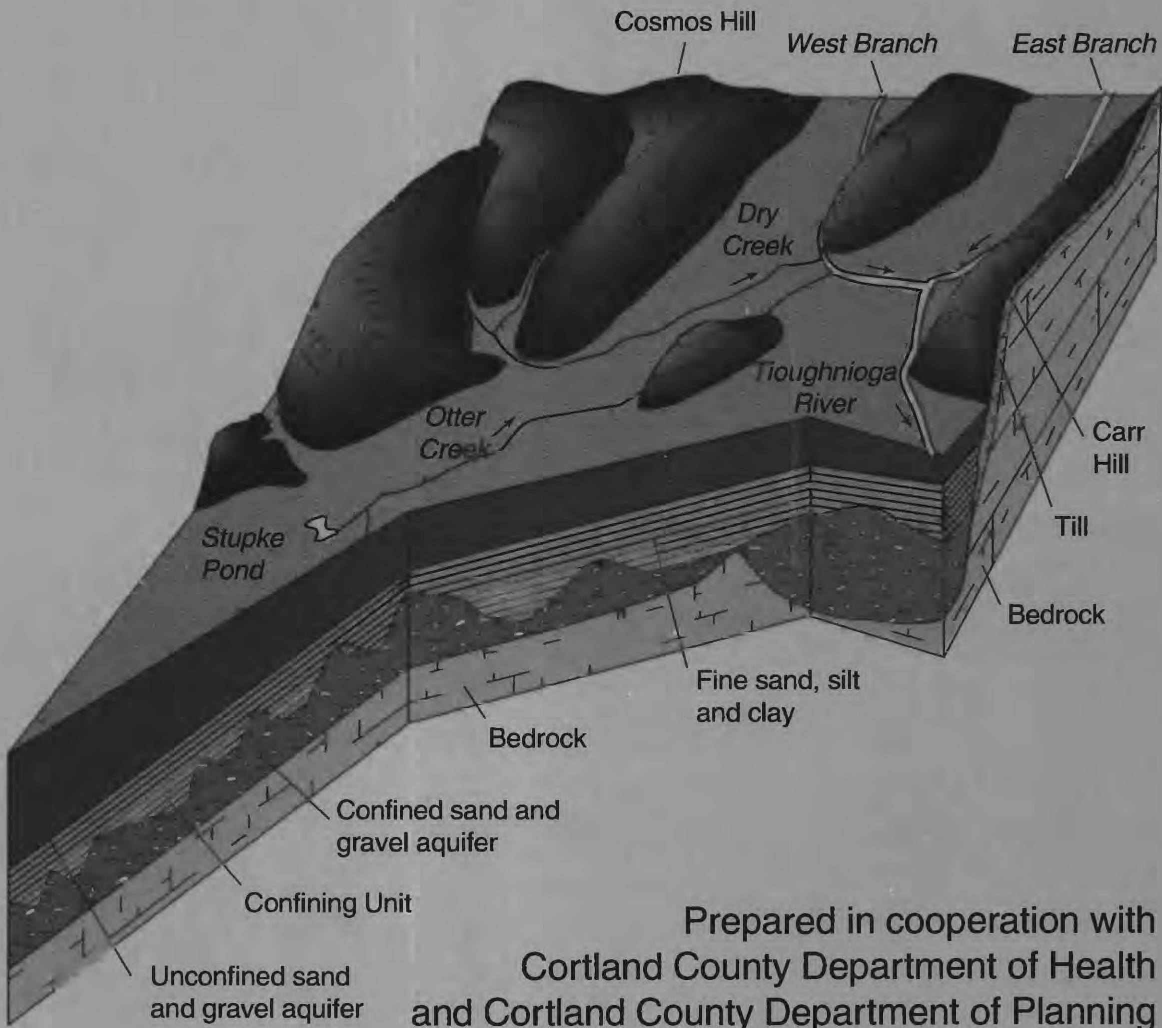
HYDROGEOLOGY, WATER QUALITY, AND SIMULATION OF GROUND-WATER FLOW IN A GLACIAL-AQUIFER SYSTEM, CORTLAND COUNTY, NEW YORK



Prepared in cooperation with
Cortland County Department of Health
and Cortland County Department of Planning

USGS
science for a changing world

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 96-4255

Hydrology, Water-Quality, and Simulation of Ground-Water Flow in a Glacial Aquifer System, Cortland County, New York

By Todd S. Miller, Donald A. Sherwood, Peter M. Jeffers, and Nancy Mueller

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 96-4255

Prepared in cooperation with the
CORTLAND COUNTY DEPARTMENT OF HEALTH
CORTLAND COUNTY DEPARTMENT OF PLANNING

USGS
science for a changing world

Ithaca, New York
1998

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Thomas J. Casadevall, Acting Director

For additional information write to:

Subdistrict Chief
U.S. Geological Survey
903 Hanshaw Road
Ithaca, NY14850

Copies of this report can be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286
Denver, CO 80225-0286

