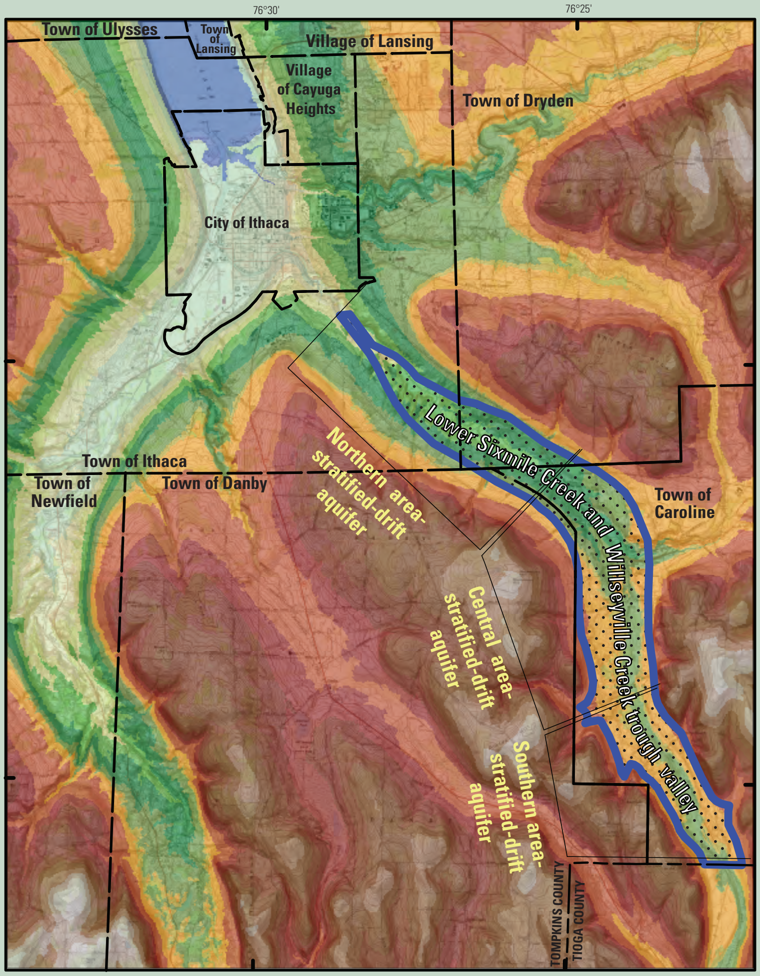
Prepared in cooperation with the Town of Caroline and the
Tompkins County Planning Department

Geohydrology of the Stratified-Drift Aquifer System in the Lower Sixmile Creek and Willseyville Creek Trough, Tompkins County, New York



Scientific Investigations Report 2010–5230

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

Front Cover. Figure 4 inside report.

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

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

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Conversion Factors, Datum, and Abbreviations

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)

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

°F= (1.8×°C) +32

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

°C= (°F-32)/1.8

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

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

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

List of Abbreviations

GWSI	Groundwater site inventory
H/V	Horizontal-to-vertical
HYSEP	Hydrograph-separation computer program
LIDAR	Light detection and ranging
MCL	Maximum Contaminant Level
NWIS	National Water Information System
NWQL	National Water Quality Laboratory
NYSDOH	New York State Department of Health
SMCL	Secondary Maximum Contaminant Level
TM	Tompkins
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

Geohydrology of the Stratified-Drift Aquifer System in the Lower Sixmile Creek and Willseyville Creek Trough, Tompkins County, New York

By Todd S. Miller and Daniel E. Karig[1]

Abstract

In 2002, the U.S. Geological Survey, in cooperation with the Tompkins County Planning Department began a series of studies of the stratified-drift aquifers in Tompkins County to provide geohydrologic data for planners to develop a strategy to manage and protect their water resources. This aquifer study in lower Sixmile Creek and Willseyville Creek trough is the second in a series of aquifer studies in Tompkins County. The study area is within the northern area of the Appalachian Plateau and extends about 9 miles from the boundary between Tompkins County and Tioga County in the south to just south of the City of Ithaca in the north. In lower Sixmile Creek and Willseyville Creek trough, confined sand and gravel aquifers comprise the major water-bearing units while less extensive unconfined units form minor aquifers.

About 600 people who live in lower Sixmile Creek and Willseyville Creek trough rely on groundwater from the stratified-drift aquifer system. In addition, water is used by non-permanent residents such as staff at commercial facilities. The estimated total groundwater withdrawn for domestic use is about 45,000 gallons per day (gal/d) or 0.07 cubic foot per second (ft^3/s) based on an average water use of 75 gal/d per person for self-supplied water systems in New York.

Scouring of bedrock in the preglacial lower Sixmile Creek and Willseyville Creek valleys by glaciers and subglacial meltwaters truncated hillside spurs, formed U-shaped, transverse valley profiles, smoothed valley walls, and deepened the valleys by as much as 300 feet (ft), forming a continuous trough. The unconsolidated deposits in the study area consist mostly of glacial drift, both unstratified drift (till) and stratified drift (laminated lake, deltaic, and glaciofluvial sediments), as well as some post-glacial stratified sediments (lake-bottom sediments that were deposited in reservoirs, peat and muck that were deposited in wetlands, and alluvium deposited by streams). Multiple advances and retreats of the ice in the study area resulted in several sequences of various types of glacial deposits. A large moraine (Valley Heads Moraine) dominates the southern part of the study area, a large delta dominates the central part, and ground moraine (mostly till) dominates the northern part. Glacial sediments in the center of the lower Sixmile Creek and Willseyville Creek trough typically range from 150 to 200 ft but can be greater than 300 ft in some places. Where the sediments are composed of sand and gravel they form aquifers.

In most parts of the lower Sixmile Creek and Willseyville Creek trough, there is an upper and a basal confined aquifer. However, underlying the central parts of the Brooktondale delta, there are as many as four confined aquifers, whereas in the northern part of the study area, only one extensive confined aquifer is present. The major sources of recharge to these confined aquifers are (1) direct infiltration of precipitation where confined aquifers crop out at land surface (mostly along the western trough wall in the southern and central parts of the study area and, to a lesser degree, along the eastern trough wall); (2) unchanneled surface and subsurface runoff from adjacent upland areas that seeps into the aquifer along the western trough walls; (3) subsurface flow from underlying till or bedrock at the lateral contacts at trough walls; (4) adjacent fine-grained stratified drift, especially when the aquifer is pumped; and (5) discharge from bedrock at the bottom and sides of the trough.

In the central part of the study area, the surficial coarse-grained sediments (sand and gravel) comprise a delta near Brooktondale and form a small unconfined aquifer (0.3 square mile). Although much of the upper part of the delta has been removed by several aggregate mining operations, sufficient amounts of sand and gravel remain in most places to form a thin unconfined aquifer. The major sources of recharge to the unconfined aquifer are (1) direct infiltration of precipitation where water moves predominantly in a downward direction through the unsaturated zone toward the water table and (2) unchanneled surface and subsurface runoff from adjacent upland areas that seep into the aquifer along the trough walls.

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Groundwater in the southern part of the Brooktondale delta flows to the west and discharges into Beaver Creek. Groundwater in the northern part of the deltaic aquifer flows to the northwest where some of the groundwater discharges to springs along the northeastern margin of the delta and flows into lower Sixmile Creek and some groundwater discharges to springs along the northwestern margin of the delta and flows into Beaver Creek. Just north of the surface-water divide in the southern part of the study area groundwater in the confined aquifers on the west side of the trough initially flows eastward from the west valley wall to the center of the valley where it then changes course and flows northward. In the northern part of the central area of the trough, the upper confined aquifer either pinches out at depth or has been eroded by Sixmile Creek and is exposed beneath the floodplain where groundwater discharges directly into Sixmile Creek. In the northern part of the study area, groundwater in the confined aquifer ultimately discharges into Sixmile Creek and to the Ithaca Reservoir.

An initial assessment of the groundwater quality of the confined aquifer system near the central portion of the study area, where most of the wells are located, was made by collecting water samples from six wells (two test wells and four residential wells) from December 2006 through August 2007 and analyzing the samples to characterize the quality of groundwater. Common ions, nutrients, and trace metals were sampled and field properties of pH, specific conductance, and temperature were measured. All common ions were below U.S. Environmental Protection Agency Drinking Water Advisory limits. These results indicate that water in the sand and gravel aquifers is predominantly calcium-bicarbonate, and groundwater used for drinking supply is generally of acceptable quality.

Nitrate was not detected in any of the samples above the detection limit of 0.06 mg/L (milligram per liter). Nitrite was not detected in five of the six samples and was negligible (0.001 mg/L) in the sixth sample. The most commonly detected trace elements were aluminum, arsenic, barium, boron, iron, lithium, manganese, nickel, and strontium, all of which were detected in every sample. The elements detected in the highest concentrations were barium, boron, iron, lithium, manganese, strontium, and uranium. Aluminum concentrations ranged from 0.9 to 95.5 micrograms per liter (µg/L); one sample exceeded the Secondary Maximum Contaminant Level of 50 µg/L. Arsenic concentrations ranged from 1.3 to 20.4 µg/L; two samples exceeded the Federal Maximum Contaminant Level for arsenic of 10 µg/L.

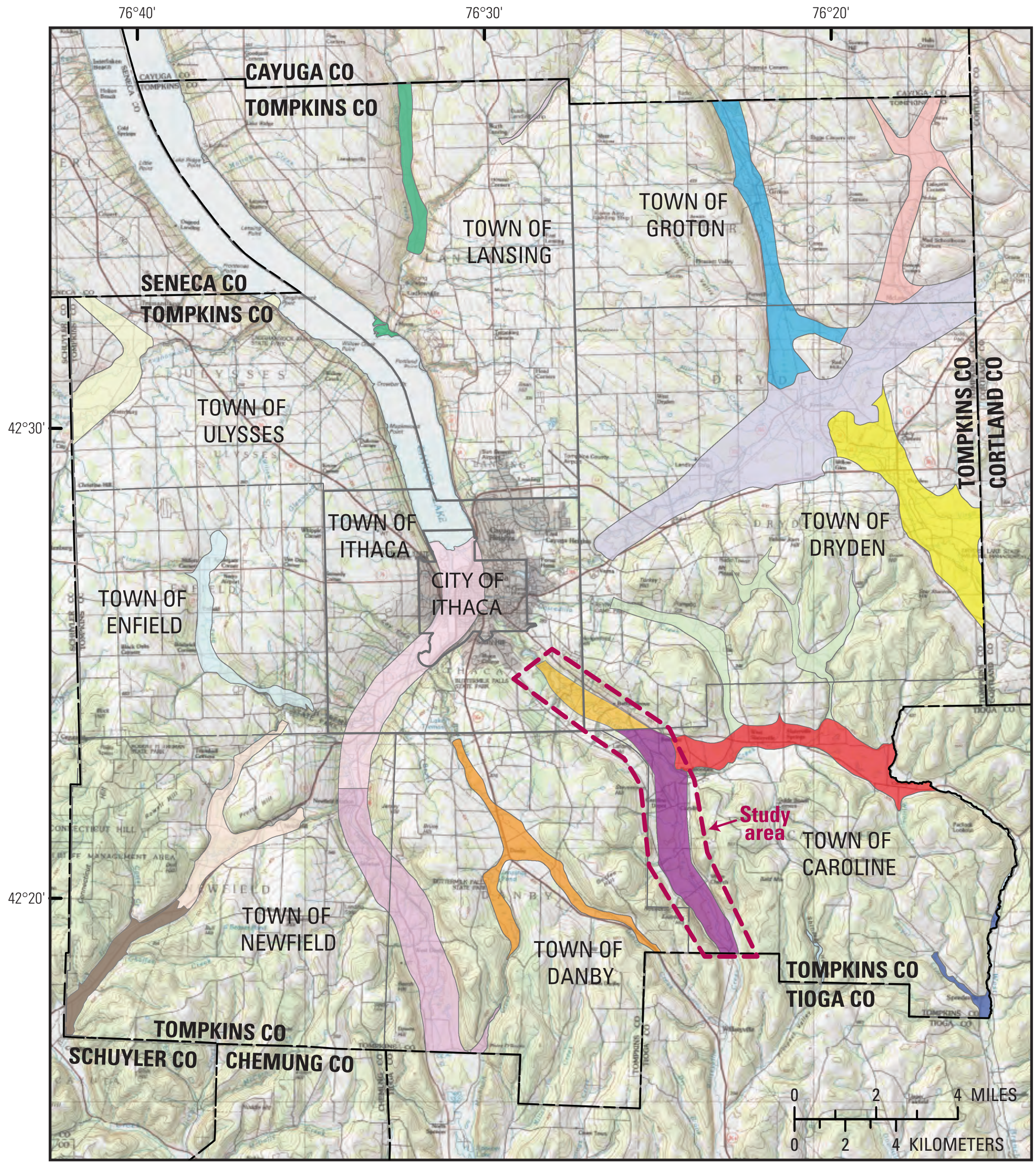
Introduction

In 2002, the U.S. Geological Survey (USGS), in cooperation with the Tompkins County Planning Department began a series of studies of the stratified-drift aquifers in Tompkins County to provide geohydrologic data for planners to develop a strategy to manage and protect their water resources. A reconnaissance-level USGS aquifer map report "Unconsolidated Aquifers in Tompkins County, New York" (Miller, 2000) was used as a guide to delineate 17 reaches of stratified-drift aquifers (fig. 1) to be investigated in more detail over a 20-year period. The aquifer reaches were based mostly on natural hydrologic boundaries, but in some cases political boundaries were also considered. Aquifer reach lengths were limited to about 3 to 10 miles each to be logistically manageable.

Tompkins County lies within the northern area of the Appalachian Uplands in central New York (fig. 2). The northern part of the county is within the glacially eroded Finger Lakes region with rounded hills of low-to-moderate relief, whereas the southern part of the county lies within the Appalachian Plateau region of moderately high relief (fig. 2). The stratified-drift aquifers in the lower Sixmile Creek and Willseyville Creek trough, described in this report, lie within the moderately high relief portion of the Appalachian Plateau region (fig. 2).

The geologic history of Sixmile Creek Basin, discussed in detail in the "Geology and Glacial Geology" section in a report by Miller (2009), has resulted in the creation of two distinct hydrophysiographic settings, which allowed the division of Sixmile Creek valley into two study areas—upper Sixmile Creek valley, including the headwaters of West Branch Owego Creek valley (Miller, 2009), and lower Sixmile Creek valley, including the headwaters of Willseyville Creek valley (fig. 3) (this study). In the upper Sixmile Creek and West Branch Owego Creek valleys study area (1) upper Sixmile Creek and East Branch Owego Creek valleys are higher in altitude, (2) the valleys were oriented perpendicular to the predominantly north to south flow of glacial ice undergoing less erosion by ice, which resulted in a hanging valley, and (3) the valleys were dominated by depositional environments that included subglacial (deposition of till), glaciofluvial, glaciolacustrine, and post-glacial fluvial processes. In contrast, in the lower Sixmile Creek and Willseyville Creek trough study area; (1) the valleys are lower in altitude; (2) were oriented roughly parallel to the direction of glacial ice flow, and therefore, were extensively scoured by ice that formed a trough; and (3) were dominated by depositional environments that included subglacial, deltaic, ice-contact, and glaciolacustrine processes.

Preglacial valleys that were oriented along the primary direction of ice movement, such as those valleys presently occupied by Cayuga Lake and lower Sixmile Creek valley (fig. 1), were extensively widened and deepened by flowing ice and subglacial meltwater. Erosion by ice had truncated bedrock hillsides (spurs), which resulted in creation of nearly straight, U-shaped bedrock troughs. Bedrock troughs in central New York are common along the northern rim of the Appalachian Plateau; many of these troughs are in the Finger Lakes region. Clayton (1965) referred to the Finger Lakes valleys as "intrusive troughs" that were carved when ice that flowed south from the Lake Ontario Lowlands encountered



Basemap created with TOPO!, scale 1:100,000
2003 National Geographic, URL www.nationalgeographic.com/topo

Aquifers mapped Miller (2000)

EXPLANATION
Aquifer reach names

- Cascadilla Creek valley and upland Sixmile Creek valley
- Enfield Creek valley
- Lower Cayuga Inlet valley
- Lower Fall Creek valley
- Lower Sixmile Creek valley (Towns of Dryden and Ithaca)
- Owasco Inlet valley
- Pony Hollow valley
- Salmon Creek/Myers Point/Locke Creek
- Taughannock Creek valley and delta
- Upper Buttermilk Creek and Danby Creek valleys
- Upper Cayuga Inlet valley
- Upper Fall Creek valley
- Upper Sixmile Creek and West Branch Owego Creek valleys
- Virgil Creek valley
- West Branch Cayuga Inlet and Fish Kill valleys
- West Branch Owego Creek valley and tributaries
- Lower Sixmile Creek and Willseyville Creek valleys (Town of Caroline)

Figure 1. Location of 17 stratified-drift aquifer reaches in Tompkins County, New York.

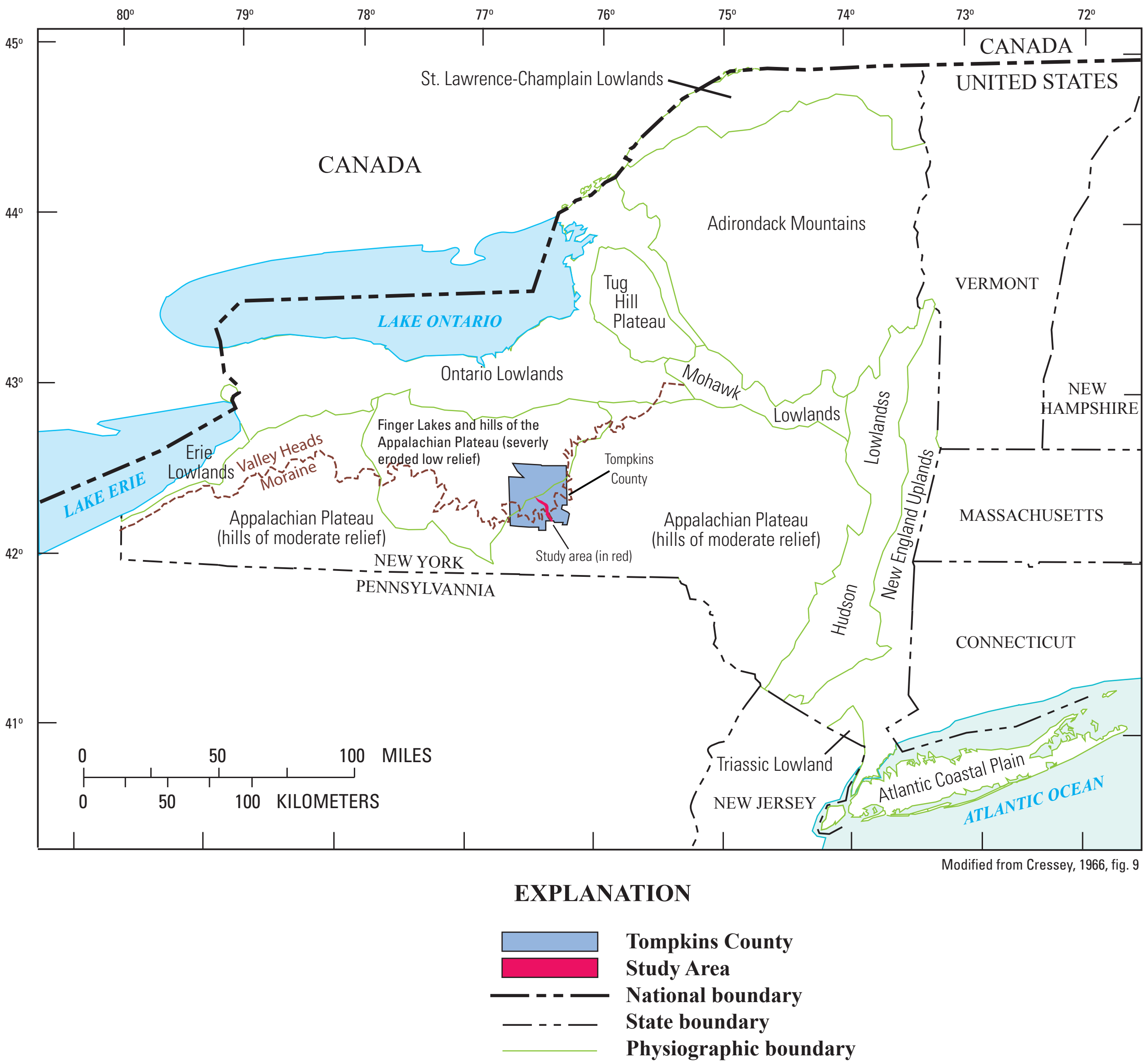
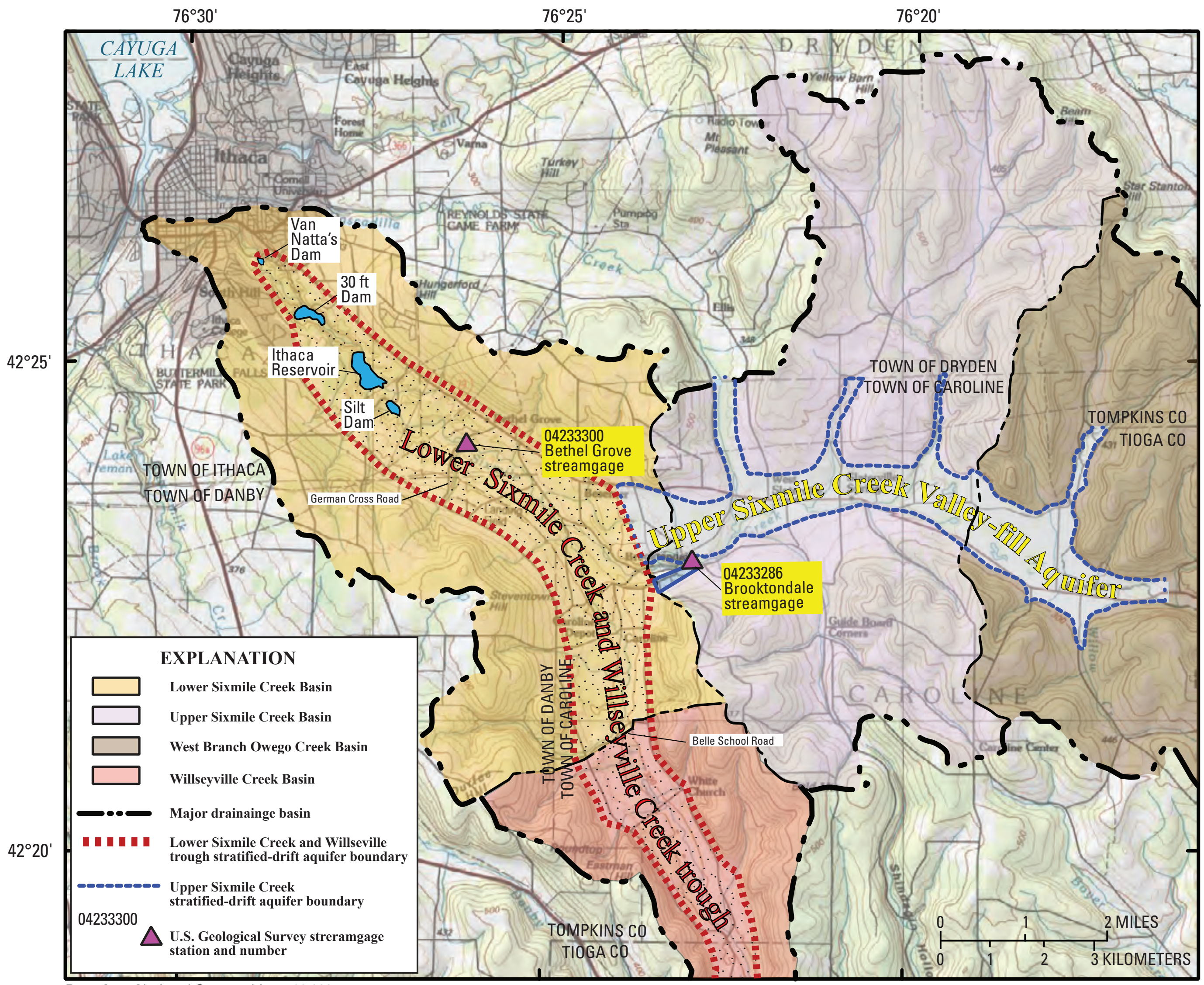


Figure 2. Physiographic features and location of the lower Sixmile Creek and Willseyville Creek trough study area in Tompkins County, New York.

a landmass of higher altitude, in this case the Appalachian Plateau, and flowed uphill, against the regional slope. Bedrock troughs are often referred to as having U-shaped profiles although many are asymmetrical with one valley wall steeper than the other. However, the more valleys and troughs intrude southward into the Appalachian Plateau (fig. 2), the more widths decrease and the valley profiles transition from broad U-shaped, to narrow U-shaped profiles. Since extensive scouring by ice of lower Sixmile Creek valley and the headwaters of Willseyville Creek valley formed a single deep trough, the study area in this report is referred to as the "lower Sixmile Creek and Willseyville Creek trough" (throughout this report as the "trough") (fig. 4).

