalent to 78 observation wells (fig. 25). Simulations were made for production well 2 pumping at 200 gal/min for 10-, 90-, and 180-day periods.

The contributing area to a well is estimated by superimposing drawdowns predicted by the nonequilibrium model onto the prepumping water-table surface. A new water-level configuration reflecting the effects of pumping can then be constructed from which flow lines to the well can be drawn. The water level (high or low) will affect the size and shape of the contributing area. For example, a low water table will result in a larger contributing area than a high water level, as can be seen from the Theis equation, which states that the size and depth of the cone of depression will be affected by the transmissivity of the system under consideration.

Increased values of transmissivity (hydraulic conductivity times saturated thickness) will increase the radius of the cone of depression but decrease the drawdown. Therefore, estimates of the contributing area to a well are ideally made from a period of low water table, when the saturated thickness and transmissivity are decreased. The water-level configuration used to calculate the contributing area was the same as that used for the steady-state simulations



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Sandy Creek, NY, 1980, 1:24,000

Figure 25.--Contributing area to the Lacona-Sandy Creek well field with production well 1 pumping at 200 gallons per minute, as calculated by the modified nonequilibrium method.

before pumping. The steady-state water-level configuration provided a more detailed head distribution than the measured water levels to which superposition could be applied. The steady-state head distribution may yield better results than could be obtained by extrapolating head data from measured water levels which can favorably bias this method, but using the same starting elevation for the water level does facilitate comparison of the mathematics of the methods themselves. The lack of adequate prepumping water-level information is an important limitation to consider when using this method, however.

The contributing area estimated for the 10-day pumping period by the nonequilibrium method is shown in figure 25 along with the position of the simulated observation wells. Included for comparison is the contributing area obtained by the numerical methods discussed previously. This simulation shows that the area contributing to the well extends approximately 200 ft south and 900 ft north of an east-west axis line drawn through the pumped well perpendicular to the axis of the impermeable boundary. The area contributing to the well includes about 0.12 mi^2 extending to the boundary of the numerical model and differs slightly from the contributing area defined by numerical flow modeling and particle tracking. The difference is much smaller than for the contributing area indicated by the uniform-flow method, however.

The contributing areas calculated for 90- and 180-day pumping periods were similar to that obtained for the 10-day pumping period, which indicates that the aquifer reached steady state 10 days after pumping began.

The effects of partial penetration of the pumped well were observed only at the pumped well itself, as no additional drawdown due to partial penetration was observed in any of the nearby simulated observation wells. Simulations made with a fully penetrating pumped well showed 0.4 ft less drawdown than those made with a partially penetrating pumped well.

No technique can delineate the contributing area to a well with absolute certainty. Present knowledge of the temporal and spatial factors in a natural system that affect the size and shape of the contributing area to a well is incomplete, and these factors usually can be only approximated. Despite these uncertainties, a careful hydrologic analysis of the main factors that govern the contributing area to a well provide a sound basis for developing a wellhead-protection program.

COMPARISON OF METHODS FOR DETERMINING CONTRIBUTING AREAS

All methods of delineating the contributing area to a well require similar types of data, but the amount of data required will increase with increasing sophistication of the techniques. The required hydrologic data (Morrissey, 1987) include the following:

1. *Water-table or potentiometric elevation of the aquifer*: This is the most important piece of information for delineating the contributing area to a well. Accurate knowledge of water levels can be used directly to estimate the recharge area to a well if the water levels reflect the stresses on the system caused by pumping. A prepumping water-level map is necessary to superimpose an analytical solution for determining drawdowns due to pumping. Water levels also are the most important information needed for calibration of numerical flow models. The type of period in which water levels are obtained (such as extremely dry, extremely wet, or average conditions) will affect the size and shape of the contributing area. Water levels obtained during a dry period will reflect a larger contributing area than those obtained during a wet period.
2. *Boundary conditions for the aquifer*: Knowledge of the boundary conditions that affect flow to a well is critical for determining contributing areas, and the sources of inflow of water to an aquifer or part thereof and locations of outflow must be specified. In analytical models, impermeable constant-head boundaries can be idealized as straight lines through application of the theory of well images. Numerical methods require specification of boundary conditions to formulate a solution and discretization of the problem domain into individual cells to enable accurate representation of boundaries. Numerical simulations also allow examination of specialized boundaries such as head-dependent flow in a leaky stream bed. The more accurate simulation of boundary conditions provided by numerical techniques than by analytical techniques is often justification for their use.
3. *Aquifer properties*: Hydraulic conductivity, saturated thickness, and storage coefficient of the aquifer are needed if analytical or numerical techniques are used. Analytical methods treat the aquifer as a homogenous unit and typically require values for transmissivity and specific yield or storage coefficient. Numerical techniques require information for each cell in the model grid; this includes values for hydraulic