Purpose and Scope

The Town of Caroline and Tompkins County need geohydrologic data regarding the major stratified-drift aquifers within the town to develop a strategy to manage and protect their water resources. Interest in the interaction between groundwater and surface water has increased in recent years as a result of widespread concerns related to water supply and water quality. This report describes the geohydrology of the stratified-drift aquifer system in the lower Sixmile Creek and Willseyville Creek trough including (1) the aquifer framework; (2) the groundwater-flow system, including water levels, groundwater and surface-water interaction, and



Base from National Geographic 1:100,000 Topographic, Shaded-Relief Map

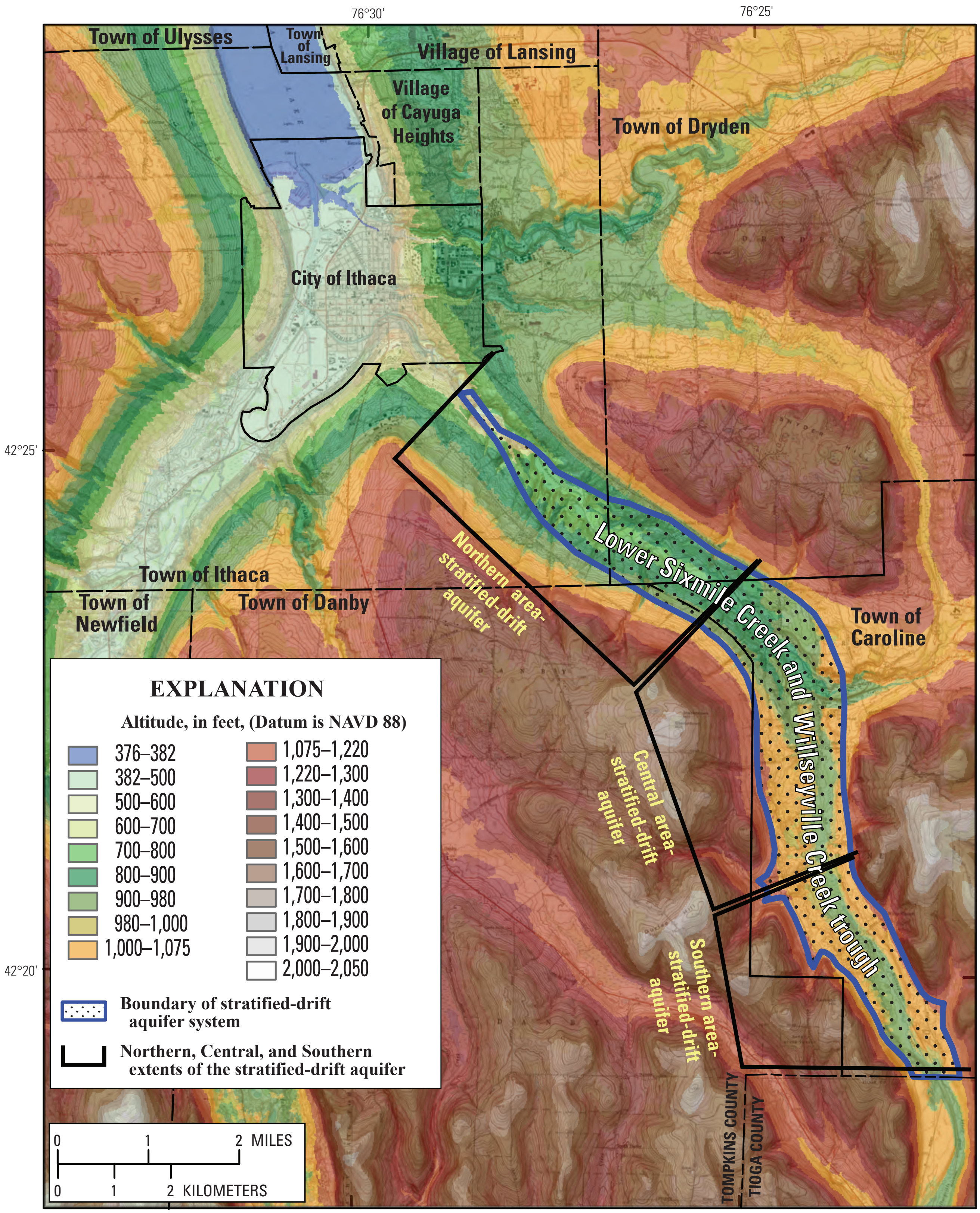
Modified from Miller (2009)

Figure 3. Location of stratified-drift aquifers extending across the lower Sixmile Creek and Willseyville Creek Basins and across the upper Sixmile Creek and West Branch Owego Creek Basins, Tompkins County, New York.

recharge and discharge conditions; and (3) water quality, including concentrations of common ions, trace metals, and nutrients. To aid in these descriptions, the following have also been included: (1) geohydrologic sections; (2) maps and diagrams depicting well locations, geology, groundwater levels, and direction of groundwater flow; and (3) tables of well records and water-quality data.

Description of Study Area

The study area is within the northern area of the Appalachian Plateau (fig. 2) and is almost 10 miles (mi) long and 0.5 to 1.0 mi wide and covers an area of 7.0 square miles (mi^2), extending northward from the Tompkins County-Tioga County border to less than 1 mi south of the City of Ithaca in the north (fig. 4). In the southern part of the study area, relief between hilltops and the valley floor range from 600 to 800 ft with hilltop altitudes generally less than 1,900 ft. In the northern part of the study area, relief between hilltops and the valley floor vary from 500 to 700 ft. Hilltops are higher in the southern part of the study area (ranging from 1,600 to 1,870 ft in altitude) than in the northern part of the study area (ranging from 1,280 to 1,600 ft in altitude) (fig. 4).



Base from U.S. Geological Survey, Seamless Data Distribution System, accessed in 2008 at http://seamless.usgs.gov/
Universal Transverse Mercator projection, Zone 18

Figure 4. Shaded relief and location of stratified-drift aquifers in the lower Sixmile Creek and Willseyville Creek trough in Tompkins County, New York.

Previous Studies

The USGS conducted a groundwater investigation of the Western Oswego River Basin (Crain, 1974) that included the present study area. The investigation by Crain included a well inventory and information on (1) geologic and hydrologic conditions that control the occurrence of groundwater in the basin, (2) quantity of groundwater available, (3) areal distribution of available groundwater, and (4) influence of groundwater discharge on streamflow. Additional well records were collected by Miller (2000) for a general countywide aquifer study of Tompkins County. The results of this study were used to produce a map report, which delineates the extent of unconsolidated aquifers in Tompkins County.

Bedrock geology was mapped by H.S. Williams and surficial geology was mapped by R.S. Tarr at a scale of 1:62,500 (Williams and others, 1909). Surficial geology also was mapped at the scale of 1:250,000 by Muller and Cadwell (1986) for a statewide reconnaissance mapping study and by Miller (2009). The bedrock gorges in the northern part of the study area were mapped by Rich and Filmer (1915). Also, several outcrops in the northern part of the study area were described by Schmidt (1947).

Data Collection

The USGS collected geologic data and stratigraphic records by reviewing well drilling records and drilling test wells at selected locations. Additionally, seismic-refraction surveys were conducted along with water-level measurements and groundwater-quality sampling.

Geologic Data

Geologic data were collected by seismic-refraction and horizontal-to-vertical (H/V) ambient-noise seismic surveys, field reconnaissance for geologic mapping, interpretation from topographic maps and orthophoto interpretation, and review of available geologic reports, soils maps, and well-drilling records. Soils data that were used in geologic interpretation were mapped at a scale of 1:20,000 (Neeley, 1961).

Seismic Surveys

Estimating sediment thickness and the geometry of the bedrock surface is a key component of many hydrogeologic studies. Seismic-refraction and horizontal-to-vertical (H/V) ambient-noise seismic methods were used to estimate the depth to bedrock at several selected locations. The seismic-refraction survey method measures refracted compressional waves of seismic energy and is based on the time for energy generated at a point, such as a small explosive charge, to travel through the ground to receivers (geophones). The velocity of sound traveling through unsaturated unconsolidated deposits, saturated unconsolidated deposits, and bedrock can be calculated and used to predict the depth to bedrock. Seismic-refraction techniques used in this study are described by Haeni (1988).

Seismic-refraction surveys were conducted at three sites to supplement data from test drilling using a 12-channel signal-enhancement seismograph (Haeni, 1988). A series of 12 geophones spaced 100 ft apart were inserted into the ground, and arrival times of compressional waves generated by explosives buried 4 to 5 ft below land surface were recorded and plotted as a function of “source-to-geophone” distances. Although the water table was relatively shallow (generally less than 5 ft below land surface), the unsaturated zone was modeled, and a three-layer (unsaturated, saturated unconsolidated sediments, and the top of bedrock) boundary-formula, computer analysis (Scott and others, 1972) was used to calculate depths to the water table and to bedrock.

The H/V ambient-noise seismic method was also used to estimate unconsolidated sediment thickness and map the bedrock surface where the use of seismic refraction was logistically not feasible. The H/V ambient-noise seismic method uses a single, broad-band three-component seismometer to record ambient seismic noise. The ratio of the averaged horizontal-to-vertical frequency spectrum is used to determine the fundamental site resonance frequency, which can be interpreted using regression equations to estimate sediment thickness and depth to bedrock (Lane and others, 2008).

Well Inventory, Test Drilling, and Water-Level Measurements

Ninety-nine well records were collected and compiled for this report (Appendix 1). Fifty well records were obtained from water-well driller’s reports that were submitted during the years 2000–09 to the New York State Department of Environmental Conservation Water Well Completion Report program. The remaining well records were from either existing data in USGS files or collected from inventorying individual wells during this study. Data from the well drillers’ reports include lithologic logs, water levels, estimated well yields, and well construction information (well and casing depths, casing diameter, and length of casing sticking up above land surface). The well inventory data were augmented by test drilling in which two wells were installed at one site in the central part of the study area using air-rotary drilling methods to obtain data on stratigraphy and water levels in this part of the aquifer where data were lacking. All records collected for this study were entered into the USGS Groundwater Site Inventory (GWSI) computer database and are accessible at http://waterdata.usgs.gov/ny/nwis/inventory.

Levels were run to selected wells to determine the altitudes of the water-level-measuring point, (typically the top of the casing) and land surface at the well. The altitudes of land surface and measuring points of the remaining wells were estimated from USGS 1:24,000 scale topographic contour maps and from Light Detection and Ranging (LIDAR) data. LIDAR is a remote sensing system used to collect topographic data. When possible, depth to water in wells was measured using an electric tape. Where measured, depths were converted to altitudes, plotted on a map, and contoured to depict the water table in unconfined aquifers and potentiometric surfaces in the confined aquifers. Historic water levels were used to help determine the potentiometric surfaces depicted for this report because of the paucity in some areas of available wells to measure. Because the contour interval used to depict groundwater surfaces was greater than any historic or modern seasonal fluctuations, their use was justified.

Water Sampling and Analysis

Groundwater samples were collected from six wells during 2006–07 and sent to the USGS National Water Quality Laboratory (NWQL) in Denver, Colorado, to be analyzed for common ions, trace metals, and nutrients. Field measurements were made for pH, specific conductance, and water temperature. The samples were collected and processed by methods described in the USGS manual for the collection of water-quality data (U.S. Geological Survey, 2004). Analytical results for selected constituents are compared with Federal drinking-water standards. The standards include Maximum Contaminant Levels (MCLs), Secondary Maximum Contaminant Levels (SMCLs), and Health Advisories (HAs) established by the U. S. Environmental Protection Agency (USEPA, 2006).

All six samples were collected from wells finished in sand and gravel. Of the six samples, four were from domestic wells, and two were from test wells installed during this study. For domestic wells, the well pump was run for about 20 minutes (or until at least three casing volumes of well water had been purged from the casing) then a raw-water spigot between the well and the pressure tank was opened, and the water was allowed to run for several more minutes to flush the spigot. Finally, the samples were collected from the raw-water spigot to avoid all influences from water-treatment systems and to ensure that the water collected was representative of the water in the aquifer. In unused test wells, a stainless-steel submersible pump was used to purge the well of from 5-to-10 casing volumes of water before collecting the water samples.

Geology

Geologic materials in the study area include sedimentary bedrock, unstratified drift (till), and stratified drift (glaciolacustrine and glaciofluvial deposits), and recent alluvium. Bedrock that underlies the study area consists of shale, siltstone, and fine-grained sandstone that were deposited in seas during the Devonian Period (416–359.2 million years ago). The rocks were uplifted during the Alleghanian Orogeny in the Late Paleozoic time (about 330 to 250 million years ago) and subsequently have undergone dissection by streams (Isachsen and others, 1991) and scouring by glaciers. Bedrock is overlain by unstratified drift (till) and stratified drift (unconsolidated sediments) except locally where bedrock crops out at land surface. These outcrop areas are present in ditches along roads, and in stream channels that are high up on the trough walls, and in interglacial and interstadial gorges that had been re-excavated by post-glacial streams.

Glacial History

The study area has undergone several major glaciations during the Pleistocene Epoch (table 1), commonly referred to as the Ice Age, which began 2.6 million years ago and ended 11,850 years before present (BP), with the end date expressed in radiocarbon years (Fullerton, 1980). Each subsequent glaciation effectively obliterated most of the previously deposited sediments; therefore, most of the sediments were deposited during and after the last glacial episode (Wisconsinan glaciation).

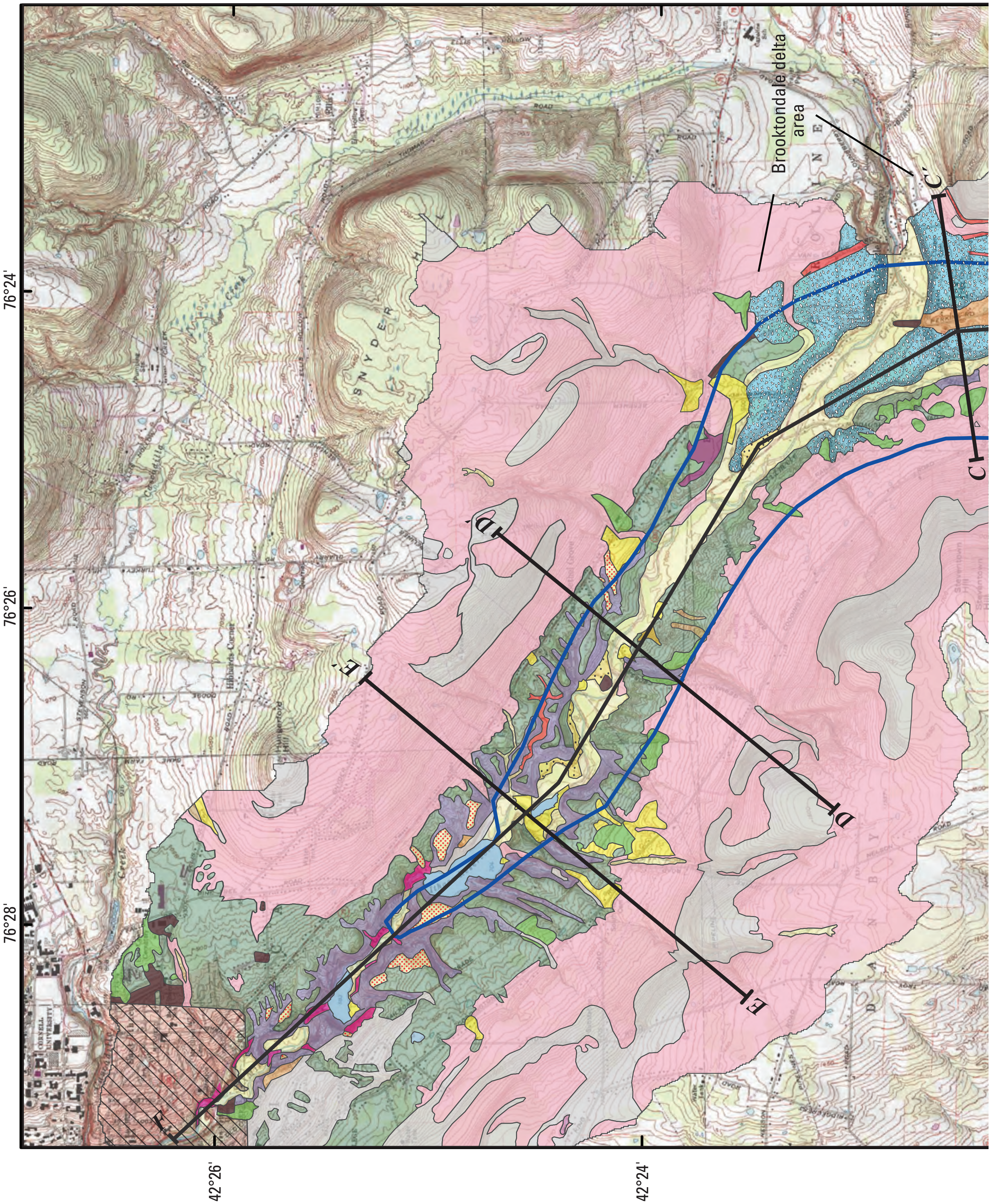
During the Wisconsinan glaciation, the Laurentide Ice Sheet expanded southward from northeastern Canada. As the main sheet ice encountered the Adirondack Mountains, a lobe (Ontario Lobe) flowed into the Lake Ontario Basin (fig. 2) where it then spread southward and covered central New York. The maximum extent of the ice reached northern Pennsylvania about 23,000 to 24,000 years before present (Muller and Calkin, 1993). Most of the geologic history in this study area reflects the events that occurred when the Ontario Lobe advanced into and retreated from central New York.

During the Wisconsinan glaciation, the climate had undergone several cycles of climate cooling and warming resulting in oscillations of the ice front. A cold period that caused the glacier to expand is called a stadial, and a warm period that caused the glacier to retreat is called an interstadial (table 1). Stadials and interstadials are of insufficient duration or intensity to be considered a glacial period, however. Some oscillations of the ice were regional and may have reflected major changes in climate, whereas other oscillations were of a local extent and may have reflected changes to ice dynamics and interaction of ice with proglacial lakes. In this study area, most sediment was deposited during Nissouri and Port Bruce Stades, Erie Interstade, and post-glacial time (table 1). However, in some places, Middle Wisconsinan sediments had escaped erosion by the last glacial episode because these sediments were in settings protected from scouring by Late Wisconsinan ice. Schmidt (1947) and Ashworth and others (1997) found detrital wood of Middle Wisconsinan age in sediments at bluffs of Sixmile Creek that was dated from 27,000 to greater than 41,900 radiocarbon years BP.

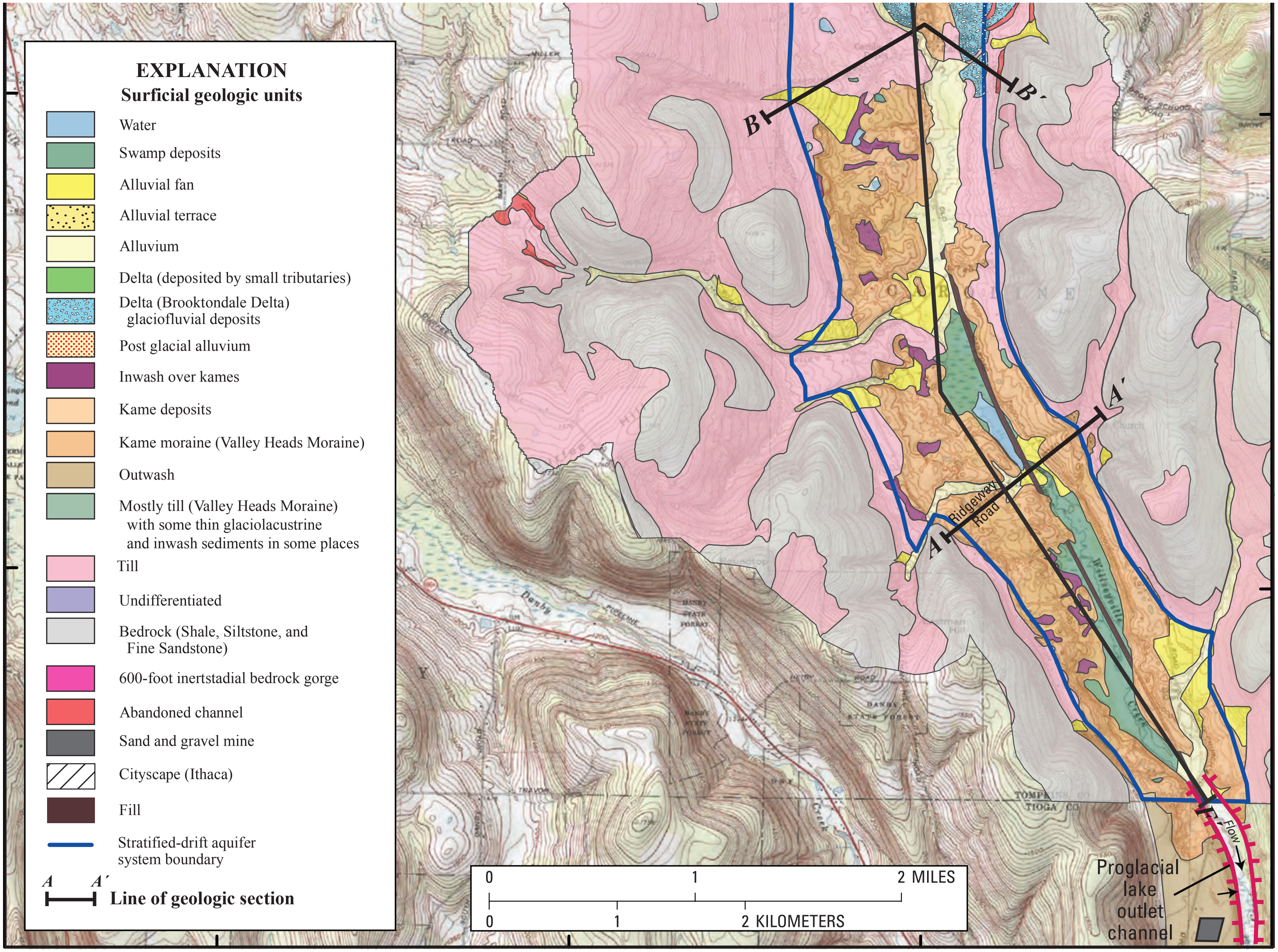
During the Erie Interstade (about 15,500 to 16,500 years BP, table 1), the ice retreated northward from Pennsylvania and is believed to have melted back north of the study area, but the location of the ice margin during the

Table 1. Time-stratigraphic classification of Pleistocene stades and interstades in northeastern North America. After Dreimanis and Karrow (1972) and Fulton and others (1984).

System Period	System Epoch	Stage	Substage	Stades and Interstades	Years Before Present	Events that affected the study area
Quaternary	Holocene	Holocene	Late Wisconsinan		11,850	Post glacial erosion and deposition by recent streams
	Pleistocene	Wisconsinan		Two Creeks Interstade	12,500	
				Port Huron Stade	13,000	
				Mackinaw Interstade	13,500	Ice retreats north of Ithaca
				Port Bruce Stade	15,500	Valley Heads readvance—forms massive moraines
				Erie Interstade	16,500	Ice retreats north of Ithaca
				Nissouri Stade	23,000	Wisconsinan ice sheet spreads across New York
			Middle Wisconsinan	Plum Point Interstade	32,000	New York is ice free
				Cherrytree Stade	36,000	Remnants of Middle Wisconsinan sediments in lower Sixmile Creek Valley (Schimdt, 1950)
				Port Talbot Interstade	53,000	
			Early Wisconsinan	Guildwood Stade	63,000	
				St. Pierre Interstade	68,000	
				Nicolet Stade	75,000	



76°24'
76°26'
76°28'
42°26'
42°24'
Brooktondale delta area
C'
C
D'
D
E'
E



Base from U.S. Geological Survey, Seamless Data Distribution System, accessed in 2008 at http://seamless.usgs.gov/
Universal Transverse Mercator projection, Zone 18

Figure 5. Surficial geology of the lower Sixmile Creek and Willseyville Creek trough, Tompkins County, New York.

retreat is uncertain (Muller and Calkin, 1993) because there are no radiocarbon data in New York for this period. Instead, evidence for the Erie Interstade is based on circumstantial data (Dyke and others, 2002). Ice readvanced into the study area during the Port Bruce Stade (about 15,500 years BP, table 1) and deposited a massive moraine (Valley Heads Moraine) extending from Brooktondale in the north to the boundary between Tompkins and Tioga Counties in the south (fig. 5). During this period, the ice likely surged back and forth in some places as evidenced by multiple till layers and disturbed deposits. The glacier retreated rapidly north from the Valley Heads ice starting around 14,400 years BP (Muller and Calkin, 1993) and probably took several hundred years to retreat north of the study area (Fullerton, 1980). The multiple advances and retreats of the ice during stadial and interstadial periods, the minor surges of ice, and remnants of older pre-late Wisconsinan deposits that survived the last glacial episode resulted in a complex array of multiple sequences of deposits in the study area that, in some places, make it difficult to correlate and map continuous geologic units.

Scouring by Ice

Scouring by flowing ice and subglacial meltwaters played a major role in modifying the preglacial landscape in the study area. In the uplands, scouring by ice extensively smoothed bedrock hillsides and slightly lowered hilltops. In the lower Sixmile Creek and Willseyville Creek valleys, extensive scouring by ice and erosion by subglacial meltwaters truncated hillside spurs, formed U-shaped transverse valley profiles, smoothed valley walls, and deepened the valleys by as much as 300 ft, all of which resulted in a continuous trough (fig. 6). Lower Sixmile Creek and Willseyville Creek valleys were extensively deepened and widened because they were aligned with the direction of ice flow (roughly north to south). In north–south oriented valleys, the ice was a greater erosional agent because it was thicker and flowed faster than in the uplands and in east–west oriented valleys. The east–west oriented upper Sixmile Creek valley (fig. 3) was perpendicular to the direction of ice movement and, consequently, underwent less scouring than lower Sixmile Creek valley. Upper Sixmile Creek valley is known as a “hanging valley” because it has a bedrock floor that is several hundred feet higher than the bedrock floor in the lower Sixmile Creek and Willseyville Creek trough. At Brooktondale, Sixmile Creek exits the hanging valley by plunging down a series of waterfalls and cascades in a bedrock gorge (fig. 3), and where it enters the trough, it flows back onto a thick sequence of unconsolidated deposits.

In some areas, the trough may be asymmetrical with one side steeper than the other, whereas in other areas, the trough walls are symmetrical. As the trough intrudes further southward into the Appalachian Plateau (fig. 2), the width of the trough decreases and the transverse valley profile transitions from a broad U-shaped profile in the north to a narrow U-shaped profile in the south.

Scouring by ice was also responsible for removing the former (preglacial) bedrock col (a high, narrow pass or depression in upland areas, generally across a ridge or through a divide, or between two adjacent hills) in the southern part of the study area (fig. 6) that once formed the major surface-water divide between the St. Lawrence River Basin and the Susquehanna River Basin. The bedrock col that had formed the divide has been replaced by an accumulation of more than 200 ft of glacial drift that is mantled in some places by 10 to 30 ft of recent alluvial sand and gravel. The present divide between the St. Lawrence River Basin and the Susquehanna River Basin is coincident with an upland tributary that has built an alluvial fan on the thick glacial-drift deposits at Belle School Road in the southern part of the study area (fig. 3).

Wisconsinan Deposits in the Study Area

The drift in the study area consists of unstratified glacial drift (till), stratified glacial drift (glaciolacustrine and glaciofluvial deposits), and some post-glacial stratified sediments (lake-bottom sediments that were deposited in reservoirs, peat and muck that were deposited in wetlands, and alluvium deposited by recent streams). The surficial geology of the study area is shown in figure 5. Most of the drift in the study area consists of fine-grained sediments such as till and glaciolacustrine fine sand, silt, and clay that are interlayered with lesser amounts of coarse-grained sediments such as sand and gravel. Although coarse-grained sediment (sand and gravel) is usually a minor component of the valley fill, it is present in sufficient amounts in most places within the trough to form the aquifers that most residents use for their water supply. Locally, the sand and gravel deposits can be as much as 100 ft thick, such as at the delta near Brooktondale in the central part of the study area, but in most places the sand and gravel deposits range in thickness from 10 to 20 ft.

The thickness of drift ranges from zero where bedrock crops out at land surface, such as in gorges and along the trough walls, to more than 300 ft in the middle of the trough in the central and southern parts of the study area. The drift progressively thins northward where Sixmile Creek enters the trough near Brooktondale because the stream progressively cuts deeper and deeper into the drift as it flows northward. Eventually, Sixmile Creek erodes through all of the drift and flows on top of the bedrock north of the Ithaca Reservoir.

The unstratified glacial drift in the study area consists of till, which is an unsorted mixture of clay, silt, sand, gravel, and rocks that were deposited directly by glacial ice, rather than by meltwater. The larger gravel and rock clasts, which are typically embedded in a fine-grained matrix consisting of clay, silt, and very fine sand, range in size from pebbles to boulders. In most places in the uplands, a layer of till that directly overlies bedrock is the sole unconsolidated deposit, whereas, in the trough, there are typically two or more till

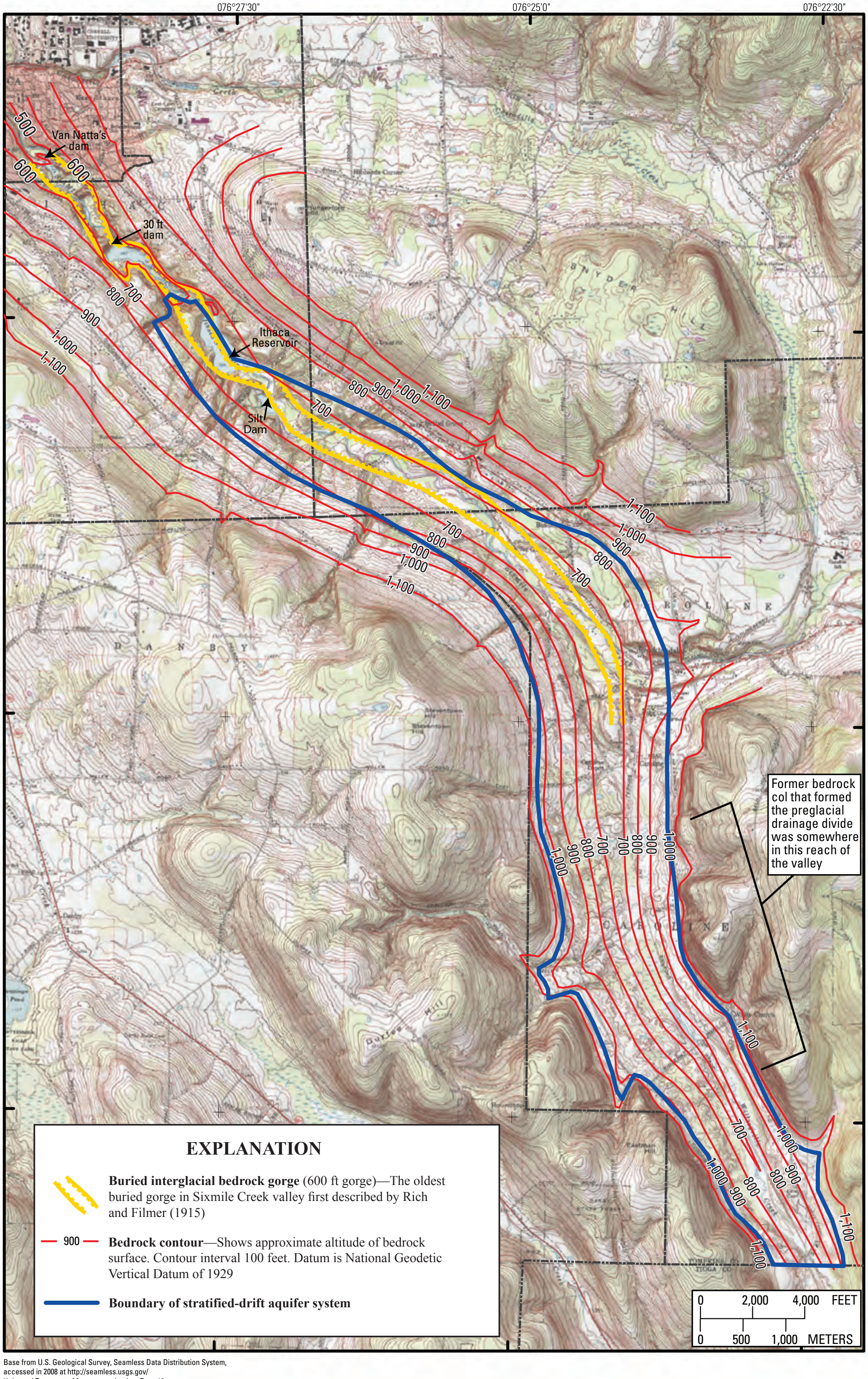


Figure 6. Bedrock structure map of lower Sixmile Creek and Willseyville Creek trough Tompkins County, New York.

units that are interlayered with stratified drift. In general, till comprises a large portion of the drift in the study area, and in the northern part of the trough (north of the delta just west of Brooktondale), till is the prevalent type of deposit, especially in the upper portion of the valley fill where it typically crops out at land surface (fig. 5).

The stratified glacial drift (glaciolacustrine and glaciofluvial deposits) consists of layered and sorted sediment. Glaciolacustrine deposits include deltas and lake-bottom sediments. One example of a glaciolacustrine deposit is the large delta west of Brooktondale in the central part of the study area (fig. 5). Deltas typically consist of three components: (1) topset beds—coarse-grained sediments (sand and gravel) that were deposited on the upper part of the delta in near-shore subaerial environments, (2) foreset beds—relatively steeply dipping, medium-coarse sediments (mostly sand and pebbly sand) deposited in shallow water at the front of the delta shore, and (3) bottomset beds—relatively flat-lying beds of fine-grained sediments (fine sand, silt, and clay) deposited in deep water at distal parts of the delta.

Glaciofluvial deposits consist of layered coarse-grained sediments (sand and gravel) that were deposited by meltwaters that flowed on top, within, and below the glacier. Meltwater that flowed through an internal network of openings and on top of the ice discharged at the ice front and deposited heads of outwash and outwash plains. Meltwaters deposited sediments on top and within the ice and these sediments were laid down as the ice disintegrated and formed kame deposits. Meltwaters that were routed through tunnels at the base of glacier deposited subglacial features, such as eskers and subglacial outwash fans.

Southern Part of Study Area

The prominent geologic feature in the southern part of the study area is a large moraine that was deposited at the terminus of a stagnant ice lobe that extended several miles south from the main ice massif and into the study area (fig. 5). The moraine is part of the most extensive moraine system in New York State—the Valley Heads Moraine system that forms a roughly 240-mi-long discontinuous ridge across central and western New York (fig. 2).

The Valley Heads Moraine system was formed during a readvance of ice during the Port Bruce Stade about 15,500 years ago (Muller and Calkin, 1993). In this study area, the moraine extends 4 mi from just south of Brooktondale to the southern border of Tompkins County (fig. 5). Randall (2001) identified the Valley Heads Moraine and the area on the backside of the moraine as one of the regions where multiple drift layers are widespread and hydrologically important. Evidence for multiple readvances and retreats includes the presence of multiple till units and disturbed sediments (caused by thrust faults, folds, or erosion by ice) within, or on top of, previously deposited glacial sediments. Evidence for the Erie Interstade also comes from the fine-grained matrix of the till that was originally sediment deposited in proglacial lakes, which became incorporated into advancing ice and included in the till. Because the ice was thin at the terminus of the glacier, it probably did not completely erode the previously deposited sediments down to bedrock. Instead, the relatively thin ice overrode and partially eroded previously deposited sediments and deposited another sequence of till and glaciofluvial sediment over the older deposits.

The topography of the moraine includes hummocky kames and kettles, kame terraces, and a large channel, carved by water that was an outlet to a post-glacial lake in the trough. The kame and kettle ice-disintegration landforms and the absence of ridges are topographic evidence that indicate that the margin of Valley Heads ice melted under stagnant ice conditions. The moraine is composed of sediments that were transported by the ice and by meltwaters that flowed beneath, within, and on top of the ice, as well as local sediments (alluvial inwash), transported by upland streams, that were deposited on or between the ice and adjacent trough walls. Records of wells finished in the morainal deposits indicate that the types of sediments that may be penetrated are till, glaciofluvial sand and gravel, and glaciolacustrine fine sand, silt, and clay. The actual contact of stratigraphic units between wells is difficult to predict due to the collapse and continual movement of sediment laid down as the ice melted. Hence, due to the chaotic depositional environment and relatively sparse geologic data in the moraine, little is known about the stratigraphy of the deposits that comprise it.

Although there is little data on the extent and thickness of stratigraphic units at the moraine, the total thickness of the drift at the Valley Heads Moraine where Ridgeway Road traverses the trough in the southern part of the study area was determined using refraction and horizontal-to-vertical (H/V) ambient-noise ratio seismic methods (figs. 5, 6, and 7). The results of the seismic surveys indicate that the drift is as much as 300 ft thick in the center of the trough and that the part of the trough where depths to bedrock are between 200 and 300 ft may represent an extension interglacial "600 ft gorge" (fig. 7).

In the low area of the trough, there is a 4-mi-long wetland that represents the vestige of a small shallow proglacial lake and its outlet channel that formed in a basin between the front of the retreating ice and the crest of the moraine (fig. 5). The altitude of the surface of the lake was controlled by the outlet channel on the moraine (fig. 5) that initially was at an altitude of about 1,010 ft before the outlet began to incise into the moraine. Then, as the outlet channel was lowered by incision, the lake level gradually dropped about 60 ft and (altitude about 950 NVGD 88), as indicated by the present altitude of the bottom of the abandoned outlet channel in the southern part of the study area.

Central Part of the Study Area

Glaciolacustrine processes were responsible for the prominent geologic features in the central part of the study area. In the proglacial lakes that formed during the

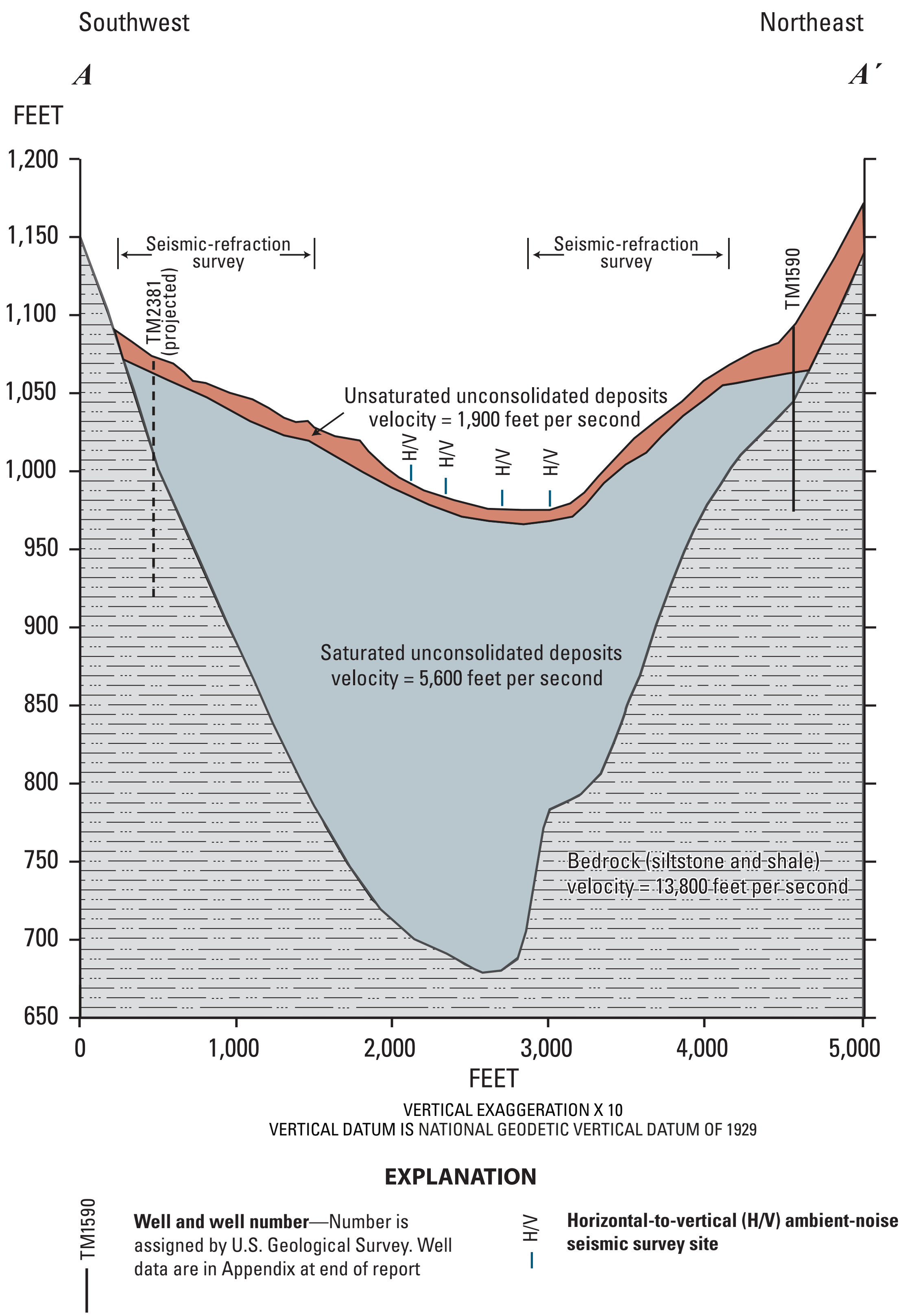


Figure 7. Geohydrologic section *A–A′* showing results of horizontal-to-vertical (H/V) ambient-noise and seismic-refraction surveys along Ridgeway Road, Town of Caroline, New York.

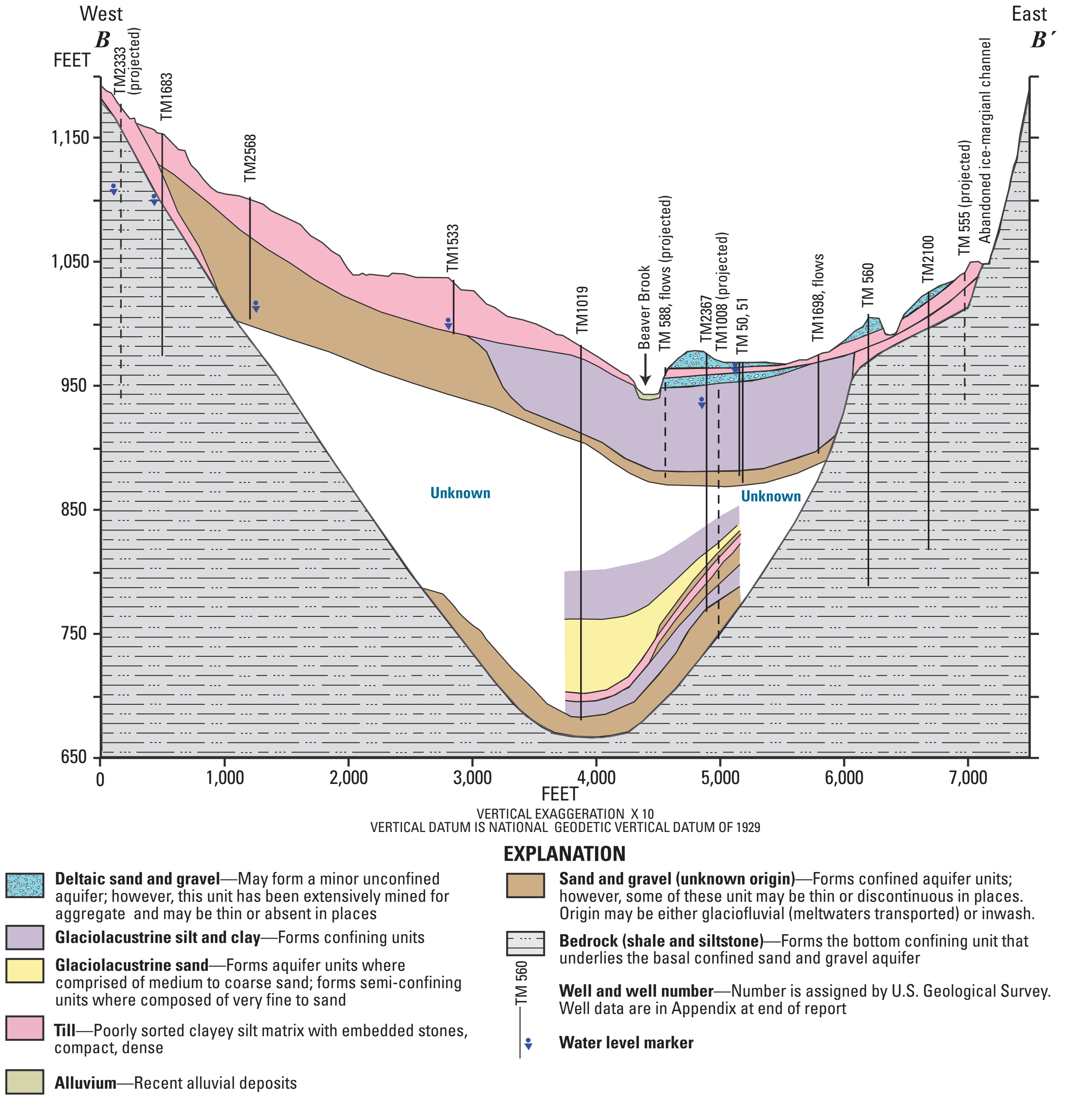


Figure 8. Geohydrologic section *B–B′* in the lower Sixmile Creek and Willseyville Creek trough, Town of Caroline, New York.

advance and retreat of ice in the central part of the trough, glaciolacustrine sediments accumulated (fig. 8) between the retreating ice and the morainal deposits that plugged the valley in the south part of the study area. Fine-grained sediments (lake-bottom fine sand, silt, and clay) were deposited in deep water, and coarse-grained sediments (deltaic sand and gravel) accumulated at the water's edge and in shallow water.

A large delta (Brooktondale Delta) was deposited west of Brooktondale when ice in lower Sixmile Creek and Willseyville trough retreated north of the mouth of upper Sixmile Creek valley, thereby unblocking upper Sixmile Creek valley and permitting sediments transported by Sixmile Creek to be disgorged into the proglacial lake in the trough. Most of the sediment was deposited into standing water, but at times, some may have been deposited against and on top of the ice during surge(s) of the glacier back into the Brooktondale area. The delta extends from its apex at the east side of the trough to the central part of the trough to the west (fig. 9).

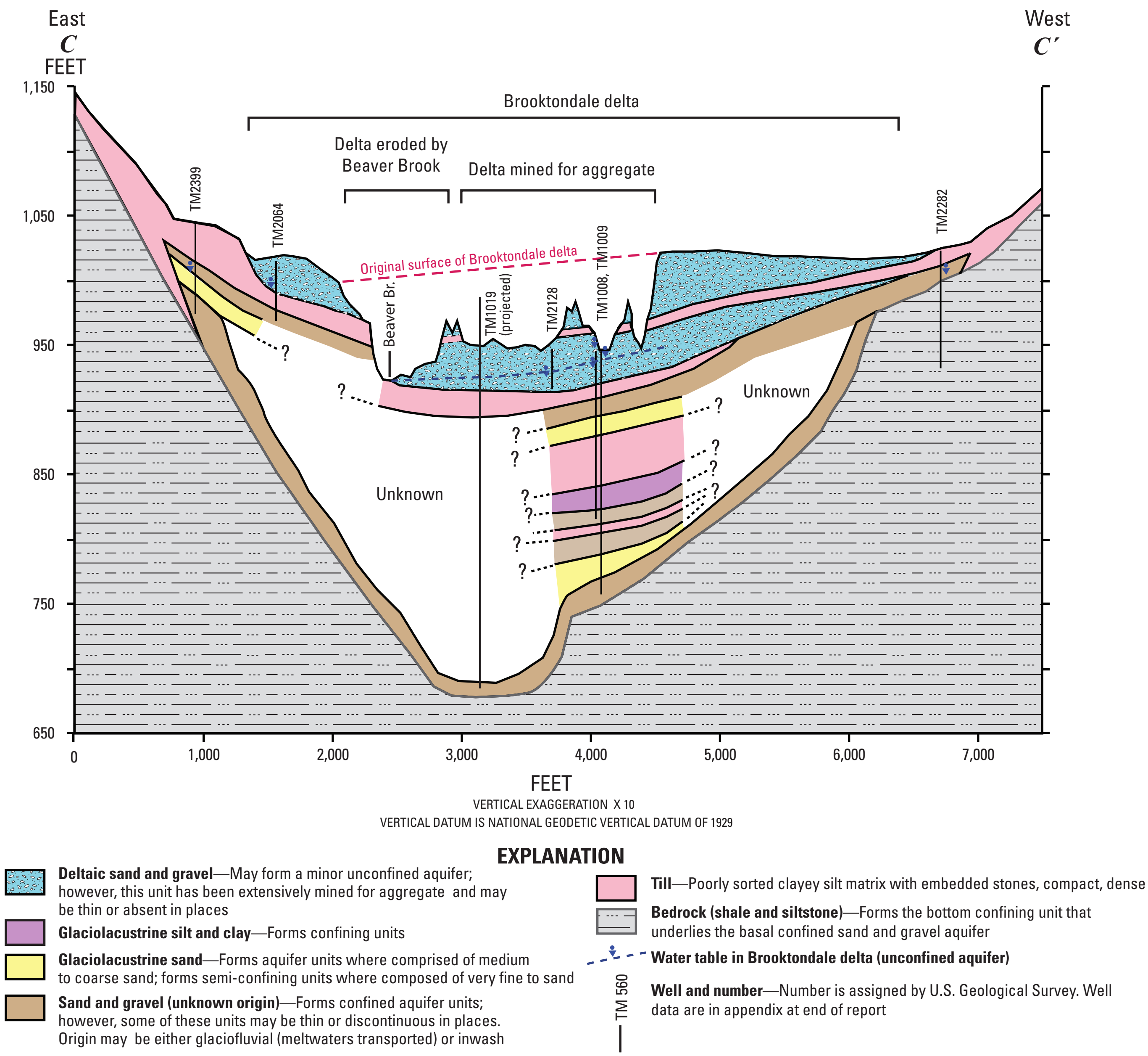


Figure 9. Geohydrologic section *C–C′* in the lower Sixmile Creek and Willseyville Creek trough, Town of Caroline, New York.

The delta consists of medium-to-coarse sand to pebbly sand (foreset beds) in the lower part of the delta and coarse gravel on top of the delta (topset beds). Presently, the delta is mined for aggregate; subsequently most of the upper part of the delta has been removed by this process. Before sand and gravel mining began, the delta was as much as 80 to 100 ft thick. The results of drilling at an USGS test-well site (TM1008, fig. 8) in the bottom of one of the sand and gravel pits indicted that there was 24 ft of surficial sand and gravel remaining below the bottom of the pit at that site. The deltaic sediments are thickest (as much as 100 ft thick) and coarsest at the apex of the delta in the east side of the trough and become thinner and finer-grained towards its edges. At well TM2367 (fig. 8), and near the southern boundary of the delta, the deposits are only 25 ft thick.

Northern Part of the Study Area

The three major geologic processes that have been instrumental in forming the geologic framework in the northern part of the study area are (1) erosion by streams during interglacial and post-glacial periods, (2) deposition in the upper zones of the drift that was dominated by subglacial environment (till and subglacial meltwater deposits), and (3) deposition in the lower zone of the drift that was dominated by glaciolacustrine (lake-bottom) and subglacial environments. Deposition of coarse-grained sediments (sand and gravel) was subordinate in the northern part of the trough, and there is a conspicuous absence of substantial amounts of glaciolacustrine sediments and sand and gravel at land surface. Surficial glaciolacustrine sediments and sand and gravel also are absent in other valleys that are crossed by the Valley Heads Moraine in central New York, (Miller and Randall, 1991). The lack of glaciolacustrine sediments at land surface is likely attributed to the absence of a major proglacial lake in the northern part of the study area; instead of a lake, there probably was highly disintegrated stagnant ice in the trough during the late phases of ice retreat in which meltwater had reversed direction in flow (from south to north) and moved back under the disintegrating ice through crevasses and tunnels and drained out to a lower outlet in another valley (Miller and Randall, 1991; Cadwell and others, 1988; Cadwell, 1972).

There are scant subsurface data in the trough north of German Crossroad because much of the area is composed of dams and reservoirs and most residents that live in this area are supplied by a public-water system (City of Ithaca) rather than by individual wells. Most geohydrologic information about this area is from test holes drilled near the Ithaca Reservoir and observations of outcrops exposed in bluffs along Sixmile Creek and in gullies cut by tributaries that drain the steep walls of the trough. Schmidt (1947) describes several varved glaciolacustrine units in the lower parts of eroded bluffs that were exposed by down cutting by Sixmile Creek just south of the Silt Dam; the units are interlayered with thin sand and gravel units in the lower parts of the drift. These deposits are overlain by a thin sand and gravel unit which, in turn, is overlain by till (fig. 10).

Till comprises most of the upper portion of drift between German Crossroad and Banks Road. Mostly till and disturbed lacustrine deposits (lake deposits that became overridden by ice or have undergone mass slumping) consisting of silt and clay, and some lenses of sand and gravel comprise the lower portion of the drift (fig. 11). Well TM1002 was reported to be cased to 88 ft below land surface and is finished in a confined sand and gravel aquifer that is probably on top or close to bedrock (fig. 10). Results of a seismic-refraction survey (fig. 10) indicate that the buried “600 ft gorge” extends at least this far south in the trough.

Since intervals of interglacial periods have been longer than the present post-glacial period, the ancestral streams in lower Sixmile Creek valley had a longer time to erode previously deposited sediments. In some places, the interglacial stream had fully penetrated (completely incised) the drift and had cut a gorge into the underlying bedrock. An interglacial gorge (called the “600 ft gorge” by Rich and Filmer, 1915) extends from Van Natta’s Dam in the north to at least German Crossroad. Some well records indicate that it probably underlies the central part of the study area (figs. 6, 10, 11, and 12) and could possibly extend beneath the southern part of the study area. Another buried gorge (called the “200 ft interstadial gorge” by Rich and Filmer, 1915) extends north from Van Natta’s Dam beyond the northern part of the study area (fig. 12). The “200 ft interstadial gorge” contains little or no unconsolidated sediments, and consequently, no sand and gravel aquifer is present in this area.