conductivity and bottom elevation for unconfined aquifers, or values of transmissivity for confined aquifers. If the simulation is transient, values for specific yield or storage coefficient must be specified, depending on whether the aquifer is confined or unconfined. Numerical analysis may be warranted in complex geohydrologic settings if the key simplifying assumptions of analytical technique cannot be satisfied. Typically, a sensitivity test of the expected range of the hydrologic variables is made to determine their effect on the size and shape of the contributing area.

4. *Well-field design criteria*: These data include the locations and rates of pumping. Often the largest expected pumping rates are chosen to give the largest (most conservative) possible contributing areas. Again, numerical techniques allow more flexibility to examine the effect of nearby pumped or recharge wells. Simulation of varying pumping schedules could be made by transient-state simulation, but this was beyond the scope of the study.

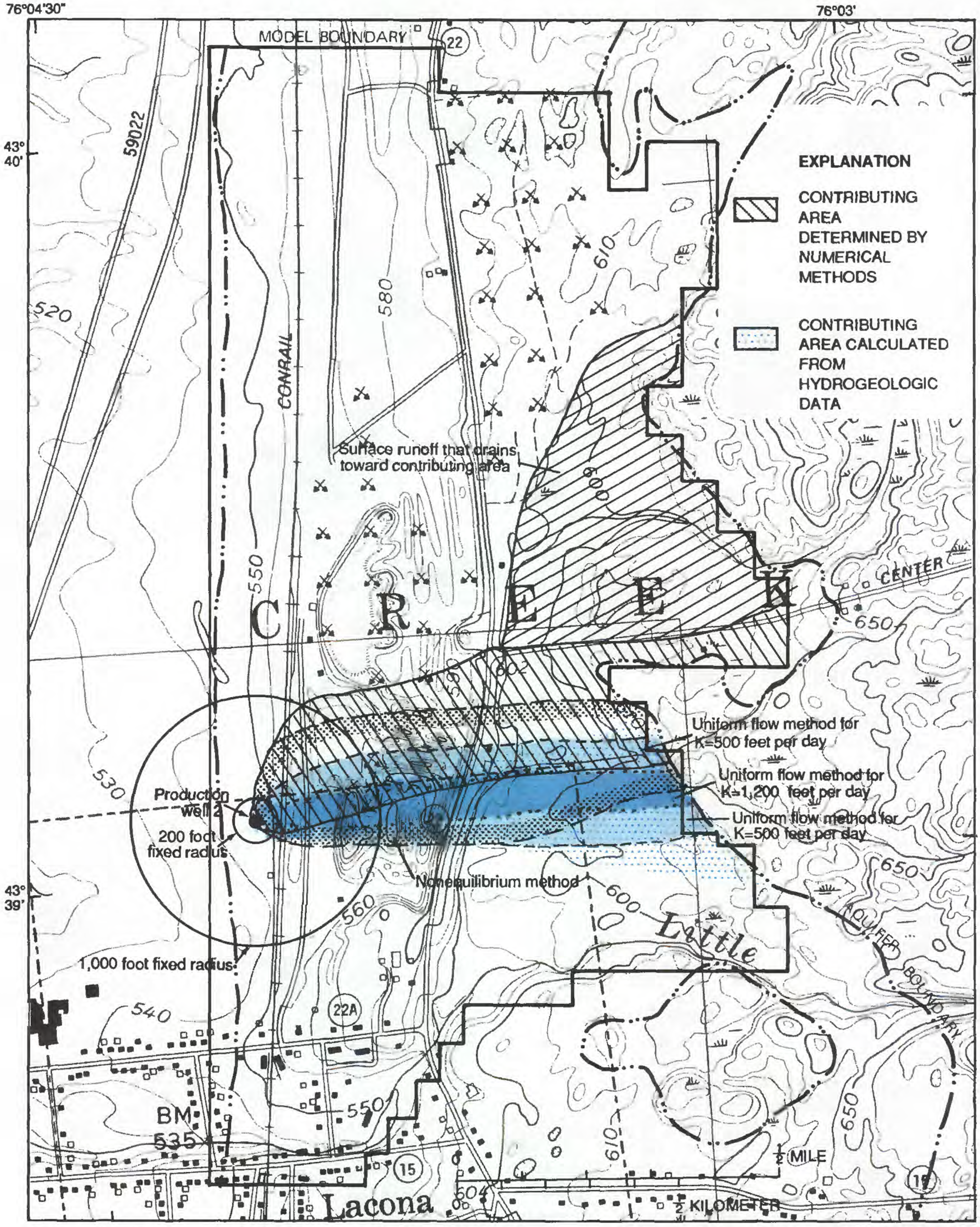
The preceding sections have presented four methods for estimating the contributing area to the Lacona-Sandy Creek well field. These are, in increasing order of complexity and sophistication; delineation based on (1) previously available hydrogeologic data, (2) the modified Dupuit uniform flow method, (3) the modified Theis nonequilibrium method, and (4) a two-dimensional numerical model. Numerical models represent the most rigorous method and were used as the basis for comparison with the other methods. A comparison of the results of each of these methods with well 2 being pumped at a rate of 200 gal/min with average rates of recharge is shown in figure 26. Also shown in figure 26 is the commonly used fixed radius method for protecting wells. The 200-ft radius is the current minimum New York State Department of Health standard protection zone around a public-supply well. Also shown is the 1,000-ft fixed radius, which has been adapted by many municipalities as a more conservative protection zone. Although the fixed radius method has the advantage of being readily applied, it is not based on scientific principles and therefore often bears little resemblance to the contributing area to a well. As illustrated in this figure, the fixed radius has little relation to the actual contributing area and will tend to overestimate the protection zone in most areas while underestimating it in some critical areas.