In the northern part of the study area just north of the Brooktondale delta, the drift in areas not incised by streams is more than 200 ft thick and progressively thins northward to less than 100 ft at the northern end of the study area (fig. 11). However, the thickness of the drift is much less in the northern part of the study area where streams have eroded much of the drift during post-glacial time. During the post-glacial period, Sixmile Creek and many of the tributaries that drain the trough walls have deeply incised channels creating ravines and gullies, some that are cut more than 100 ft deep into the drift. Near the silt dam (figs. 3 and 6), Sixmile Creek has cut a channel over 100 ft deep and 1,000 ft wide that penetrates most of the drift and is close to the top of bedrock in the U-shaped trough floor (fig. 11). North of the “60 ft Dam,” at the outlet of the Ithaca Reservoir (fig. 6), Sixmile Creek has fully penetrated the drift and has entered the “600 ft gorge”.

Hydrology of the Stratified-Drift Aquifer System

Characterization of the stratified-drift aquifer system in the lower Sixmile Creek and Willseyville Creek trough included describing the (1) aquifer type (confined or unconfined); (2) aquifer framework; (3) groundwater-flow system, including water levels and recharge and discharge conditions; and (4) water quality, including concentrations of inorganic chemical constituents and nutrients. Because drilling is expensive and access to desired locations is sometimes not possible, most data used to characterize the geologic framework of the aquifers are obtained from existing well records. Many of the wells used in this study are within the central portion of the study area; however, attempts were made to characterize the southern and northern portions of the aquifer system using available well logs, water-level data, and correlations made from seismic data. The locations of wells used to characterize the stratified-drift aquifer system are shown in figure 13, and well records are presented in Appendix 1.

There are three types of aquifers in the lower Sixmile Creek and Willseyville Creek trough — confined, unconfined, and a combination of both (fig. 14). Based on aquifer type, the distribution of aquifers is summarized as follows: (1) an unconfined aquifer aquifer in the southern area of the trough, (2) an unconfined deltaic aquifer (underlain by a confined aquifer) in the central part, and (3) confined aquifers at various depths throughout the trough (locally overlain by discontinuous unconfined aquifer material).

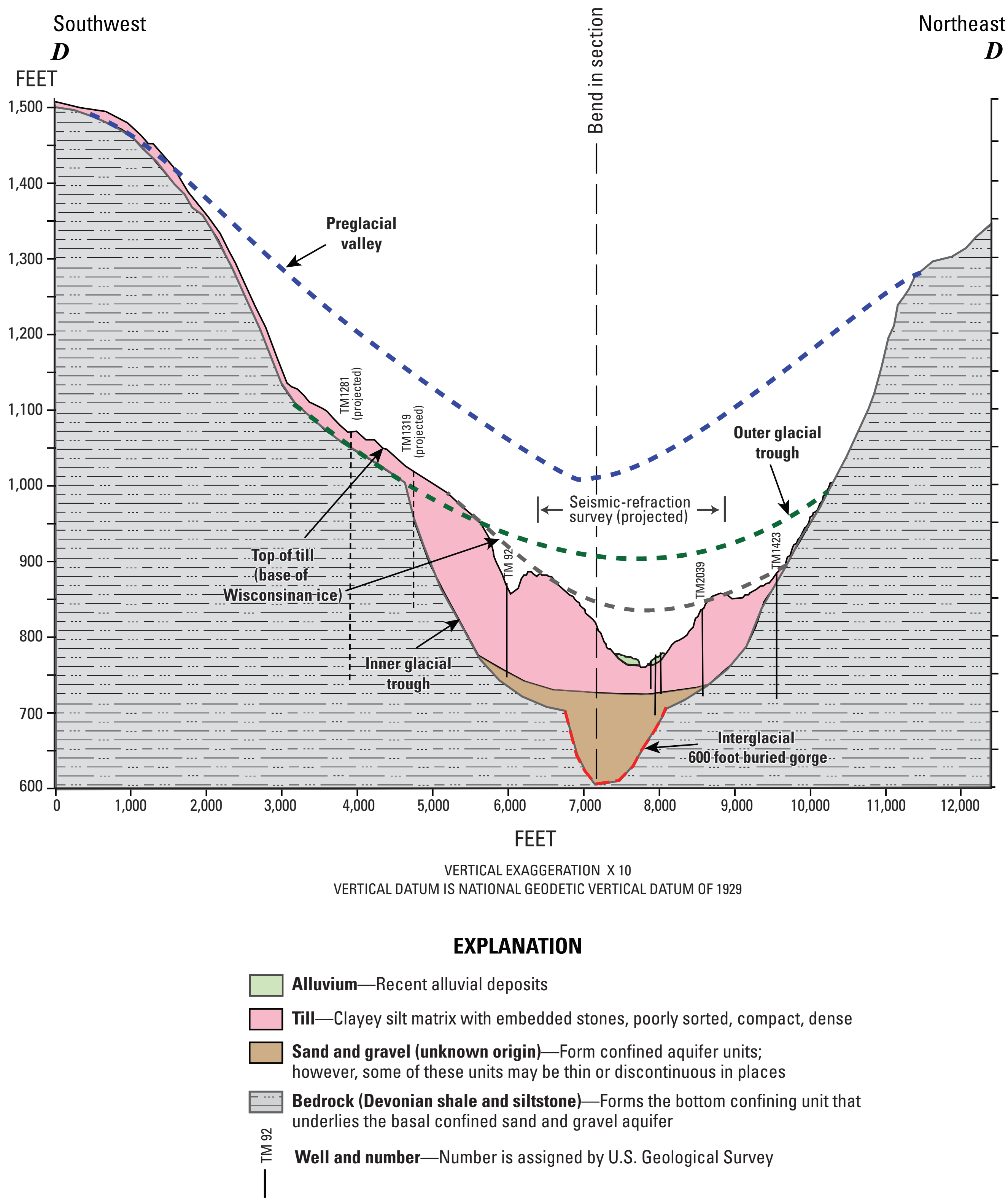


Figure 10. Geohydrologic section *D–D′* in the lower Sixmile Creek and Willseyville Creek trough, Tompkins County, New York.

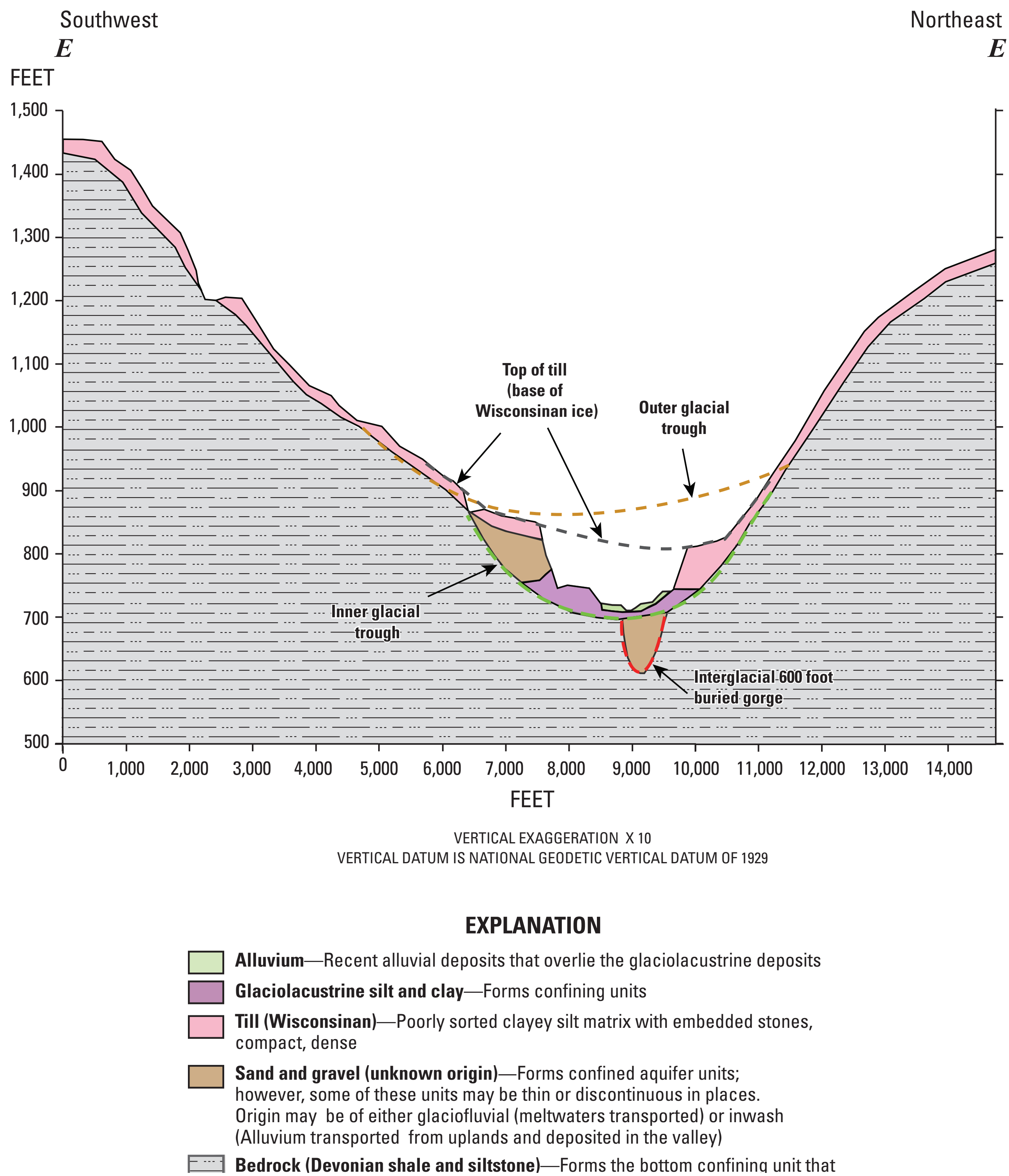


Figure 11. Geohydrologic section *E–E′* in the lower Sixmile Creek and Willseyville Creek trough, Tompkins County, New York.

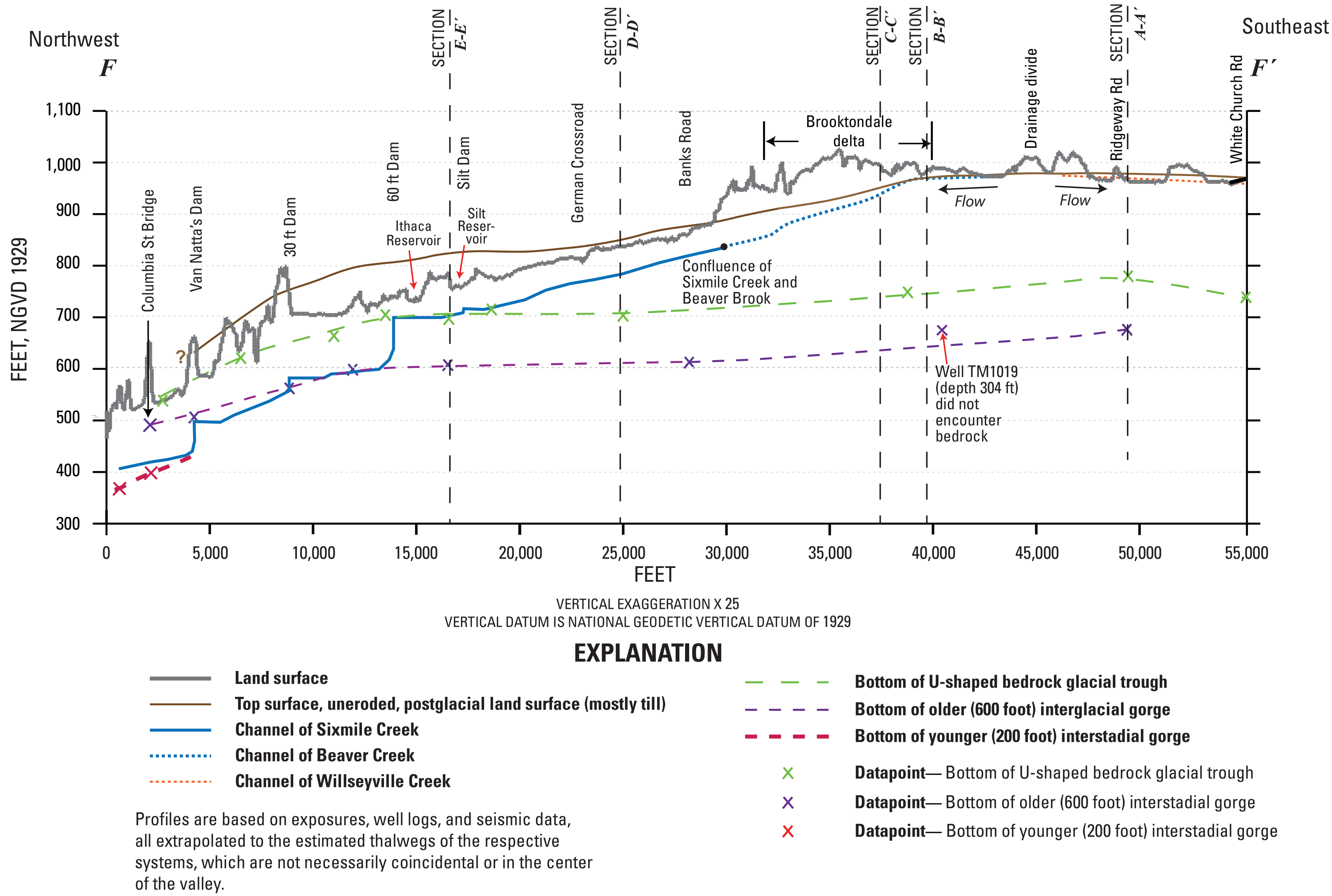
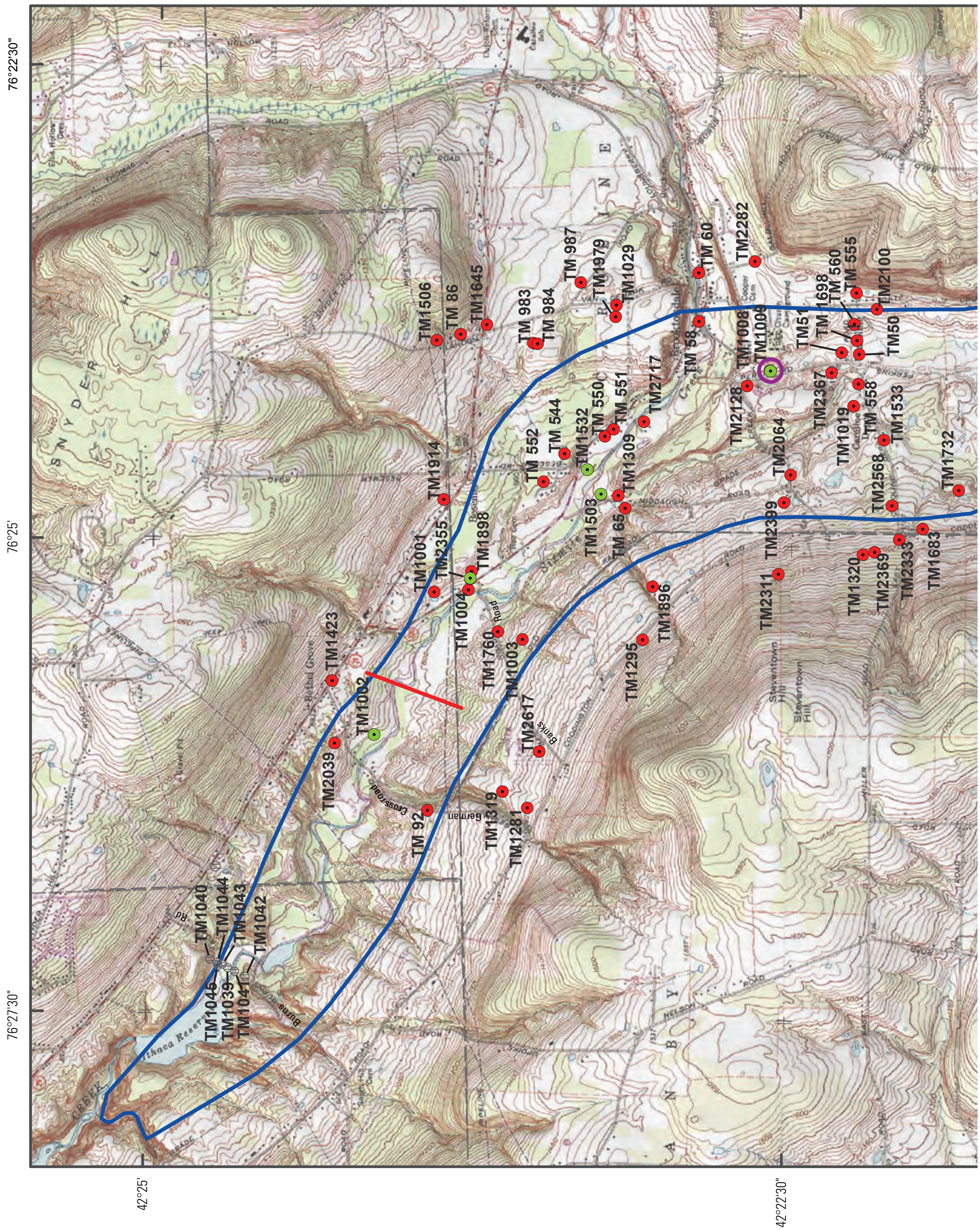


Figure 12. Geohydrologic section *F–F′* of glacial and fluvial systems in the Sixmile Creek and Willseyville Creek trough, Towns of Caroline, Dryden, and Ithaca, New York.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Steventown Hill
Ithaca Reservoir

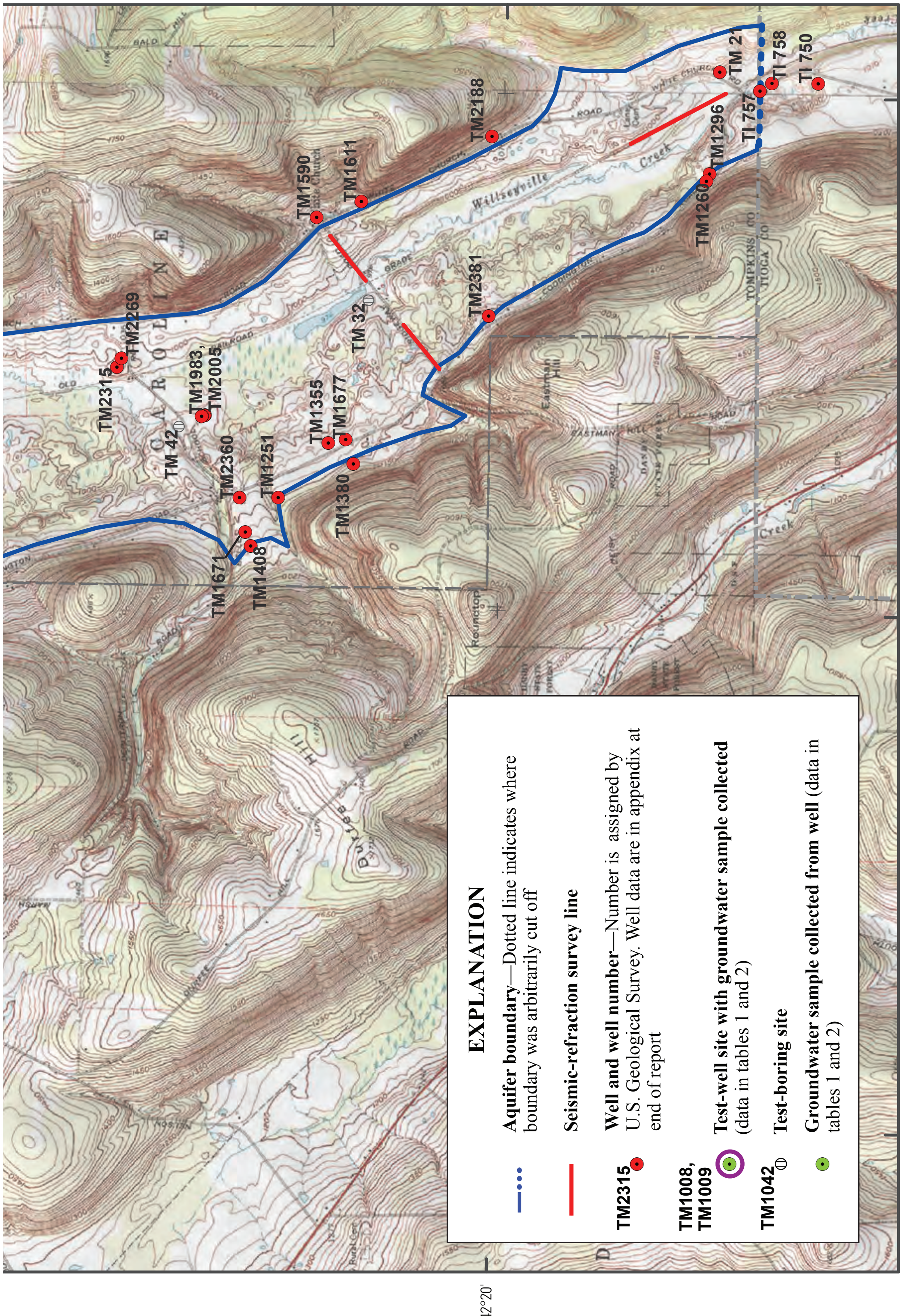


Figure 13. Location of wells in lower Sixmile Creek valley and Willseyville Creek trough, Tompkins County, New York.

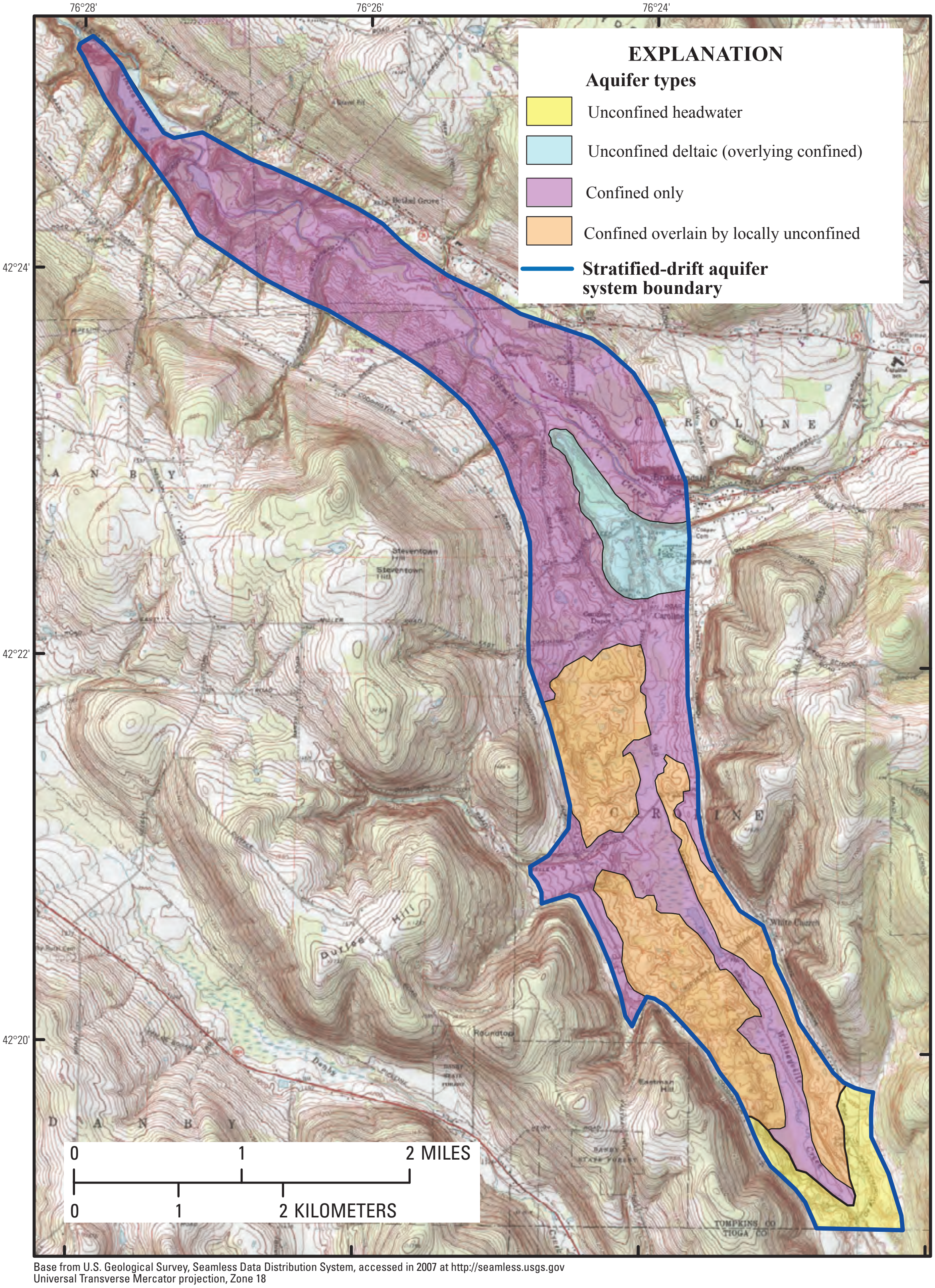


Figure 14. Aquifer types in lower Sixmile Creek and Willseyville Creek trough, Tompkins County, New York.

Aquifer Types

The lower Sixmile Creek and Willseyville Creek trough contains unconfined and confined sand and gravel aquifers that overlie the bedrock aquifers throughout the trough (however, the bedrock aquifers are not the main focus of this report and are considered here as the base of the stratified-drift aquifer system). An unconfined aquifer has an upper surface (water table) that is open to the atmosphere through permeable material and in which the water level is free to rise and decline. Unconfined aquifers are typically closer to land surface than confined aquifers. In contrast, an unconsolidated confined aquifer (also known as an artesian aquifer) is a permeable deposit located between confining layers. Confining layers are made up of geologic material with lower permeability (low hydraulic conductivity) than the surrounding deposits that impedes the flow of groundwater. In this study area, the confining layers consist of till, or lacustrine very fine sand, silt, and clay. In a confined aquifer, the potentiometric surface is always above the top of the aquifer unit in which the water is stored. When a well is drilled into a confined aquifer, water in the well casing is forced up to its potentiometric surface, and if the pressure in the confined aquifer is great enough, it may cause the water in the well to flow above land surface, in which case the well is referred to as a flowing-artesian well.

Aquifer Geometry

The aquifer geometry in the study area is complex as a result of glacial processes, previously deposited sediments that were eroded, or redeposition of sediment on top of older sediment, resulting in multiple sequences of unconsolidated deposits in the study area. Additionally, interglacial, interstadial, and post-glacial erosion modified the unconsolidated deposits—in some places, streams have cut gorges down to the bedrock floor of the trough breaching or entirely eroding the aquifers. Unconfined aquifers are present only locally, such as at the Brooktondale Delta in the central part and near the terminal moraine in the extreme southern part of the trough. In the study area, there is one continuous uppermost confined aquifer throughout the central and southern parts—one continuous basal-confined aquifer throughout the entire trough, and locally, only multiple intermediate confined aquifers such as in the central portion of the trough beneath the Brooktondale Delta.

Sufficient well records were available to characterize some parts of the stratified drift in the trough, but there are also large areas where data were insufficient, such as in the southern part of the trough. More subsurface data are available for the shallower parts of the trough than the deeper parts because water-well drillers typically stop at the first major water-bearing unit that is penetrated.

Unconfined Headwater Aquifer

Headwater aquifers typically are present in through valleys where drift forms a drainage divide (in this case the divide between the Susquehanna River Basin and the St. Lawrence River Basin shown in figure 3). Kame, alluvial, and a small amount of outwash sand and gravel deposits at the terminus of the Valley Heads Moraine in the southern part of the study area (figs. 2 and 5) form an unconfined headwater aquifer that begins at the southern boundary of Tompkins County and extends south into Tioga County (fig. 14). The part of the unconfined aquifer that is within Tompkins County is only 0.3 square mile (mi^2) and consists mostly of coarse-grained sand and gravel in the upper part of the aquifer, but the total thickness is unknown. Drilling data indicate that the aquifer is at least 25 ft thick, based on (1) the record for a well (TM1260, 26 ft deep) sited along the edge of the trough, which shows that sand and gravel extends from 0 to 26 ft below land surface (with a reported yield of 4.5 gallons per minute (gal/min) and (2) visual inspection of a sand and gravel mine in Tioga County (0.6 mi south of the Tompkins and Tioga Counties border, fig. 5), which has been excavated into coarse sand and gravel to about 30 ft below land surface. However, results from a seismic-refraction survey in the southern part of the study area indicate that the unconsolidated deposits are more than 200 ft thick in the center of the trough. At other locations in central New York, the crest of the Valley Heads Moraine and the outwash in front of it contain large aquifers that are typically 80 to 140 ft thick (Miller, 2009; Miller and others, 1998; Kappel and Miller, 2003; Kappel and others, 2001; and Randall and others, 1988). This condition may exist in this study area, too, but no wells are drilled deep enough to confirm this.

Unconfined Deltaic Aquifer

The sand and gravel that comprises the delta near Brooktondale (figs. 5 and 9) forms a small unconfined aquifer (0.3 mi^2 in area) in the central part of the study area. Although much of the upper part of the delta has been removed (up to 65 ft in places) by several aggregate mining operators, there remain sufficient amounts of sand and gravel in most places to form a thin aquifer that is relatively unused. The deltaic aquifer is wedge shaped and thickest near its apex near Brooktondale on the east side of the trough and thins radially to the west, north, and south as it fans out across the trough. The edge of the delta on the west side of the trough is at an altitude of about 1,010 ft, where it terminates by lapping onto till and kame moraine deposits (fig. 5). In 2008, the altitudes of land surface at the bottom of the aggregate mines ranged from 940 ft to 960 ft.

Three well records (fig. 13, appendix 1) in the delta area were used to define the thickness and bottom of the deltaic aquifer. The well record for test well TM1008, (figs. 9 and 13, appendix 1), drilled for this study in the bottom of one of the aggregate mines (altitude of land surface is 945 NVGD

88), indicates that the well penetrated 24 ft of sand and gravel overlying clay (bottom of aquifer at altitude 920 ft NVGD 88) below the floor of the pit. Data from a commercial well (TM2128, figs. 9 and 13, appendix 1) drilled by an aggregate-mining company and used for washing gravel indicate that there is at least 33 ft of sand and gravel below the floor of the pit, which puts the altitude of the bottom of the deltaic unconfined aquifer at less than 915 ft. At well TM2367 (figs. 8 and 13, appendix 1) near the southern edge of the delta and outside of the gravel pit in an area that has not been mined, 25 ft of sand and gravel remains that overlies a lacustrine silty sand unit, indicating that the bottom altitude of the unconfined deltaic aquifer is 953 ft.

Confined and Locally Unconfined Aquifers

The most areally extensive aquifers in the study area are confined sand and gravel aquifers, which are relatively thin compared to the till and glaciolacustrine clay, silt, and very fine sand that confine these aquifers throughout the lower Sixmile Creek and Willseyville Creek trough. As an exception, locally, such as in the Brooktondale delta area (fig. 9) and at the southernmost area of the trough where the Valley Heads Moraine is present, sand and gravel deposits are thicker and comprise a larger part of the stratified-drift sediments.

In the southern part of the study area, which has the lowest population density, there are few well data that could be used to characterize aquifers in the trough (fig. 7). However, it is reasonable to assume that there may exist at least a basal confined aquifer on top of bedrock similar to the central part of the trough (fig. 7) and similar to other glaciated valleys in central New York, but no wells are drilled deep enough in the southern part of the study area to confirm this.

In the central part of the trough, there are typically two continuous and extensive confined aquifers (an upper confined aquifer and a basal confined aquifer) but locally there can be up to four confined aquifers. Wells that are along the sides of the trough (TM1671, TM2360, and TM2315; fig. 13) indicate there is likely only one confined aquifer along the flanks of the trough because these wells penetrated one sand and gravel unit and are likely finished close to bedrock, based on information extrapolated from surrounding wells. It isn’t until near Belle School Road that there is sufficient well data to characterize the aquifers in the central part of the study area. Well records for two adjacent wells along Belle School Road (TM1983 and TM2005, fig. 13) in the central part of the trough indicate that there is at least one confined aquifer unit and possibly a second (basal confined aquifer) that hadn’t been penetrated by drilling. Well TM1983 (fig. 13) was cased to 220 ft and finished in a sand unit that heaved up the casing 40 ft, causing the well to be abandoned. Nearby, well TM2005 (fig. 13) was drilled to a depth of 30 ft and finished in sand and gravel underlying till (bottom of till at 27 ft).

In the central part of the study area, south of the Brooktondale Delta, well records indicate that there are at least two continuous confined aquifers in the central part of the trough (fig. 8). Wells TM 50, TM 51, TM 588, and TM1698, (figs. 8 and 13) are finished in a confined aquifer 90 to 105 ft below land surface and are either flowing artesian or have water levels 2 to 3 ft below land surface. Wells TM2367 and TM1019 (figs. 8 and 13), 207 and 304 ft deep, respectively, are finished in confined sand and gravel units that are likely on top, or close to, bedrock, based on seismic refraction data nearby. The depth to water in well TM2367 was 40 ft (altitude water level was 938 ft) on May 21, 2007, which is several tens of feet lower than levels of wells finished in the upper confined aquifer that were either under flowing conditions or had water levels several feet deep (altitudes ranging from 968 to greater than 975 ft). Well TM1019 is the deepest well (304 ft) in the study area that is in a sand and gravel aquifer.

Underlying the unconfined deltaic aquifer near Brooktondale in the central part of the study area are four confined sand and gravel aquifers (fig. 9). The uppermost confined aquifer (fig. 9) probably correlates to the continuous upper confined aquifer found at depths 90 to 105 ft in geohydrologic section B—B′ (fig. 8). Test well TM1008 (figs. 9 and 15) was drilled to a depth 187 ft and finished in a continuous, basal confined sand and gravel aquifer that directly overlies bedrock. Test well TM1009 was drilled to a depth 130 ft, and the casing was perforated from 122 to 126 ft. It is finished in one of the discontinuous confined sand and gravel aquifers in the middle section of the trough (figs. 9 and 15). Water levels differed by 4 to 5 ft in test wells TM1008 and TM1009 (fig. 15), indicating that the confining unit between the aquifers impedes groundwater movement between the two aquifers. The relatively large amounts of sand and gravel that form the confined aquifers that underlie the Brooktondale Delta make this area potentially one of the most favorable parts of the study area for large amounts of groundwater withdrawal.

About 0.6 mi north of the Brooktondale delta (fig. 13), wells TM 65, TM1309, and TM1503 in the western part of the valley were drilled deeper (from 94 to 197 ft) than wells TM 550, TM 551, and TM1532 in the lower Sixmile Creek floodplain in the eastern part of the trough (from 70 to 95 ft). Wells TM 544 and TM 552, on a terrace 50 to 60 ft higher in altitude than the floodplain in the eastern part of the trough, were finished in a confined sand and gravel unit 163 and 180 ft deep, respectively. These well records suggest that there are two confined sand and gravel aquifers in most places in the eastern part of the trough but probably only one deep confined aquifer in the western part. Two of the deep wells in the western part of the trough (TM1503 and TM1309) were finished in sandy deposits. In the eastern part of the trough, well TM1532 (fig. 13) was drilled to a depth of 95 ft and had the largest reported yield (greater than 50 gal/min) for a domestic well in the study area.

The farthest north in the trough that domestic wells tap the upper confined sand and gravel aquifer is near German Crossroad (figs. 11 and 13). From German Crossroad to the north, Sixmile Creek and other streams have removed large amounts of the upper unconsolidated deposits, some of which

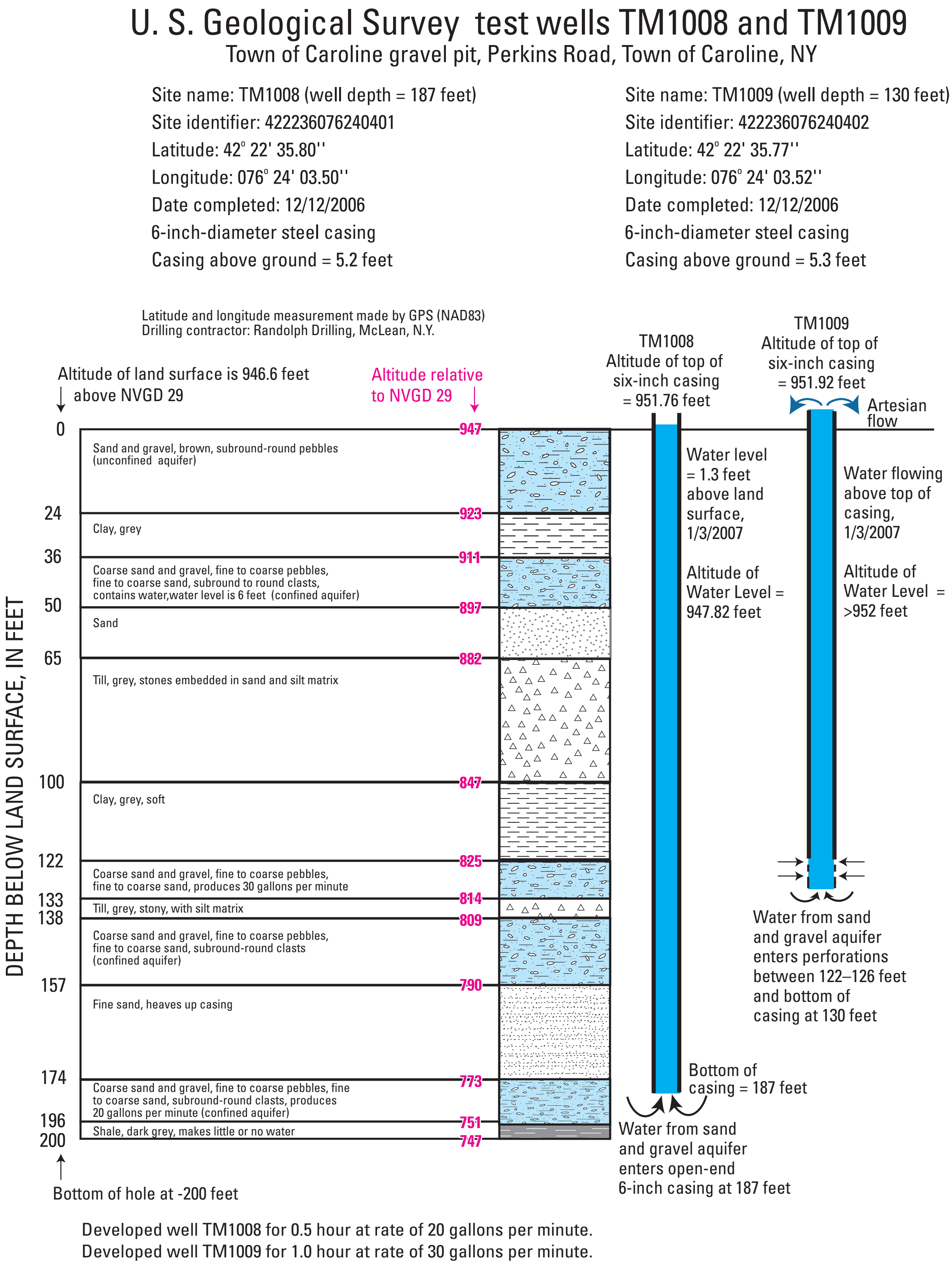


Figure 15. Well log and construction details of USGS test wells TM1008 and TM1009, Perkins Road, Town of Caroline, New York.

may have included aquifer material (figs. 10 and 11). Wells TM1002 and TM 62 (88 and 172 ft deep, respectively) are finished in the basal confined aquifer on top of the inner glacial U-shaped trough (fig. 10). A buried bedrock gorge (likely an extension of the interglacial “600 ft buried gorge”) was detected using seismic-refraction surveys in the central part of the trough (fig. 10).

North of the Silt Dam, Near Burns Road (fig.13), Sixmile Creek has incised through all of the valley fill and is at or near bedrock that forms the bottom of the inner glacial trough except in areas where the “600 ft buried gorge” underlies the trough north of the Silt Dam (fig. 11). From this area and to the north, Sixmile Creek and some major tributaries have fully penetrated the valley fill and sand and gravel aquifers that are exposed in the remaining bluffs, allowing groundwater to discharge from the aquifers. These exposed sand and gravel aquifers may not be viable as a year-round water resource because they may be marginally, or only seasonally, saturated.

North of the Silt Dam and underlying the Ithaca Reservoir the only major sand and gravel aquifer remaining is within the interglacial “600 ft buried gorge”. North of the northern end of Ithaca Reservoir, Sixmile Creek has reentered the interglacial “600 ft buried gorge” and has eroded most of the unconsolidated deposits that previously filled the gorge. Presently (2010) the stream is restricted by the bedrock floor and walls of the gorge. The absence of all unconsolidated deposits from the gorge just downstream from the Ithaca Reservoir marks the northern boundary of the sand and gravel aquifers in the trough (figs. 4 and 14).

Bedrock Aquifers

While the focus of this study is not on water derived from bedrock, bedrock aquifers are important water sources in the region because they underlie the entire area. Yields available from individual wells completed in bedrock are generally much less than yields from wells in sand and gravel. In most cases, bedrock aquifers are the only source of water in the uplands. The lower Sixmile Creek Basin is underlain by Devonian-age sedimentary rocks consisting mostly of shales and siltstones. Water movement is controlled by secondary permeability in the joints or fractures in the rock and typically predominates along bedding planes in sedimentary bedrock. The density, width of opening, and connectivity of water-bearing fractures decrease with depth due to the diminishing effects of weathering and the increasing weight of overlying rock with increasing depth that result in fewer, less-open, and less-connected fractures. Therefore, most water that is available to wells is generally in the upper 200 ft of bedrock; however, there is indication that, in some areas, salty water is present in the bedrock (TM2717, appendix 1). Therefore, water from the bedrock may not be potable in certain places. In the lower Sixmile Creek and Willseyville Creek Basins, well yields typically range from 2 to 5 gal/min, but in some wells yields are less than 1 gal/min and others yield up to 30 gal/min.

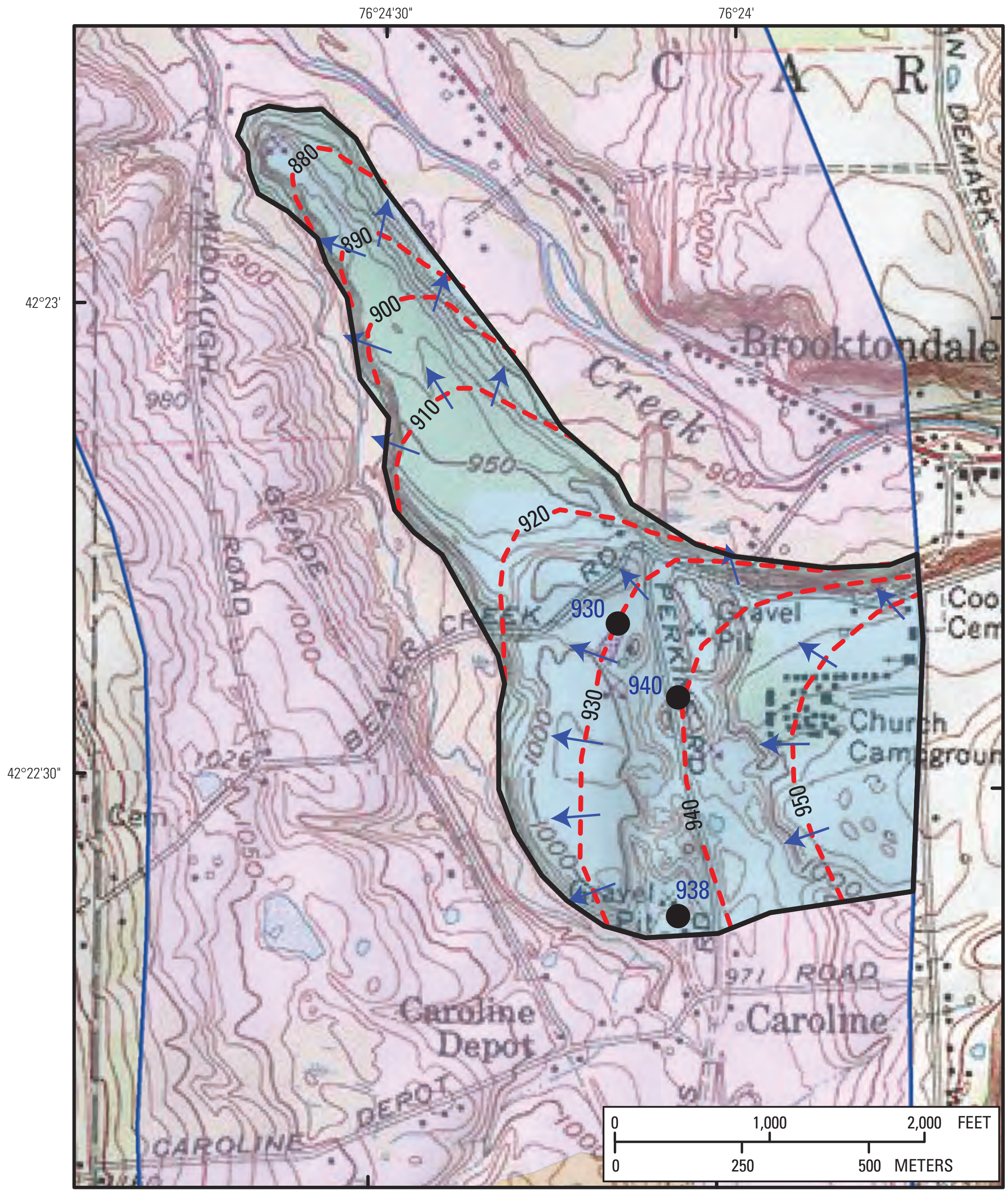
Groundwater Levels and Flowpaths

Natural changes in aquifer storage, exhibited by fluctuations in groundwater levels, generally follow seasonal patterns in the study area. Changes in aquifer storage between any two points in time are calculated as the difference in water levels between the two times multiplied by the storage coefficient. For unconfined aquifers, gravity drainage and filling of pores is the dominant mechanism for storage change, and generally the storage coefficient (specific yield) ranges from about 0.02 for fine-grained sediments to 0.35 for very coarse-grained sediments (Freeze and Cherry, 1979). Storage changes for confined aquifers are dominated by water and sediment compression and expansion, and storage coefficient values are much less. Storage coefficients reported for confined stratified-drift aquifers in the glaciated Northeast range from 10^{-2} to 10^{-4} (Kontis and others, 2004; Crain, 1966; and Randall, 1979). Values of storage coefficient are best determined with aquifer tests that affect a fairly large part of the aquifer.

Changes in storage in an aquifer include short, relatively well-defined periods of increased storage in the spring and late fall, when recharge to the aquifer exceeds discharge from the aquifer, and longer periods of decreased storage in the summer and winter, when discharge generally exceeds recharge. Also, a regional drought that reduces recharge over a large area over multiple seasons can result in reduced storage and yield from sand and gravel aquifers.

A generalized depiction of the water table in the unconfined aquifer (Brooktondale delta) is shown in figure 16 and was constructed using water-level measurements made during this investigation from 2005 to 2007 and from locations of springs at the lower flanks of bluffs along the north and west margins of the delta. Groundwater flows roughly perpendicular to water-table contours in unconfined aquifers or to potentiometric-surface contours in confined aquifers. Groundwater in the southern part of the unconfined aquifer flows to the west and discharges into Beaver Creek. Groundwater in the northern part of the unconfined aquifer flows to the northwest where some of the groundwater discharges to springs along the northern margin of the delta ending up in downstream reaches of Sixmile Creek while some groundwater discharges to springs along the western margin of the delta and flows into Beaver Creek.

Groundwater in the uppermost confined aquifer in the trough flows predominantly to the north from the surface-water divide that separates drainage that flows northward into the St. Lawrence River Basin and southward into the Susquehanna River Basin (fig. 17). Just north of the surface-water divide in the southern part of the study area, groundwater in the morainal deposits in the western side of the trough initially flows eastward from the west valley wall to the center of the valley where it changes course and flows northward (fig. 17). Direction of groundwater flow to the south of the surface-water divide is unknown because of lack of water-level data.



Base from U.S. Geological Survey, Seamless Data Distribution System, accessed in 2008 at http://seamless.usgs.gov/
Universal Transverse Mercator projection, Zone 18

EXPLANATION

Boundary of unconfined aquifer—Approximate boundary of the unconfined aquifer Brooktondale Delta area

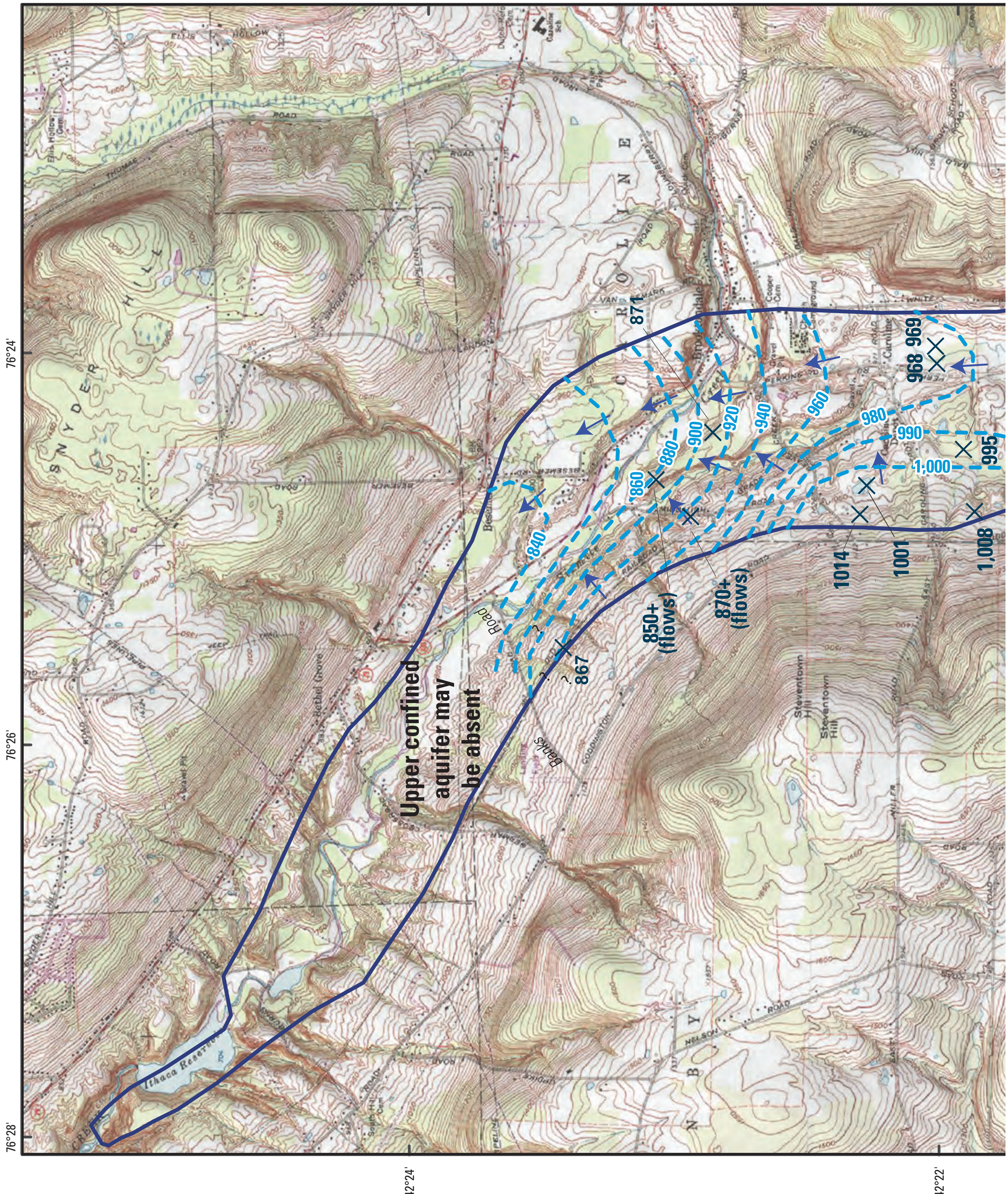
Boundary of confined aquifer—Approximate boundary of the confined aquifer

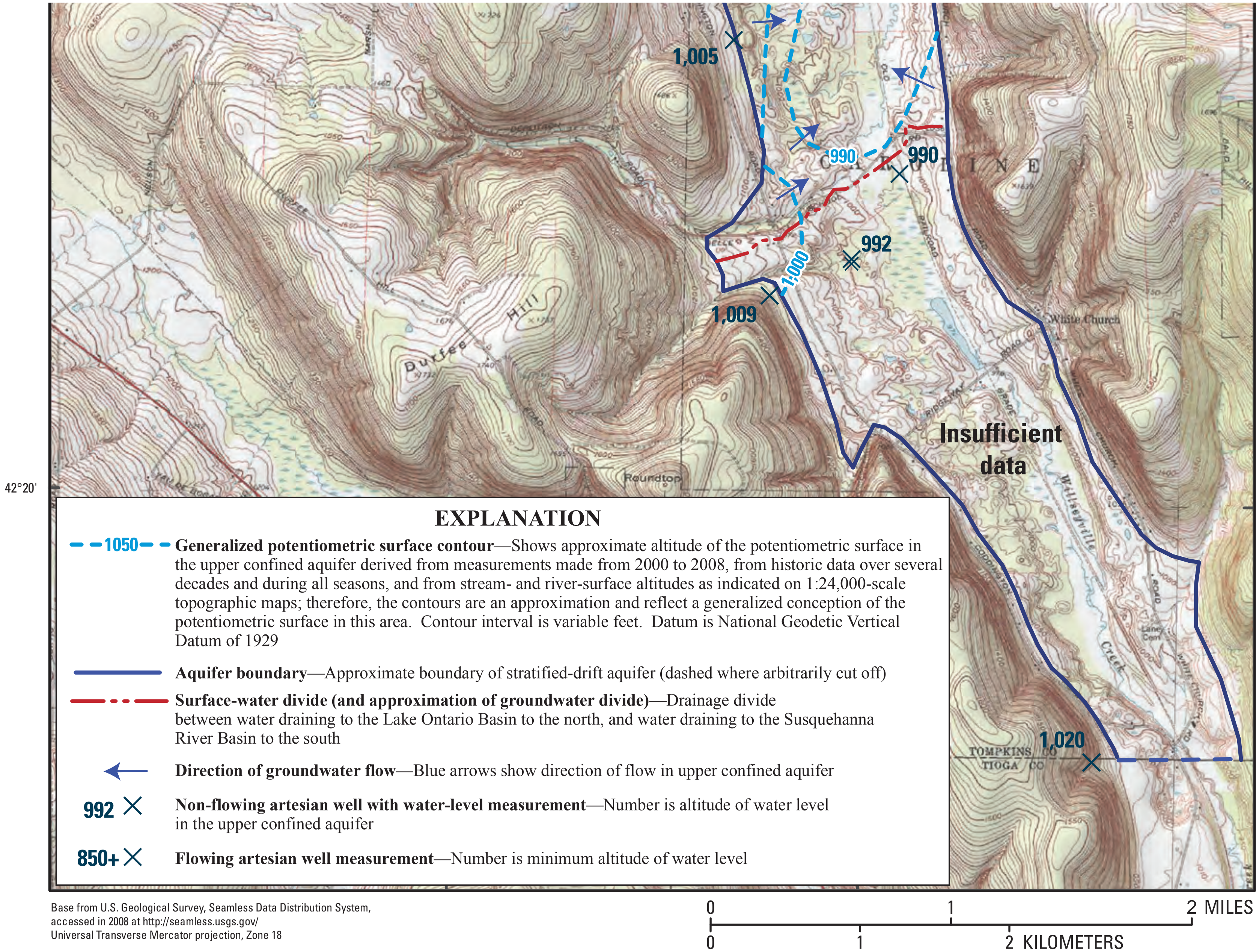
930 **Generalized water-table altitude**—Shows approximate altitude of the water level in the unconfined aquifer near Brooktondale derived from measurements made from 2005 to 2007, from historic data over several decades and during all seasons, and from stream- and river-surface altitudes as indicated on 1:24,000-scale topographic maps; therefore, the contours are an approximation and reflect a generalized conception of the water-table in this area. Contour interval 10 feet. Datum is National Geodetic Vertical Datum of 1929

Direction of groundwater flow—Blue arrows show direction of flow in unconfined aquifer

938 **Well with water-level measurement**—Blue number is altitude of water level in the unconfined aquifer

Figure 16. Water table in the unconfined aquifer (Brooktondale Delta) in lower Sixmile Creek and Willseyville Creek trough, Tompkins County, New York.