Delineation of a well's contributing area from available geohydrologic data, although not entirely quantitative, can provide a useful first approximation. In simple geohydrologic systems, where data are sufficient, these estimates can be made with relative certainty, but this technique becomes less quantitative in more complex hydrogeologic settings, such as aquifers that have vertical flow components and those influenced by a hydraulic connection to surface-water systems. The greatest uncertainty in this method, however, is developing flow lines from insufficient head data or from head data that do not reflect the effects of pumping. Despite these limitations, compilation of all available hydrologic information is essential for whatever method is chosen because these data provide at least a preliminary estimate of the contributing area and reveal where additional information is needed and whether a more sophisticated method is warranted.

Estimates of the contributing area to the Lacona-Sandy Creek well field based on hydrogeologic data reflect the water-table configuration at the time the data were collected (mostly summer 1983). The contributing area estimated by numerical modeling and particle tracking for simulated pumping rates of 200 gal/min at production wells 1 and 2 is similar to that obtained from available hydrogeologic information if the part of the aquifer that drains toward the contributing area is included. The contributing area without the aquifer area that drains toward it is about half as large as the contributing area obtained by numerical techniques for this pumping rate. Determinations of the contributing area for other pumping scenarios would require additional field information that reflects the conditions of interest.

The contributing area obtained by the modified uniform-flow method (Dupuit equation) differs in both size and shape from that obtained by numerical techniques. For a hydraulic conductivity of 1,200 ft/d, the size of the contributing area calculated by the uniform flow method for production wells 1 and 2 (fig. 24A and 24B) is 64 and 69 percent smaller, respectively, than the contributing area calculated by numerical techniques (fig. 21A and 21B). This difference diminishes for contributing areas based on a hydraulic conductivity of 500 ft/d, which is only 10 percent smaller than the contributing area calculated by numerical techniques for production well 1, and 23 percent smaller than that calculated for well 2. In addition, the contributing area indicated by the uniform-flow method lies outside the area indicated by the numerical method. This difference is greater for the contributing area for production well 2 than production well 1 because the water table predicted by the numerical model in this area shows ground-water flow to have a slightly more northward trend than that reported by Miller and others (1989). The contributing area indicated by the uniform-flow method intercepts the intermittent tributary that parallels Lacona-Orwell Road, however; thus, the contributing area could be extrapolated to include this tributary watershed and bring the two methods into closer agreement.

The contributing area indicated by the modified nonequilibrium method (Theis equation) was applied only to production well 2, pumping at 200 gal/min.



Base from New York State Department of Transportation
Sandy Creek, NY, 1980, 1:24,000

Figure 26.--Comparison of contributing areas as calculated from hydrogeologic data, numerical and analytical methods, and the fixed-radius methods.

The resulting contributing area (0.12 mi^2) is only 8 percent smaller than the 0.13-mi^2 area obtained by numerical techniques, and differs in position only slightly. The improved agreement between this analytical method and the numerical method is due to the effects of the linear boundary, which in the analytical method resembles field conditions more closely. These results may also be in closer agreement than if the head distribution had been extrapolated from measured water levels rather than the nonpumping steady-state head distribution simulated by the numerical model.

The selection of techniques for delineating contributing areas to a well ultimately depends on the degree of accuracy required and the resources available for making the analysis. Analytical approaches, while easier to apply, are truly valid only where the key simplifying assumptions closely satisfy field conditions. The varied composition of aquifers in the Northeast can be a disadvantage in the use of analytical techniques. Local variations in hydraulic conditions, and boundary conditions other than simple line sources or sinks that can be treated by well images, cannot be correctly simulated, but, when used with caution, analytical techniques can provide worthwhile analysis. The numerical techniques are more detailed and thus require more data, time, and technical expertise, and therefore should be considered when (1) the simplifying assumptions of an analytical technique yield unacceptable results, and (2) the well under consideration is of particular importance and(or) at risk of contamination. All methods considered in this report provide a more realistic determination of the contributing area to a well than the commonly used fixed-radius approach.

At present, the Tug Hill region is mostly rural, and the potential for contamination of the water supply is small. Therefore, delineation of contributing areas may not warrant the expense or resources necessary to develop more sophisticated delineation techniques. In developed areas, however, where the potential for contamination is greater and acquiring land for the purpose of protecting water supplies is commonly difficult and expensive, the use of more sophisticated approaches may be warranted to protect the most critical areas of recharge.

SUMMARY

Sources of water to the municipal ground-water supplies of Adams, Mannsville, Lacona-Sandy Creek, Pulaski, Orwell, and Camden were delineated from available hydrogeologic information. Adams, Lacona and Sandy Creek, and Pulaski in the northern part and central sections of the Tug Hill aquifer, and Pulaski, in the central part, obtain water from thin beach deposits that formed along the edge of proglacial Lake Iroquois. Mannsville, in the northern part of the aquifer, derives its water from recent alluvial sand and gravel deposits, and Orwell, in the central part, derives its water from shallow kame deposits associated with the Orwell-Bennett Bridge moraine. Camden, in the southern part of the aquifer, relies on clusters of dug wells in a kame-outwash complex. Contributing areas estimated from available hydrogeologic data are: Adams, 0.90 mi^2 plus 6 mi^2 from a tributary watershed; Mannsville, 0.10 plus 11 mi^2 from an upland tributary watershed; Lacona-Sandy Creek, 0.30 mi^2 plus 0.61 mi^2 and 0.53 mi^2 from two tributary watersheds; Pulaski 0.85 mi^2 plus a 17-mi^2 tributary watershed; Orwell, 0.03 mi^2; and Camden, between 0.01 and 0.02 mi^2 from for the clusters of dug wells.