Upper confined aquifer may be absent
840
860
880
900
920
940
960
980
990
1,000
871
867
850+ (flows)
870+ (flows)
968
969
995
1014
1001
1,008
76°24'
76°26'
76°28'
42°24'
42°22'



Base from U.S. Geological Survey, Seamless Data Distribution System, accessed in 2008 at http://seamless.usgs.gov/
Universal Transverse Mercator projection, Zone 18

Figure 17. Potentiometric surface in the upper confined aquifer in lower Sixmile Creek and Willseyville Creek trough, Tompkins County, New York.

The groundwater in the uppermost confined aquifer is artesian in most places and flowing artesian in some low areas in the trough. However, in some places along the margins of the trough walls where the confined aquifer and the associated confining unit lap up higher on the valley walls, the water level is below the bottom of the confining unit (till), and a small portion of the aquifer is unconfined. In areas above altitude of 1,050 ft, such as along the margins of the trough, the depth to water in wells finished in the upper confined aquifer is as much as 95 ft below land surface. In low-lying areas, the depth to water is either only several feet below land surface or above land surface (flowing artesian conditions). North of Banks Road (fig. 17), the uppermost confined aquifer, which is composed of kame deposits of the Valley Heads Moraine, is absent because these deposits pinch out.

Groundwater-flow patterns in the basal confined aquifer are similar to those in the uppermost confined aquifer although water levels in some areas can differ greatly. Groundwater in the basal confined aquifer flows predominantly northward from the surface-water divide (fig. 18). Just north of the surface-water divide, groundwater in the morainal deposits on the western side of the trough initially flows eastward from the west valley wall to the center of the valley turning northward in the central part of the aquifer and northwestward in the northern part of the aquifer (fig. 18). Groundwater eventually discharges to lower Sixmile Creek and to the Ithaca Reservoir near the northern terminus of the basal confined aquifer (fig. 18).

Most wells in the basal confined aquifer in low-lying areas are under flowing-artesian conditions with hydraulic heads 10 to 40 ft above land surface, such as well TM1002. However, wells in areas that are located 50 to 100 ft above the floodplain, such as on terraces and kames along the trough walls, have heads that are below land surface and do not flow, for example well TM2367. The existence of a basal confined aquifer in the Willseyville Creek part of the trough is unverifiable because of a lack of detailed well data; however, it is likely that one exists based on the fact that basal aquifers that extend throughout entire valleys are common in other major troughs in central New York.

In some areas, multiple confined aquifers are present in the trough, such as at the Town of Caroline sand and gravel pit about 0.5 mi west of Brooktondale (fig. 9). At the bottom of the pit, a nested pair of test wells were drilled (fig. 13). Well TM1008 (well depth 187 ft) was finished in the basal confined aquifer and well TM1009 (well depth 130 ft) was finished in one of the intermediate-depth, confined sand and gravel aquifers (figs. 9 and 15). Bedrock was penetrated at 196 ft. Water levels were measured in the wells from January 1, 2007, to February 11, 2009, to determine the head relations between the two aquifers units (fig. 19). Heads were found to be consistently 4 to 5 ft higher in well TM1009 (finished in a shallower confined aquifer) than in well TM1008 (finished in a deeper confined aquifer), which indicates that the vertical component of the hydraulic gradient is downward in this area. Heads in both wells were above land surface in the bottom of the sand and gravel pit in which they were drilled.The similar water-level trends and consistent magnitude of head changes between the two aquifers, shown in the hydrograph in figure 19, suggest that the aquifers may have the same recharge area and are somewhat hydraulically connected.

Sources of Recharge

The amount of recharge to stratified-drift aquifers is a key determinant of the long-term availability of water. More recharge is available to unconfined aquifers than to confined aquifers. In general, there are a number of sources of recharge to stratified-drift aquifers (fig. 20). Four principal sources are: (1) direct infiltration of precipitation (rain and snow melt) where the aquifer crops out at land surface, (2) surface runoff and subsurface flow from adjacent unchanneled upland areas, (3) leakage from tributary streams where flow is over an unconfined aquifer, and (4) upward leakage from the bedrock and leakage from adjacent fine-grained confining units, especially during pumping. Sources of recharge to the aquifers in the lower Sixmile Creek and Willseyville Creek trough vary from place to place, and in some areas they are unknown as a result of the complex geohydrologic conditions present in the study area.Three distinct hydrologic settings that receive recharge are present in the study area (fig. 20)—the isolated basal aquifer, the unconfined delta and confined aquifers, and confined aquifers, which correspond to the northern, central, and southern parts of the trough respectively.

Unconfined Aquifers

The major sources of recharge to the unconfined aquifers (Brooktondale Delta in the central part and the headwater aquifer at the crest of the Valley Heads Moraine in the southern part of the study area) in the lower Sixmile Creek and Willseyville Creek trough are (1) direct infiltration of precipitation where water moves predominantly in a downward direction through the unsaturated zone toward the water table and (2) unchanneled surface runoff and subsurface inflow from adjacent upland areas that seep into the aquifer along the trough walls (figs. 20B and 20C). Over areas of sand and gravel, runoff is generally negligible so that all precipitation that is not lost to evapotranspiration recharges the unconfined aquifer. Unchanneled upland runoff typically contributes about 18 to 23 percent of the total recharge to unconfined stratified-drift aquifers in central New York (Miller and others, 1998; Kontis and others, 2004; Miller and others, 2008). Seepage losses from upland tributary streams comprise a relatively small amount of recharge to the aquifers in this study area because (1) the area of unconfined aquifers is small (most of the major aquifers are confined), (2) no streams cross the Brooktondale Delta (an unconfined aquifer), and (3) the area where confined aquifers crop out at land surface along the trough walls is relatively small.

Confined Aquifers

The major sources of recharge to the confined aquifers in the southern part of the study area are (1) direct infiltration of precipitation where confined aquifers crop out at land surface—mostly along the west trough wall and to a lesser degree along the east trough wall; (2) unchanneled surface and subsurface runoff from adjacent upland areas that seeps into the aquifer along the west trough walls; (3) subsurface inflow from underlying till or bedrock at the lateral contacts at trough walls, (4) adjacent fine-grained stratified drift, especially when the aquifer is pumped; and (5) bedrock at the bottom of the trough (fig. 20C).

Wells finished in the kame moraine along the western margin of the trough in the central part of the stratified-drift aquifer area have water levels several tens of feet higher in altitude than wells finished in the confined aquifers in the middle of the trough. This hydraulic-head relation is consistent with the concept that recharge from unchanneled runoff from adjacent hillsides and smaller amounts from precipitation and discharge from streams is entering the aquifers along the west trough wall (figs. 17 and 18). Due to relatively small amounts of kame moraine deposits along the eastern part of the trough (fig. 5), there is less recharge from that side of the trough. Little or no recharge from surface sources occurs in the middle of the trough because fine-grained deposits (till and lacustrine fine sand, silt, and clay) crop out at, or near, land surface, impeding movement of water into the confined aquifers (fig. 20C).

In the northern part of the study area (fig. 4), the basal confined aquifer is completely surrounded by confining units and is isolated (fig. 20A) from major sources of recharge such as (1) precipitation that falls directly over the valley, (2) streams flowing across the valley, and (3) runoff from adjacent hillsides. Therefore, the amount of recharge to the confined aquifer in this area is relatively small. In general, relatively little recharge may occur through subsurface flow from the bedrock and from overlying fine-grained sediments (fig. 20A).

The hydrograph depicted in figure 19 shows the period when the confined aquifers in the central part of the study are recharged. The recharge period (when groundwater storage in the aquifer is increasing) is represented when groundwater levels are rising, which occurs mostly during late fall, winter, and early spring, particularly just before and just after the growing season (fig. 19). Little recharge occurs during the growing season from late spring to early fall when the rate of evapotranspiration typically exceeds the rate of precipitation.

Groundwater Discharge

In the northern and central extents of the stratified-drift aquifer (fig. 4), most groundwater ultimately discharges into lower Sixmile Creek. Lesser amounts of groundwater discharge to pumping wells. Transpiration limits recharge when water vapor escapes from living vegetation back into the atmosphere, and in some cases even induces discharge directly from the aquifer where roots extend below the water table mostly during the spring when the ground can be saturated and close to, or at, land surface. In the southeastern part of Tompkins County, evapotranspiration is estimated to range between 19 to 20 inches per year or roughly half of the annual precipitation in this area (Kontis and others, 2004, plate 1). Due to lack of well and water-level data in the southern part of the study area, the groundwater flow patterns and location of groundwater discharge are unknown.

Unconfined Aquifer at the Brooktondale Delta

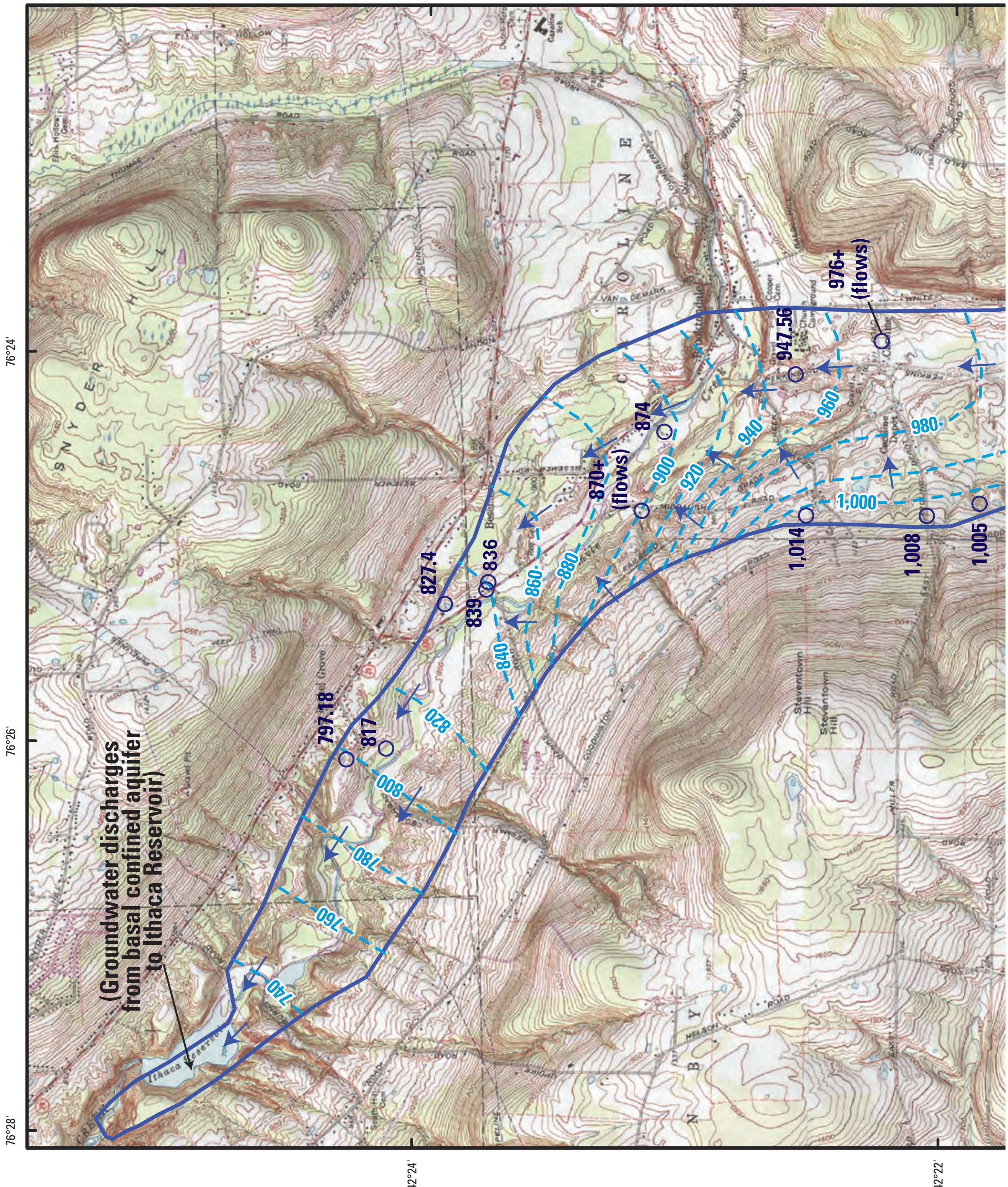
Most of the recharge from precipitation directly over the delta and from runoff from adjacent hillsides on the east side of the trough enters the unconfined aquifer at the Brooktondale Delta and flows westward and northwestward discharging at springs along the western and northern edges of the delta (fig. 16). Groundwater in the southern part of the deltaic aquifer flows to the west and discharges into Beaver Creek. Groundwater in the northern part of the deltaic aquifer flows to the northwest where some of the groundwater discharges via springs along the northern margin of the delta to Sixmile Creek, and some discharges to springs along the western margin of the delta and then to Beaver Creek. Groundwater also discharges to ponds that have been created where gravel mining has extended below the water table. Groundwater is also withdrawn for washing the aggregate at the gravel pits, but there is little consumptive loss of water because most of the water is allowed to return to the aquifer.

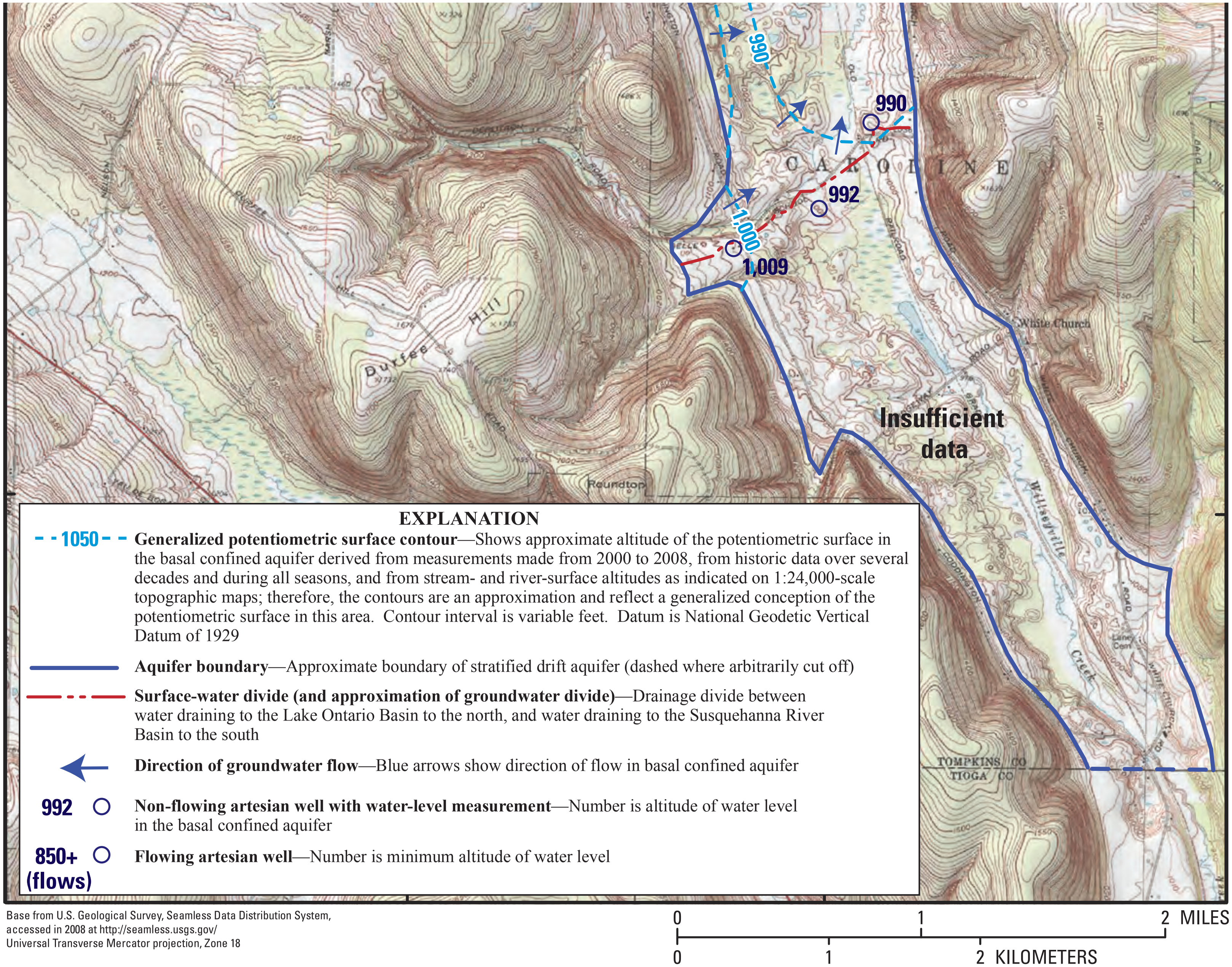
Confined Aquifers

In the northern and central extents of the stratified-drift aquifer of the study area, groundwater in the confined aquifers discharges mostly to Sixmile Creek, to the Ithaca Reservoir, and to pumped wells. Since the confined aquifers are at depths greater than 10 ft below land surface, there is negligible loss through evapotranspiration.

Groundwater in the basal confined aquifer flows predominantly north and northwestward and discharges to Sixmile Creek and to the Ithaca Reservoir. At the Ithaca Reservoir, Sixmile Creek has down cut and removed the layer that confines the basal aquifer, allowing water from the basal aquifer to discharge directly into Sixmile Creek and the Ithaca Reservoir. North of the Ithaca Reservoir, Sixmile Creek has fully penetrated the valley-fill in both the U-shaped valley and in the interglacial gorge (fig. 12) and the aquifer is absent.

Groundwater in the upper confined aquifer also discharges to Sixmile Creek. The northern extent of the upper confined aquifer ends near Banks Road (fig. 17) where the aquifer pinches out at depth or where it has been penetrated by Sixmile Creek.


(Groundwater discharges from basal confined aquifer to Ithaca Reservoir)
740
760
780
800
820
840
860
880
900
920
940
960
980
1,000
797.18
817
827.4
836
839
870+ (flows)
874
947.56
976+ (flows)
1,014
1,008
1,005
76°24'
76°26'
76°28'
42°24'
42°22'



Base from U.S. Geological Survey, Seamless Data Distribution System, accessed in 2008 at http://seamless.usgs.gov/
Universal Transverse Mercator projection, Zone 18

Figure 18. Potentiometric surface in the basal confined aquifer in lower Sixmile Creek and Willseyville Creek trough, Tompkins County, New York.

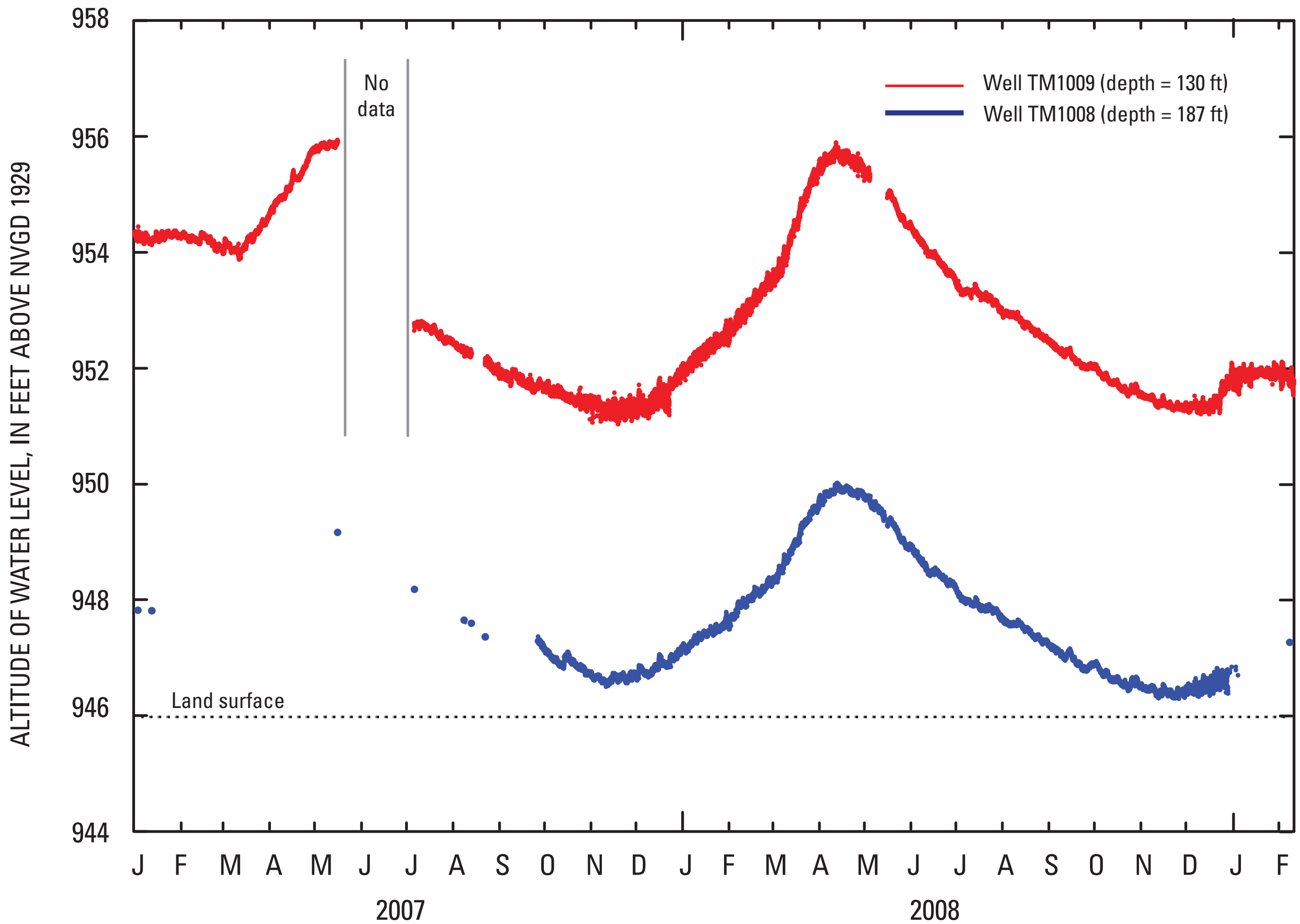


Figure 19. Hydrograph showing altitude of groundwater levels from January 1, 2007 to February 11, 2009 in test wells TM1008 and TM1009 at Town of Caroline sand and gravel pit, Perkins Road, Brooktondale, New York.

The base-flow and storm-runoff components (fig. 21) of total streamflow at Sixmile Creek at Brooktondale streamgage station (upper Sixmile Creek Basin) and at Sixmile Creek at Bethel Grove streamgage station (lower Sixmile Creek Basin,) (fig. 3) were calculated by using a hydrograph-separation, computer program HYSEP (Sloto and Crouse, 1996) and continuous discharge data for 2003–07. HYSEP calculates base flow as a percentage of total mean annual flow. The two Sixmile Creek streamgage stations meet the recommended requirements for using the HYSEP program because they are not regulated by dams or flood-control reservoirs upstream, which could cause a decrease in stormflow and an increase in base flow after a storm. These streamflow records span a relatively short period (5 years); therefore, the accuracy of these estimates is not as great as would be with at least 30 years of record.

Results of the hydrograph-separation analyses for 2003–07 indicate that base flow constitutes about 64 and 56 percent of total annual discharge at Sixmile Creek at Brooktondale and Sixmile Creek at Bethel Grove, respectively (fig. 21). The results of the hydrograph-separation analyses indicate that the flow past Brooktondale has a greater component that is base flow (groundwater) than at Bethel Grove, which suggests that greater amounts of groundwater discharge to streams from aquifers in the upper Sixmile Creek valley than in the lower Sixmile Creek valley.

The greater percentage of base flow in the upper part compared to the lower part of Sixmile Creek Basin is due to several factors. First, at the Brooktondale streamgage station, the stream has eroded and fully penetrated the valley fill deposits, including the aquifers, resulting in little or no groundwater underflow past the streamgage because the groundwater in the stratified-drift deposits is forced to discharge to the stream at this point. At the Bethel Grove streamgage station, the stream has only partially penetrated the stratified-drift deposits, allowing a significant portion of the groundwater to flow beneath the streamgage station as underflow mostly through the basal confined aquifer and

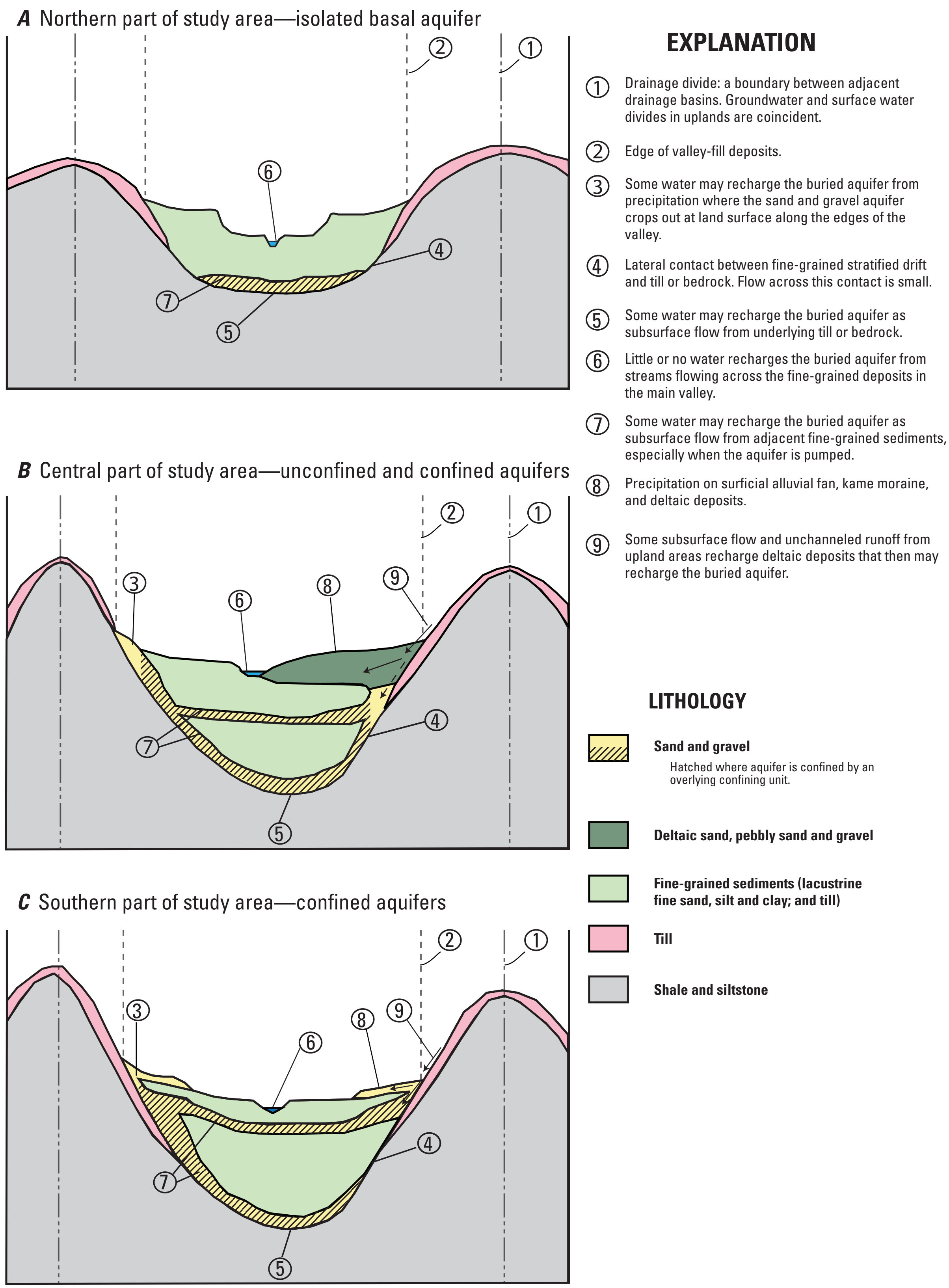


Figure 20. Sources of recharge in aquifers *A,* the northern part of the lower Sixmile Creek and Willseyville Creek trough, *B,* the central part, and *C,* the southern part, Tompkins County, New York.

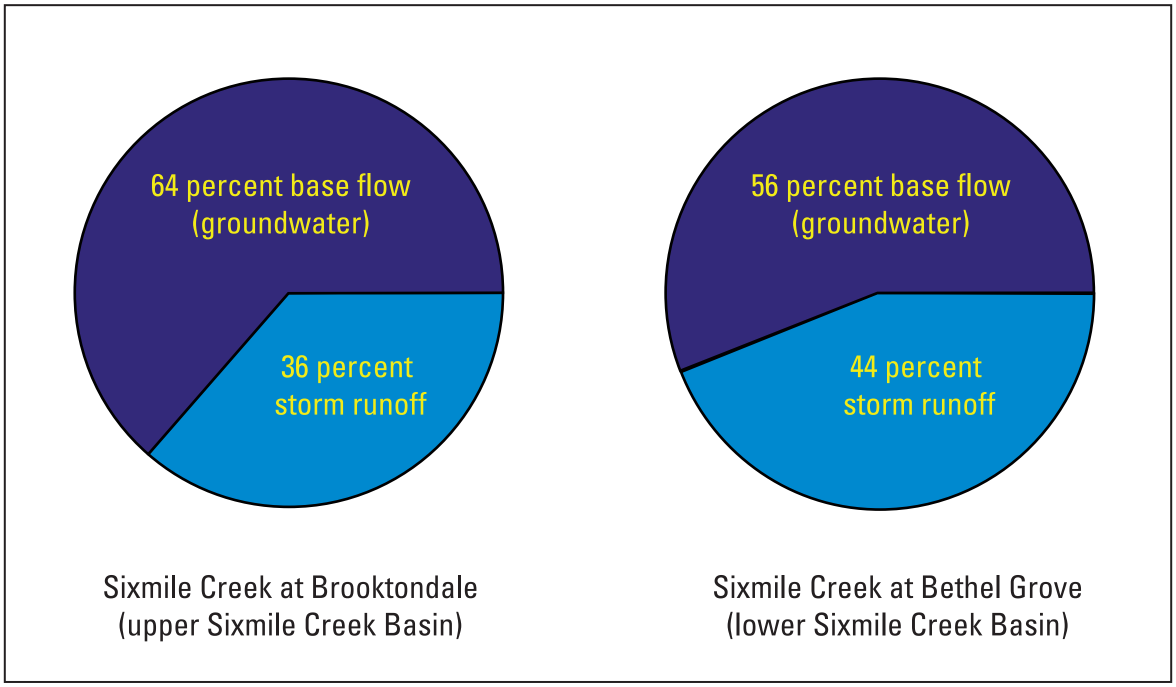


Figure 21. Graphs showing results of hydrograph separation analyses for Sixmile Creek at Brooktondale (upper Sixmile Creek Basin) and Sixmile Creek at Bethel Grove streamgages (lower Sixmile Creek Basin) for the period 2002–07. Locations of streamgages are shown in figure 3.

to enter the stream further down valley where the channel has fully penetrated the stratified-drift deposits and flows on bedrock in the "600 ft gorge." Second, the volume of surficial sand and gravel is greater in upper Sixmile Creek Basin than in lower Sixmile Creek Basin, allowing more groundwater to be transmitted through the aquifers to the stream in the upper part of the basin. Because the presence of surficial sand and gravel deposits reduces rapid runoff, precipitation is stored as groundwater that is gradually released to streams. In valleys with relatively large amounts of surficial sand and gravel, there is proportionally more infiltration of precipitation and storage capacity; therefore, more groundwater discharges to streams than in valleys that contain mostly till and lacustrine deposits, which have poor infiltration capacity and rapid runoff.

Pumping Withdrawals

Most groundwater withdrawals from confined sand and gravel aquifers in the lower Sixmile Creek and Willseyville Creek trough are from open-ended, 6-inch (in.) diameter domestic wells, with other minor amounts from farm and commercial wells that tap the confined aquifers. No large municipal pumping wells are in the study area. Some groundwater is withdrawn seasonally from the unconfined aquifer (Brooktondale Delta) by an aggregate-mining operation for washing purposes. Domestic water use is water used for indoor and outdoor household purposes. In lower Sixmile Creek and Willseyville Creek trough an estimated 600 people rely solely on groundwater from the stratified-drift aquifer system. Homeowner wells that were just within the areal extent of the aquifer's boundaries, but were finished in bedrock, were not included as users of the sand and gravel aquifers. Additionally, water is used by non-permanent residents such as staff at commercial facilities. The estimated total groundwater use for human consumption is estimated to be about 45,000 gal/d or 0.07 cubic feet per second (ft^3/s) based on an average water use of 75 gal/d per person for self-supplied water systems in New York (Hutson and others, 2000, table 6) times the estimated 600 people that pump from the stratified-drift aquifers. However, unknown quantities of water are also withdrawn from wells in the stratified-drift aquifers from (1) several small crop farms, (2) an unknown number of flowing artesian wells that continually discharge water from the aquifer, and (3) about six small commercial facilities.

Groundwater Quality

Because all drinking water is derived solely from the confined aquifers, water-quality samples were collected only from those wells. Water samples were collected from six wells — two test wells (TM1008 and TM1009) and four private residential wells (TM1002, TM1503, TM1532, and TM2355) from December 2006 through August 2007 to characterize the chemical quality of groundwater. Field measurements were made for pH, specific conductance, and water temperature. The concentrations of 42 constituents that included nutrients, major inorganic ions, and trace elements were determined by the USGS National Water Quality Laboratory (NWQL) in Denver, Colorado. Wells that were sampled are shown in figure 13. Analytical results for selected constituents are compared with Federal drinking-water standards. The standards include Maximum Contaminant Levels (MCLs), Secondary Maximum Contaminant Levels (SMCLs), and Health Advisories (HAs) established by the USEPA (2006).

Physical Properties

Wells that were sampled ranged from 88 to 197 ft deep. The pH of the samples (table 2) ranged from 7.6 to 8.1; no pH measurement was outside the accepted SMCL range of 6.5 to 8.5. Specific conductances of the samples ranged from 291 to 492 microsiemens per centimeter (µS/cm) (table 2).

Major Inorganic Ions

The cation that was detected in the greatest concentration was calcium, ranging from 30.5 to 63.6 mg/L (table 2). Sodium values ranged from 9.47 to 28.8 mg/L. No samples exceeded the USEPA Drinking Water Health Advisory (HA) for sodium, which recommends sodium concentrations in drinking water do not exceed 60 mg/L on the basis of taste. This health advisory is intended as a guideline for users. Silica values ranged from 7.46 to 13.2 mg/L. Calcium and magnesium contribute to water hardness and one of the six sampled wells yielded water with a hardness greater than 180 mg/L, which is classified as “very hard” (Hem, 1985).

The anion that was detected in the greatest concentration was bicarbonate, while chloride and sulfate were detected in generally lesser concentrations. Bicarbonate (as $CaCO_3$) ranged from 173 to 199 mg/L (table 2). Bicarbonate values were calculated from the alkalinity concentrations, which are given in milligrams per liter of $CaCO_3$. Chloride values ranged from 0.67 to 35.6 mg/L, not exceeding the SMCL of 250 mg/L (table 3). Sulfate values ranged from 8.08 to 47.1 mg/L and did not exceed the SMCL of 250 mg/L.

Nutrients

Groundwater samples were analyzed for several nitrogen and phosphorous species (table 2). Ammonia concentrations ranged from 0.019 to 0.377 mg/L as nitrogen (N). Organic nitrogen concentrations were negligible in four samples, but in two samples (TM1008 and TM1009) the organic nitrogen concentrations were more than 50 percent of the reduced nitrogen. Nitrate was not detected in any of the samples above the detection limit of 0.06 mg/L. Confined aquifers are less susceptible to contamination than unconfined aquifers because confining units prevent chemicals that are applied on the land surface from easily infiltrating through the confining material and into the confined aquifers. Nitrite was not detected in five of the six samples and was negligible in only one. Orthophosphate was detected in five of the six samples, but concentrations were typically low; the maximum concentration was 0.031 mg/L (as phosphorus).

Trace Elements

The most commonly detected trace elements were aluminum, arsenic, barium, boron, iron, lithium, manganese, nickel, molybdenum, uranium, zinc, and strontium, all of which were detected in every sample (table 3). The trace elements detected in the greatest concentrations were barium, boron, iron, lithium, manganese, and strontium. Aluminum concentrations ranged from 0.9 to 95.5 µg/L; one sample (TM1532) exceeded the SMCL (50 µg/L). Arsenic concentrations ranged from 1.3 to 20.4 µg/L; two samples (TM1002 and TM1532) exceeded the MCL for arsenic of 10 µg/L. Barium concentrations ranged from 120 to 408 µg/L, but the MCL for barium (2,000 µg/L) was not exceeded. Boron concentrations ranged from 9 to 174 µg/L; MCLs have not been established for boron. Iron concentrations ranged from 165 to 528 µg/L; two samples (TM1503 and TM2355) exceeded the SMCL for iron (300 µg/L). Lead was detected in two samples, but neither sample exceeded the MCL (15 µg/L). Lithium concentrations ranged from 4.7 to 53.5 µg/L; MCLs have not been established for lithium. Manganese concentrations ranged from 58.0 to 93.2 µg/L; the Federal SMCL for manganese (50 µg/L) was exceeded in all six samples, but the New York State MCL (300 µg/L) was not exceeded in any sample. Strontium concentrations ranged from 122 to 567 µg/L, but no MCLs have been established for strontium. Uranium concentrations ranged from 0.05 to 1.75 µg/L; no samples exceeded the Federal MCL of 30 µg/L.

Table 2. Physical properties, concentrations of major inorganic ions, and concentratins of nutrients in groundwater samples from confined aquifers in the lower Sixmile Creek and Willseyville Creek trough, Tompkins County, New York, 2006-2007.

[S&G, sand and gravel; 72008, USGS National Water Information System (NWIS) parameter code; mg/L, milligrams per liter; ug/L, micrograms per liter; <, less than; - -, not analyzed. Sampling site locations are shown in figure 13.]

		USGS site name	**TM1008**	**TM1009**	**TM1002**	**TM1503**	**TM1532**	**TM2355**	
		Date sampled	**12/13/2006**	**12/13/2006**	**12/20/2006**	**12/20/2006**	**12/20/2006**	**8/16/2007**	
		Well identification number	**422236 076240401**	**422236 076240402**	**422407 076260101**	**422315 076244401**	**422318 076243801**	**422345 076251101**	
		Aquifer type	**S&G, basal confined**	**S&G, basal confined**	**S&G, intermediate confined**	**S&G, basal confined**	**S&G, upper confined**	**S&G, basal confined**	
Physical properties	Parameter code	Units	Values of physical properties						Drinking water standard
Well depth, below land surface	72008	ft	187	126	88	197	95	145	
pH (field)	00400	pH	8.0	7.8	7.7	8.1	8.1	7.6	
Specific conductance (field)	00095	uS/cm	318	492	266	291	335	339	
Water Temperature	00010	°C	9.8	9.8	9.5	8.0	13.0	19.4	
Major Inorganic Ions			Concentration of chemical constituents						
Hardness, filtered, as $CaCO_3$	00900	mg/L	139	222	124	126	113	152	
Calcium, filtered	00915	mg/L	41	63.6	36.3	34.4	30.5	42.7	
Magnesium, filtered	00925	mg/L	8.63	14.8	7.84	9.44	8.71	10.7	
Potassium, filtered	00935	mg/L	0.66	0.88	0.74	0.67	0.74	0.83	
Sodium, filtered	00930	mg/L	9.47	10.5	11.1	13.7	28.8	13.3	60[a]
Alkalinity, filtered, as $CaCO_3$, (lab)	29801	mg/L	146	142	143	145	145	163	250[c]
Bicarbonate, filtered, as $CaCO_3$	29805	mg/L	178	173	174	177	177	199	
Chlorides, filtered	00940	mg/L	8.77	35.6	0.67	1.56	13.8	2.1	
Fluoride, filtered	00950	mg/L	0.17	0.09	0.31	0.39	0.71	0.29	2.2[b]
Silica, filtered	00955	mg/L	10.2	7.46	12.8	11.9	11.3	13.2	
Sulfate, filtered	00945	mg/L	11.4	47.1	8.08	12.5	13.5	15.9	250[c]
Dissolved solids, at 180 °C	01056	mg/L	170	266	167	173	198	196	
Nutrients									
Ammonia, as N, filtered	00608	mg/L	0.067	0.019	0.224	0.256	0.377	0.151	
Nitrate, as N, NO_2+NO_3, filtered	00631	mg/L	<0.060	<0.060	<0.060	<0.060	<0.060	<0.060	10[b]
Nitrite, as N, filtered	00613	mg/L	<0.002	<0.002	<0.002	<0.002	0.001	<0.002	1[b]
Organic+ammonia, as N, filtered	00607	mg/L	0.2	0.1	0.3	0.3	0.5	0.2	

Table 2. Physical properties, concentrations of major inorganic ions, and concentratins of nutrients in groundwater samples from confined aquifers in the lower Sixmile Creek and Willseyville Creek trough, Tompkins County, New York, 2006-2007.

[S&G, sand and gravel; 72008, USGS National Water Information System (NWIS) parameter code; mg/L, milligrams per liter; ug/L, micrograms per liter; <, less than; - -, not analyzed. Sampling site locations are shown in figure 13.]

		USGS site name	**TM1008**	**TM1009**	**TM1002**	**TM1503**	**TM1532**	**TM2355**	
		Date sampled	**12/13/2006**	**12/13/2006**	**12/20/2006**	**12/20/2006**	**12/20/2006**	**8/16/2007**	
		Well identification number	**422236 076240401**	**422236 076240402**	**422407 076260101**	**422315 076244401**	**422318 076243801**	**422345 076251101**	
		Aquifer type	**S&G, basal confined**	**S&G, basal confined**	**S&G, intermediate confined**	**S&G, basal confined**	**S&G, upper confined**	**S&G, basal confined**	
Nutrients	Parameter code	Units	Concentration of chemical constituents						Drinking water standard
Organic+ammonia, as N, unfiltered	00605	mg/L	0.6	0.2	0.3	0.3	0.4	--	
Orthophosphate, as P, filtered	00671	mg/L	<0.006	0.003	0.031	0.011	0.011	0.031	
Phosphorus, filtered	00666	mg/L	<0.006	<.006	0.031	0.008	0.008	--	
Phosphorus, unfiltered	00665	mg/L	--	--	0.034	0.03	0.012	--	

[a] USEPA Drinking Water Advisory Taste Threshold.

[b] NYSDOH Maximum Contaminant Level.

[c] USEPA Secondary Drinking Water standard.

Table 3. Concentrations of trace metals in groundwater samples from confined aquifers in the lower Sixmile Creek and Willseyville Creek trough, Tompkins County, New York, 2006–2007.

[E, estimated; S&G, sand and gravel; 01106, USGS National Water Information System (NWIS) parameter code; mg/L, milligrams per liter; ug/L, micrograms per liter; <, less than; - -, not analyzed]. Sampling sites locations are shown in figure 13.]

		USGS site name	TM1008	TM1009	TM1002	TM1503	TM1532	TM2355		
		Date sampled	12/13/2006	12/13/2006	12/20/2006	12/20/2006	12/20/2006	8/16/2007		
		Well identification number	422236 076240401	422236 076240402	422407 076260101	422315 076244401	422318 076243801	422345 076251101		
		Aquifer type	S&G basal confined	S&G basal confined	S&G intermediate confined	S&G basal confined	S&G upper confined	S&G basal confined		
Trace metals	Parameter code (filtered)	Units	Concentrations of chemical constituents						Parameter code (unfiltered)	Drinking water standard
Well depth, below land surface		ft	187	126	88	197	95	145		
Aluminum, filtered	01106	ug/L	E1.1	E1.3	E0.9	2.5	95.5	33	01105	50[c]
Antimony, filtered	01095	ug/L	0.19	2.02	<0.06	<0.06	<0.06	<0.2	01097	6[a,b]
Arsenic, filtered	01000	ug/L	2.0	1.3	13.1	4.5	20.4	3.8	01002	10[a]
Barium, filtered	01005	ug/L	408	194	228	180	120	203	01007	2,000[a,b]
Beryllium, filtered	01010	ug/L	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	01012	4[a,b]
Boron, filtered	01020	ug/L	19	9	31	48	174	34	01020	
Cadmium, filtered	01025	ug/L	<0.04	E0.02	<0.04	<0.04	E0.03	E0.01	01027	5[a,b]
Chromium, filtered	01030	ug/L	<0.12	<0.12	<0.12	<0.12	<0.12	<0.60	01034	100[a,b]
Cobalt, filtered	01035	ug/L	0.07	0.60	<0.04	<0.04	0.06	E0.02	01037	
Copper, filtered	01040	ug/L	<0.40	<0.40	<0.40	<0.40	0.57	<1.2	01042	1,000[c]
Iron, filtered	01046	ug/L	296	192	255	528	165	316	01045	300[b,c]
Lead, filtered	01049	ug/L	<0.12	<0.12	<0.12	<0.12	0.35	1.14	01051	15[d]
Lithium, filtered	01130	ug/L	7.3	10.0	4.7	6.4	53.5	7.9	01132	
Manganese, filtered	01056	ug/L	93.2	77.5	61.7	58.0	93.2	63.4	01055	50[c]–300[b]
Molybdenum, filtered	01060	ug/L	2.4	1.3	4.3	5.5	19.5	3.5	01062	
Nickel, filtered	01065	ug/L	0.14	1.6	0.08	0.20	0.16	E0.11	01067	
Selenium, filtered	01145	ug/L	<0.08	0.38	<0.08	<0.08	<0.08	<0.08	01147	50[a,b]
Silver, filtered	01075	ug/L	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	01077	100[a,b]
Strontium, filtered	01080	ug/L	234	122	393	567	552	388	01082	
Thallium, filtered	01057	ug/L	<0.04	<0.04	<0.04	E0.02	<0.04	<0.18	01059	
Vanadium, filtered	01085	ug/L	E0.03	0.10	<0.04	<0.04	<0.08	--	--	
Uranium, natural, filtered	22703	ug/L	0.25	1.75	0.13	0.05	0.38	0.43	28011	30[a]
Zinc, filtered	01090	ug/L	1.1	0.67	0.68	1.3	1.9	E1.5	01092	5,000[b,c]

[a] USEPA Maximum Contaminant Level.

[b] NYSDOH Maximum Contaminant Level.

[c] USEPA Secondary Maximum Contaminant Level.

[d] USEPA Treatment Technique.

[e] USEPA Proposed Maximum Contaminant Level.

Comparison to Other Stratified-Drift Aquifers in Tompkins County

Calcium dominates the cation composition and bicarbonate dominates the anion composition in samples from this study area and most samples from the three other areas (fig. 22). The exceptions are two samples collected in Upper Buttermilk Creek and Danby Creek valleys and two samples collected in Upper Sixmile Creek and West Branch Owego Creek valleys, which were sodium bicarbonate-to-sodium chloride type waters (fig. 22). The chemistry of water from two wells in upper Sixmile Creek valley that were of a sodium bicarbonate-to-sodium chloride type water (fig. 22) was due to enrichment from brackish water in bedrock that locally discharges to the valley fill (Miller, 2009). One sample (TM1009) in this study area was a mix of calcium-bicarbonate and calcium-sulfate water (fig. 22). Similar water chemistry in stratified-drift aquifers in all four study areas is not surprising because the geologic settings of the areas are similar—Valley Heads drift and Devonian shales and siltstones.

Summary

In 2002, the U.S. Geological Survey, in cooperation with the Tompkins County Planning Department, began a series of studies of the stratified-drift aquifers in Tompkins County to provide geohydrologic data for planners to develop a strategy to manage and protect their water resources. This aquifer study, in lower Sixmile Creek and Willseyville Creek trough, is the second in that series of aquifer studies. This study area is within the northern area of the Appalachian Plateau and extends 9.7 mi from the boundary between Tompkins County and Tioga County in the south, northward to just south of the City of Ithaca. In lower Sixmile Creek and Willseyville Creek trough, the major aquifers are confined, but there also is at least one unconfined aquifer in the Brooktondale Delta area that is relatively unused.

Scouring of bedrock in the preglacial lower Sixmile Creek and Willseyville Creek valleys by glaciers and subglacial meltwaters has truncated hillside spurs, formed U-shaped transverse valley profiles, smoothed valley walls, and deepened the valleys by as much as 300 ft, forming a continuous trough, which was subsequently filled with unconsolidated deposits. The unconsolidated deposits in the study area consist mostly of glacial drift, both unstratified drift (till) and stratified drift (laminated lake, deltaic, and glaciofluvial sediments), as well as some post-glacial stratified sediments (lake-bottom sediments deposited in reservoirs, peat and muck deposited in wetlands, and alluvium deposited by streams). The multiple advance and retreat of the ice in the study area resulted in multiple sequences of various glacial deposits. A large moraine (Valley Heads Moraine) dominates the southern part of the study area; a large delta dominates the central part, and ground moraine (mostly till) dominates the northern part. Glacial sediments in the center of the trough typically range from 150 to 200 ft but can be greater than 300 ft in some places.

The surficial, coarse-grained sediments (sand and gravel) that comprise the delta near Brooktondale form a small unconfined aquifer (0.3 mi^2 in area) in the central part of the study area, which is relatively unused as a water supply. Much of the upper part of the delta has been removed by several aggregate mining operations, but there remain sufficient amounts of sand and gravel in most places to form a thin aquifer. The major sources of recharge to the unconfined aquifer are direct infiltration of precipitation where water moves predominantly in a downward direction through the unsaturated zone toward the water table and unchanneled surface and subsurface runoff from adjacent upland areas that seep into the aquifer along the trough walls.

In most parts of the study area, two confined aquifers are present—an upper confined and a basal confined. However, underlying the central part of the Brooktondale Delta, there are as many as four confined aquifers. The major sources of recharge to the confined aquifers are (1) direct infiltration of precipitation where the aquifers crop out at land surface, mostly along the west trough wall in the south and central parts of the study area, and to a lesser degree, along the east trough wall; (2) unchanneled surface and subsurface runoff from adjacent upland areas that seeps into the aquifer along the west trough walls; (3) subsurface flow from underlying till or bedrock at the lateral contacts between the aquifers and the trough walls; and (4) from bedrock adjacent to the aquifers in the bottom and sides of the trough.