The applicability of two analytical methods (uniform flow method and nonequilibrium flow method) and a two-dimensional numerical flow model for estimating the contributing area to the Lacona-Sandy Creek well field were examined. In general, analytical methods are easier to apply than numerical methods but are limited in application because the simplifying assumptions implicit in their solution often fail to meet or closely satisfy field conditions. Hydrogeologic factors typically encountered in the northeastern United States constrain the use of analytical methods, such as the nonuniform aquifer composition, complex boundary conditions, and the applicability of superposition. Estimates of contributing area by analytical methods must therefore be used with caution in this region but can be used for preliminary investigations.

The individual contributing area to wells 1 and 2 at the Lacona-Sandy Creek well field computed by the uniform-flow method (Dupuit equation) modified for a sloping water table and a horizontal hydraulic conductivity of 1,200 ft/d was 64 and 69 percent smaller than the contributing area predicted by numerical techniques. For a horizontal hydraulic conductivity of 500 ft/d, the contributing area predicted by the uniform-flow method was 10 and 23 percent smaller than that defined by the numerical method. The position of the contributing area indicated by the uniform-flow method also differs from the area defined by numerical methods.

Drawdowns predicted by the nonequilibrium method (Theis equation), adjusted for a single linear impermeable boundary, partial penetration of the pumped well, and dewatering of the aquifer were superimposed on the steady-state water-table configuration generated by the numerical model to determine flow lines to the well. The contributing area indicated by this method (0.12 mi^2) compares favorably in size (0.13 mi^2) and shape with the contributing area obtained by numerical techniques.

Numerical two-dimensional analysis coupled with a semianalytical particle tracker was the most rigorous and time-consuming technique evaluated. Numerical techniques offer greater flexibility than other techniques for simulating the hydrogeologic factors that affect flow to a well, including varied pumping rates, recharge rates, and nonuniform aquifer composition. Detailed analysis of the contributing area to a well can be combined with the semianalytical particle tracker to obtain the time-of-travel along flow lines to a well.

Numerical simulation of differing pumping and recharge rates indicated that these factors can substantially affect the size of the contributing area. The minimal pumping rate simulated, 200 gal/min, gives a contributing area of 0.11 mi^2 and 0.13 mi^2 for production wells 1 and 2, respectively. Simulations of the maximum pumping rate for wells 1, 2, and 3 operating simultaneously (well 1 at 200 gal/min; well 2 at 400 gal/min; and well 3 at 125 gal/min) quadruples the size of the contributing area to 0.48 mi^2. Similarly, decreases in the rate of recharge increased the size of the contributing area. The contributing area for wells 1 and 2, each operating at 200 gal/min, was 0.29 mi^2 at a recharge rate of 27 in/yr and 0.42 mi^2 a rate of 18 in/yr. Flow-path analysis indicates that (1) the contributing area differs significantly in size and shape from the zone of influence, and (2) flow paths and traveltimes are relatively short; flow-path lengths were estimated to be less than a mile, and traveltime from the eastern edge of the aquifer to the pumped well generally was between 500 and 1,000 days.

Hydrologic budgets calculated by the numerical simulations indicate that most water that reaches the wells is diverted from its natural points of discharge (springs and wetlands) along the western flank of the aquifer. A small amount of the water is diverted to the wells that normally would discharge to the lower reach of Little Sandy Creek, and simulations of higher pumpage or lower recharge rates indicate that some induced infiltration occurs from Little Sandy Creek.

The selection of a technique for delineating a contributing area ultimately depends on the resources available for making analysis and the degree of accuracy required. Wells critical to water supplies and in developed areas that are prone to contamination warrant sophisticated delineation techniques, particularly in complex hydrogeologic settings. The temporal and physical factors that affect the size and shape of the contributing area to a well in a natural system can be only approximated, however; thus no technique can delineate the contributing area with absolute certainty. Despite the incomplete knowledge of the factors that affect the contributing area to a well, the methods presented in this report provide a more reliable estimate of the contributing area than the commonly used fixed-radius method.

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