Groundwater in the southern part of the deltaic aquifer flows to the west and discharges into Beaver Creek. Groundwater in the northern part of the deltaic aquifer flows to the northwest where some of the groundwater discharges to springs along the northern margin of the delta to Sixmile Creek, and some discharges to springs along the western margin of the delta and then to Beaver Creek. Groundwater also discharges to ponds that have been created where gravel mining extends below the water table.

Just north of a major surface-water divide in the southern part of the study area, groundwater in the confined aquifers on the west side of the trough initially flows eastward from the west valley wall to the center of the valley, changing course and flowing northward. The upper confined aquifer at the northern edge of the central area of the trough either pinches out at depth or has been penetrated by Sixmile Creek and is exposed beneath the floodplain where groundwater discharges into Sixmile Creek. Groundwater in the basal confined aquifer ultimately discharges into Sixmile Creek and to the Ithaca Reservoir in the northern part of the study area.

In lower Sixmile Creek and Willseyville Creek trough about 600 people rely on groundwater from the stratified-drift aquifer system. In addition, water is used by non-permanent residents such as staff at commercial facilities. The estimated total groundwater use for the estimated 600 persons withdrawing water from the stratified-drift aquifers for human

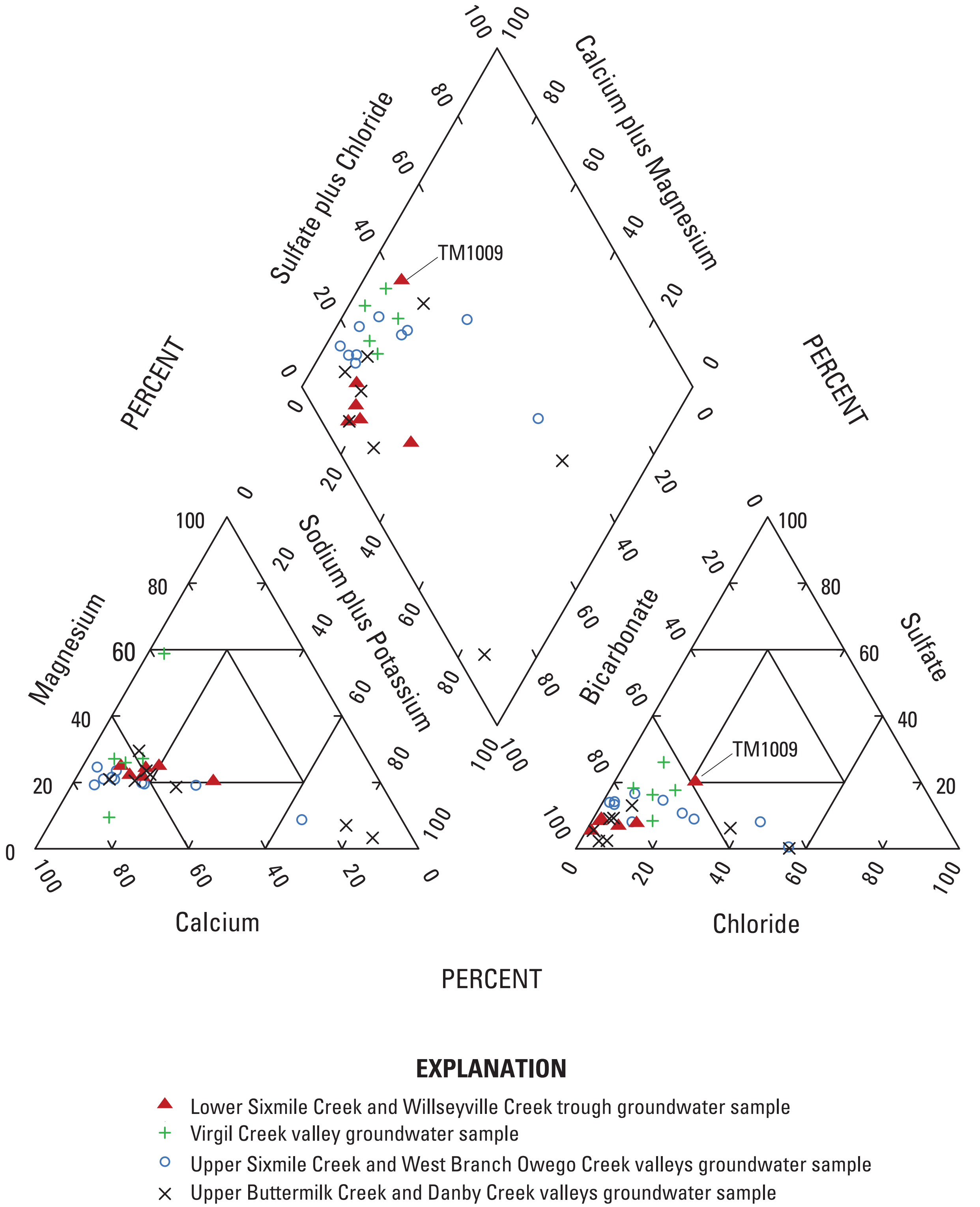


Figure 22. Piper diagram illustrating variability in major ion composition of groundwater in lower Sixmile Creek and Willseyville Creek trough, upper Sixmile Creek and West Branch Owego Creek valleys, Virgil Creek valley, and upper Buttermilk and Danby Creek valleys, Tompkins County, New York.

consumption is about 45,000 gal/d or 0.07 ft^3/s based on an average water use of 75 gal/d per person (for self-supplied water systems in New York) .

Water samples were collected from six wells (two test wells and four private residential wells) from December 2006 through August 2007 and analyzed to characterize the chemical quality of groundwater in the confined aquifers. Results indicate that groundwater used for human consumption is generally of acceptable quality, although concentrations of some constituents exceeded at least one drinking-water standard at three of the six wells.

Water in the sand-and-gravel aquifers is predominantly a calcium-bicarbonate type. The cation that was detected in the largest concentration was calcium, ranging from 30.5 to 63.6 mg/L. Sodium values ranged from 9.47 to 28.8 mg/L; no samples exceeded the USEPA Drinking Water Advisory for sodium. The anion that was detected in the greatest concentration was bicarbonate, while chloride and sulfate were detected in generally lesser concentrations. Bicarbonate values (as $CaCO_3$) ranged from 173 to 199 mg/L. Chloride values ranged from 0.67 to 35.6 mg/L and did not exceed the Secondary Maximum Contaminant Level of 250 mg/L. Sulfate values ranged from 8.08 to 47.1 mg/L and did not exceed the Secondary Maximum Contaminant Level of 250 mg/L. Nitrate was not detected in any of the samples above the detection limit of 0.06 mg/L. Nitrite was not detected in five of the six samples and was negligible in the other sample.

The most commonly detected trace elements were aluminum, arsenic, barium, boron, iron, lithium, manganese, nickel, and strontium, all of which were detected in every sample. The elements detected in the largest concentrations were barium, boron, iron, lithium, manganese, strontium, and uranium. Aluminum concentrations ranged from 0.9 to 95.5 µg/L; one sample exceeded the Secondary Maximum Contaminant Level of 50 µg/L. Arsenic concentrations ranged from 1.3 to 20.4 µg/L; two samples exceeded the USEPA Maximum Contaminant Level of 10 µg/L for arsenic.

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Appendix 1. Records of selected wells in lower Sixmile Creek and Willseyville Creek trough, Tompkins and Tioga Counties, New York.

[S&G, sand and gravel; --, no data; ft, feet; dia. (in), diameter in inches; gal/min, gallons per minute; gal/ft, gallons per foot; psi, pounds per square inch; do., ditto; >, greater than]

Well number	Date drilled	Well depth (ft)	Depth of casing (ft)	Casing diameter (in)	Altitude land surface (ft)	Aquifer type	Water level below land surface (ft)	Altitude water level (ft)	Date water level measured	Depth to bedrock (ft)	Altitude top of bedrock (ft)	Reported yield (gal/min)	Remarks
TM 21	1962	45	45	6	981	S&G	--	--	--	--	--	--	Owner reports well depth 40–50 ft.
TM 32	10/7/1980	77	--	--	988	S&G	15	968	10/7/1980	--	--	--	USGS test boring. 0–6 silt, 6–16 silt with pebbles (till?), 16–33 gravel, 33–53 silty gravel, 53–71 silty sand, 71–77 clay (laminated), 77–77.5 ft till?
TM 42	10/9/1980	73	--	--	986	S&G	9	986	10/9/1980	--	--	--	USGS test boring. 0–16 pebbly sandy silt (alluvium), 16–28 silt, 28–33 dirty gravel, 32–51 interlayered dirty gravel, sand, slit, and clay, 51–71 ft grey pebbly and clayey silt (till).
TM 50	1965	105	105	6	971	S&G (confined)	2	969	1965	--	--	--	Sulfur odor.
TM 51	1950	94	94	6	971	S&G (confined)	3	968	11/1/1965	--	--	--	Sulfur odor.
TM 58	1961	25	--	--	900	Till	--	--	--	--	--	--	Test boring. 0–6 S&G, 6–25 ft till.
TM 60	8/22/1966	101	29	5	935	Shale	Flows	--	8/22/1966	29	906	30	0–29 S&G, 29–101 ft shale.
TM 65	1958	146	146	6	868	S&G (confined)	Flows	--	--	--	--	--	Flows. Sulfur and iron.
TM 82	1965	104	44	6	990	Shale	24	966	11/1/1965	42	948	10	0–42 till, 42–104 ft shale.
TM 86	1965	206	28	6	1,130	Shale	40	1,090	11/1/1965	28	1,102	3	Bedrock at 28 ft.
TM 92	6/15/1957	172	172	5	920	S&G (confined)	--	--	--	--	--	--	--
TM 93	1964	150	15	6	970	Shale	--	--	--	15	955	--	--
TM 95	1951	167	60	6	900	Shale	--	--	--	60	840	--	--

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TM 102	1964	96	22	6	935	Shale	--	--	--	18	917	2	--
TM 103	1965	235	67	6	900	Shale	--	--	--	67	833	2	--
TM 544	--	163	163	6	917	S&G (confined)	--	--	--	--	--	--	--
TM 550	--	74	74	6	863	S&G (confined)	--	--	--	--	--	--	--
TM 551	--	70	70	6	865	S&G (confined)	--	--	--	--	--	--	--
TM 552	--	180	180	6	902	S&G (confined)	--	--	--	--	--	--	--
TM 555	--	100	28	6	1,046	Shale	--	--	--	28	1,018	--	--
TM 560	--	190	40	6	1,114	Shale	--	--	--	40	974	--	--
TM 567	4/15/1991	83	30	6	1,055	Shale	--	--	--	30	1,025	--	--
TM 588	--	97	97	6	1,061	S&G (confined)	Flows	>1,061		--	--	--	--
TM 983	6/18/1993	55	55	6	1,019.1	S&G (confined)	13	1,006.09	6/16/2003	--	--	25	No log. 0–55 ft. Well ended in S&G.
TM 984	6/26/1993	50	50	6	1,020.5	S&G (confined)	12.14	1,008.36	6/16/2003	--	--	30	No log. 0–55 ft. Well ended in S&G.
TM 987	--	40	40	0	1,055	S&G (confined)	--	--	--	--	--	--	--
TM1001	--	104	94	6	830.4	Shale	6	824.4	6/6/2005	94	736	--	Well drilled 10 ft into bedrock.
TM1002	--	88	88	6	777	S&G (confined)	+40	817	11/1/2006	--	--	4	--
TM1003	9/15/1993	130	130	6	935	S&G (confined)	5	930	9/15/1993	--	--	--	0–10 clay, 10–20 S&G, 20–30 till, 30–80 silty sand, 80–100 S&G, 100–120 clay, 120–130 S&G.
TM1004	7/27/2006	42	--	--	815	Till	4	811	7/27/2006	--	--	--	Bridge test boring. 0–5 till, 5–35 clay, 35–42 ft till.

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[S&G, sand and gravel; --, no data; ft, feet; dia. (in), diameter in inches; gal/min, gallons per minute; gal/ft, gallons per foot; psi, pounds per square inch; do., ditto; >, greater than]

Well number	Date drilled	Well depth (ft)	Depth of casing (ft)	Casing diameter (in)	Altitude land surface (ft)	Aquifer type	Water level below land surface (ft)	Altitude water level (ft)	Date water level measured	Depth to bedrock (ft)	Altitude top of bedrock (ft)	Reported yield (gal/min)	Remarks
TM1008	12/12/2006	187	187	6	946	S&G (confined)	Flows	947.56	12/16/2006	196	750	20	0–24 S&G, 24–36 clay, 36–50 S&G, 50–65 sand, 65–100 till, 100–122 clay, 122–133 S&G, 133–138 till, 138–157 S&G, 157–174 fine sand, 174–196 S&G, 196–200 ft shale.
TM1009	12/14/2006	130	130	6	946	S&G (confined)	Flows	951.69	12/2/2008	--	--	25	0–24 S&G, 24–36 clay, 36–50 S&G, 50–65 sand, 65–100 till, 100–122 clay, 122–130 S&G, perforated casing 122–126 ft.
TM1019	6/15/1979	304	304	6	985	S&G (confined)	--	--	--	--	--	20	0–10 till 10–30 fine sand, 30–74 clay, 74–78 S&G, 78–153 clay, 153–172 fine sand, 172–222 clay, 222–283 fine sand, 283–300 till, 300–302 clay, 302–304 ft gravel.
TM1029	4/8/2005	69	69	5	1,015	S&G (confined)	48.15	966.62	4/8/2005	--	--	--	0–19 S&G, 19–27 silt and clay, 27–37 ft S&G.
TM1035	11/3/1938	74	--	--	711.3	--	--	--	--	64	647.3	--	Local number DH–1. 0–8 S&G, 8–31 silty S&G, 31–37 sandy clay, 37–64 ft sand with clay, 64–74 bedrock.

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TM1036	11/1/1938	40	--	--	750	--	--	--	--	40	710	--	Local number DH–2. 0–11 brown clay, 11–14 silt and ft sand, 14–40 silt and S&G (loose), 40 ft shale.
TM1037	11/5/1938	94	--	--	709.4	--	--	--	--	94	615.4	--	Local number DH–3. 0–10 S&G, 10–30 till, 30–78 sand with silt & gravel, 78–82 sand, 82–94 till, 94 bedrock.
TM1038	1/3/1938	125	--	--	742.7	--	--	--	--	--	--	--	Local number DH–4. 0–20 S&G, 20–85 till?
TM1039	11/2/1938	42	--	--	711.4	--	--	--	--	42	669.1	--	Local number DH–5. 0–6.5 S&G, silt, sand, gravel and boulders, 16–32 silty f. sand, 32–42 till, 42 ft bedrock.
TM1040	11/6/1938	8	--	--	715.3	--	--	--	--	8	707.3	--	Local number DH–6. 0–8 silty S&G, 8 ft bedrock.
TM1041	11/9/1938		--	--		--	--	--	--			--	Local number DH–9.
TM1042	1/3/1938	125	0	0	742.7	--	--	0	--	0	-	0	0–20 S&G, 20–85 ft till?,
TM1043	11/2/1938	42	0	0	711.4	--	--	0	--	42.3	669.1	0	0–6.5 alluvial sand and gravel, silt, sand, gravel and boulders, 16–32 beds of silty fine sand, 32–42 till, 42 ft bedrock.
TM1044	11/6/1938	8	0	0	715.3	--	--	0	--	8	707.3	0	0–8 silty sand and gravel, 8 ft bedrock
TM1045	11/7/1938	30	0	0	730	--	--	0	--	22	708	0	

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TM1251	8/18/2000	179	46	6	1,097	Shale	40	1,057	8/18/2000	44	1,053	3	0–40 dry gravel, 40–44 wet gravel, 44–179 ft shale.
TM1260	10/7/2000	26	26	5	1,045	S&G (unconfined)	10	1,035	10/7/2000	0	--	4.5	0–26 ft sand and gravel.
TM1281	11/16/2000	338	26	6	1,075	Shale	3	1,072	11/16/2000	25	1,050	0.25	Yield 0.25 gal/min. 0–25 till, 25–338 ft shale.
TM1296	11/22/2000	75	51	5	1,042	Shale	22	1,020	11/22/2000	51	991	10	0–51 hardpan (till?), 51–75 ft shale.
TM1295	1/29/2001	120	20	6	1,128	Shale	45	1,083	1/29/2001	10	1,118	5	0–10 till, 10–120 ft shale. DD = 30 ft @ 5 gal/min.
TM1309	4/14/2001	94	94	5	858	Sand (confined)	Flows	>862.50	4/14/2001	--	--	1	Flows 0.25 gal/min. 0–42 clay w/ S&G, 42–94 clay and flowing sand, 94 ft sand.
TM1319	7/13/2001	200	55	6	1,038	Shale	43	995	7/13/2001	53	985	2	0–53 gravel, 53–200 ft shale.
TM1320	5/25/2001	150	35	5	1,210	Shale	15	1,195	5/25/2001	27	1,183	4.5	0–17 till, 17–19 S&G, 19–27 till, 27–150 ft grey shale.
TM1355	6/3/2002	188	67	6	1,065	Shale	70	995	6/3/2002	64	1,001	5	0–10 till, 10–13 S&G, 13–30 till, 30–32 gravel, 32–64 till, 64–188 ft shale.
TM1380	9/6/2001	199	30	6	1,115	Shale	--	--	--	26	1,089	3	0–26 till, 26–199 ft shale.
TM1408	5/7/2003	90	90	6	1,128	S&G?	--	--	--	91	1,037	8	Bedrock at 91 ft.
TM1423	12/12/2001	173	28	6	874.4	Shale	14.48	859.48	11/17/2006	27	847.4	3	0–27 clay, 27–173 ft shale.
TM1503	5/31/2002	197	197	5	855	Sandy gravel (confined)	Flows	--	--	--	--	8	0–7 till, 7–20 clay, 20–58 till, 58–62 gravel, 62–74 till, 74–112 clay and sand,112–127 sand, 127–196 clay and sand, 196–197 ft S&G.

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TM1506	6/4/2002	343	31	6	1,180	Shale	--	--	--	31	1,149	0.5	0–31 till, 31–343 ft shale.
TM1532	7/2/2002	95	95	6	852	S&G (confined)	Flows	--	--	--	--	50	Artesian flow. 0–11 till, 11–16 gravel, 16–95 hardpan and clay (till?), 95–100 ft gravel.
TM1533	6/28/2002	58	58	6	1,035	S&G (confined)	40	995	6/28/2002	--	--	10	0–57 hardpan (till?), 57–58 ft large gravel.
TM1590	9/6/2002	120	52	6	1,091	Shale	32	1,059	9/6/2002	49	1,042	10	0–49 till, 49–120 ft shale.
TM1611	10/9/2002	280	21	6	1,082	Shale	25	1,057	10/9/2002	8	1,074	2	0–8 till, 8–280 ft shale.
TM1645	1/8/2003	31	31	5	1,070	S&G (confined)	4	1,066	1/8/2003	--	--	20	0–26 clay and some gravel, 26–31 ft gravel.
TM1671	4/29/2003	135	126	6	1,112	Shale	60	1,052	4/29/2003	126	986	5	0–100 till, 100–126 black sand, 126–135 ft shale.
TM1677	4/28/2003	240	29	6	1,077	Shale	--	--	--	22	1,055	1.5	0–22 till, 22–240 ft shale.
TM1683	5/20/2003	180	59	6	1,155	Shale	80	1,075	5/20/2003	58	1,097	2	0–30 till, 30–40 dirty gravel, 40–58 till, 58–180 ft shale.
TM1698	6/3/2003	78	78	6	974	S&G (confined)	Flows	--	6/3/2003	--	--	25	Artesian flow. 0–3 Hardpan, 3–18 clay, 18–76 sand, 76–78 ft gravel.
TM1732	7/23/2003	101	101	6	1,085	S&G (unconfined)	80	1,005	7/23/2003	--	--	10	0–30 till, 30–60 dry gravel, 60–80 coarse sand, 80–100 ft gravel.
TM1760	3/23/2004	78	78	6	872	S&G (confined)	5	867	3/23/2004	--	--	15	0–10 till, 10–40 sandy clay, 40–50 S&G, 50–70 silty sand, 70–78 ft S&G.
TM1896	8/5/2004	66	66	6	1,070	S&G (confined)	--	--	--	--	--	10	--

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TM1898	8/13/2004	135	135	6	838	S&G (confined)	2	836	8/14/2004	--	--	8	0–25 clay, 25–100 clay and silt, 100–105 silty gravel, 105–130 fine sand, 130–135 ft gravel.
TM1914	9/17/2004	100	58	6	907	Shale	13	894	9/17/2004	57	850	2	0–18 till, 18–57 cemented gravel, 57–100 ft shale.
TM1979	3/16/2005	300	104	6	1,025.4	Shale	77.50	947.7	4/8/2005	104	921.4	0.25	0–10 S&G, 10–27 clay & sand, 27–80 till, 80–104 S&G, 104–300 ft shale.
TM1983	4/15/2005	220	220	6	1,002	Sand	10	992	4/15/2005	--	--	6	0–16 till, 16–26 S&G, 26–65 till, 65–70 S&G, 70–95 fine sand, 95–185 clay, 185–204 sand, 204–220 ft sand.
TM2005	4/22/2005	30	30	6	1,002	S&G (confined)	12	990	4/22/2005	--	--	12	0–14 S&G, 14–27 till, 27–30 ft S&G. Drawdown = 4 ft at 12 gal/min. Specific capacity = 3 gal/ft
TM2039	7/13/2005	120	120	6	847.6	Shale (and S&G?)	50.40	797.18	11/1/2006	116	731.6	25	0–97 clay, 97–116 clay & gravel (till?), 116–120 ft shale.
TM2064	8/6/2005	45	45	6	1,020	S&G (confined)	15	1,005	8/6/2005	--	--	25	0–25 S&G, 25–38 clay with gravel (till), 38–45 ft S&G.
TM2100	9/28/2005	220	33	6	1,025	Shale	30	995	9/29/2005	28	997	3	0–6 gravel, 6–15 clay, 15–28 till, 28–220 ft shale.
TM2128	11/2/2005	33	33	6	960	S&G (unconfined)	18	942	11/2/2005	--	--	10	0–33 ft S&G.
TM2188	4/4/2006	150	20	6	1,085	Shale	30	1,055	4/4/2006	19	1,066	8	0–19 till, 19–150 ft gray shale.

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TM2269	8/30/2006	160	116	6	1,017	Shale	900	9270	8/30/2006	115	9020	0.5	0–10 gravel, 10–34 fine sand, 34–35 S&G, 35–115 silty clay, 100–115 till, 115–160 ft shale.
TM2282	9/21/2006	94	26	6	1,026	Shale	160	1,0100	9/21/2006	24	1,0020	40	0–15 till, 15–24 sand and gravel. 24–94 ft shale. Spec cap. = 0.06 gal/ft.
TM2311	11/10/2006	300	20	6	1,225	Shale	130	1,2210	11/13/2006	5	1,2200	1.5	0–5 till, 5–300 ft shale.
TM2315	11/16/2006	40	84	6	1,016	S&G (unconfined)	260	9900	11/16/2006	--	--	50	0–20 gravel, 20–34 fine sand, 34–42 S&G, 42–84 ft clay. Casing perforated 37–40 ft.
TM2333	1/22/2007	240	24	6	1,181	Shale	720	1,1090	1/22/2007	24	1,1570	40	0–24 till, 24–160 ft grey shale.
TM2355	4/4/2007	145	145	6	829	S&G (confined)	Flows	8390	4/4/2007	--	--	60	Flowing artesian well (18 psi). 0–7 till, 7–80 soft clay, 80–116 hard clay, 116–130 S&G and heaving sand, 130–143 heaving sand, 143–145 S&G.
TM2360	4/24/2007	108	108	6	1,089	S&G (confined)	800	1,0090	4/24/2007	--	--	70	0–13 hardpan, 13–18 gravel, 18–105 hard-pan and some gravel, 105–108 ft S&G.
TM2367	5/21/2007	207	207	6	978	S&G (confined)	400	9380	5/21/2007	--	--	120	0–25 S&G, 25–70 silty sand, 70–153 clay, 173–176 S&G, 176–186 clay, 186–196 S&G, 196–205 clay, 205–207 ft S&G.
TM2369	5/25/2007	240	29	6	1,215	Shale	500	1,1650	5/24/2007	28	1,1870	30	0–28 till, 28–240 ft grey shale.

Appendix 1. Records of selected wells in lower Sixmile Creek and Willseyville Creek trough, Tompkins and Tioga Counties, New York.

[S&G, sand and gravel; --, no data; ft, feet; dia. (in), diameter in inches; gal/min, gallons per minute; gal/ft, gallons per foot; psi, pounds per square inch; do., ditto; >, greater than]

Well number	Date drilled	Well depth (ft)	Depth of casing (ft)	Casing diameter (in)	Altitude land surface (ft)	Aquifer type	Water level below land surface (ft)	Altitude water level (ft)	Date water level measured	Depth to bedrock (ft)	Altitude top of bedrock (ft)	Reported yield (gal/min)	Remarks
TM2381	6/11/2007	140	60	6	1,068	Shale	300	1,0380	6/11/2007	60	1,0080	100	0–24 till, 24–25 S&G, 25–40 till, 40–60 dirty S&G, 60–140 ft grey shale.
TM2399	7/10/2007	68	68	6	1,044	S&G (confined)	300	1,0140	7/10/2007	--	--	300	0–30 till, 30–40 S&G, 40–52 fine to coarse sand, 52–60 S&G, 60–68 ft coarse gravel.
TM2563	8/11/2008	220	58	6	1,201.5	Shale	800	1,121.5	8/11/2008	55	1,1460	50	0–20 till, 20–40 inter-bedded till and clay, 55–220 ft shale.
TM2568	8/16/2008	106	106	6	1,106	S&G (unconfined)	950	1,0110	8/16/2008	--	--	80	0–106 S&G.
TM2617	12/15/2008	200	43	6	1,062	Shale	600	1,0020	12/15/2008	43	1,0190	60	--
TM2717	11/12/2009	81	197	6	871	Sand	00	8710	11/19/2009	196	6750	200	Casing perf 72–81ft. 0–8 S&G, 8–38 clay till?, 38–40 S&G, 40–45 till, 45–59 clay, 59–72 grav & fs, 72–88 f–ms (20 gal/min), 88–100 silty S&G or till,100–110 fs, 110–142 S&clay, 142–196 dirty grav or till, 196–216 shale (.5 gal/min) BR–salty
TI 750	6/16/1966	83	83	5	995	Sand and gravel		00	--	0	00	00	WRI 85–4127
TI 757	--	30	30	6	968	S&G (unconfined)	--	--	--	--	--	--	Well in Tioga County
TI 758		30	30	6	958	Sand and gravel	50	9530	--	0	00	00	

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