CONTENTS

Abstract 1
Introduction 2
Purpose and Scope 3
Previous Investigations 3
Methods of Investigation 3
Well Inventory, Test Drilling, Levels, Water-Level Measurements, and Aquifer Test 4
Streamflow Measurements 4
Seismic-Refraction Surveys 4
Water Sampling and Analysis 4
Simulation Models 5
Description of the Study Area 5
Physiography and Bedrock Geology 5
Climate 6
Land Use 8
Acknowledgments 9
Hydrogeology 9
Glacial Geology 10
Bedrock Scouring 10
Kames and Kame Terraces 12
Valley Heads Moraine System 15
Proglacial Lakes and Lacustrine Deposits in Valleys 15
Glaciofluvial Sediments (Outwash) of the Valley Heads Episode 16
Ice Readvance and Drainage of Proglacial Lake During Late Stages of Deglaciation 16
Hydrology of the Glacial-Aquifer System 17
Geometry of Aquifers and Confining Unit 18
Hydraulic Conductivity 18
Unconfined Aquifer 19
Confined Aquifer 20
Confining Unit 20
Ground-Water Levels and Flowpaths 21
Unconfined Aquifer 21
Confined Aquifer 21
Sources of Recharge 22
Direct Infiltration of Precipitation on the Valley 22
Upland Sources 22
Induced Infiltration by Ground-Water Withdrawals 25
Infiltration from Recharge Basins 25
Ground-Water Discharge 25
Seepage to Streams 25
Municipal and Industrial Withdrawals 26
Underflow From the Study Area 26
Water Quality 26
Volatile Organic Compounds 28
Extent and Migration of Trichloroethylene in the Unconfined Aquifer 28
Horizontal Migration 28
Vertical Migration 29
Effects of Remediation Efforts 29
Long-Term Trends of Trichloroethylene Concentrations 35
Fate and Migration of Trichloroethylene 35
Inorganic Chemical Constituents and Physical Characteristics 38
Specific Conductance, pH, and Alkalinity 38
Chloride and Sodium 38
Trace Elements (Iron and Manganese) 39
Nitrogen 41
Temporal Changes 42
Ground-Water Chemistry and Land Use 42

Simulation of Ground-Water Flow 45
Description and Design of Numerical Model 45
Model Grid 47
Geometry of Model Layers 47
Hydraulic Conductivity 48
Unconfined Aquifer 48
Confined Aquifer 48
Stream-Aquifer Interaction 48
Boundary Conditions 49
Ground-Water Withdrawals and Recharge Basins 50
Model Calibration 50
Model Sensitivity 56
Model Applications 58
Areas Contributing Recharge to Municipal Wells 58
Flowpaths to Wells and Streams from Sources of Contamination 59
Typewriter Plant 59
Superfund Site 59
Summary 61
References Cited 64

APPENDIXES

1. Records of wells and test borings in the Cortland, N.Y., study area 67
2. Inorganic chemical analyses of ground water from selected wells in the glacial-aquifer system in the Cortland, N.Y. study area 75
3. Organic chemical analyses of ground water from selected wells in the glacial-aquifer system in the Cortland, N.Y. study area 81

PLATES

1-5 Maps of Cortland, N.Y. study area showing:
1. Well locations and surficial geology in a glacial-aquifer system ....
2. Altitude of potentiometric surface, direction of ground-water flow, and contributing areas to public-water supply wells during high-recharge conditions in the unconfined glacial aquifer, Cortland, New York ....
3. Altitude of potentiometric surface, direction of ground-water flow, and contributing areas to public-water supply wells during average-recharge conditions in the unconfined glacial aquifer, Cortland, New York ....
4. Altitude of potentiometric surface, direction of ground-water flow, and contributing areas to public-water supply wells during low-recharge conditions in the unconfined glacial aquifer, Cortland, New York ....
5. Finite-difference grid and boundaries used to model the glacial-aquifer system ....

FIGURES

1. Map showing location and principal geographic features of study area, Cortland County, N.Y 2
2. Map showing physiographic features of New York 6
3. Diagram showing geologic time scale and when geologic units in the study area were formed 7
4. Graph showing annual precipitation at Cortland, 1973-92 8
5. Graph showing monthly precipitation and departure from normal at Cortland, from January 1990 through May 1993 9
6. Map showing preglacial drainage in study area 10
7. Hydrogeologic sections:
A. Section A-A′ 11
B. Section B-B′ 12
C. Section C-C′ 13

D. Section D-D′ 14
8. Map showing bedrock surface altitude in Cortland study area 14
9. Map showing location of Valley Heads ice and moraines that dammed drainage in valleys of the Tioughnioga River basin 15
10. Map showing upper surface altitude of lacustrine unit in Cortland study area 17
11. Map showing positions of the Valley Heads ice, and of outwash that was deposited in valleys of the Tioughnioga River basin 18
12. Block diagram showing generalized hydrogeologic framework of the glacial-aquifer system in the Cortland study area 19
13. Block diagram showing sources of recharge to stratified drift in valleys in the glaciated Northeast 24
14. Map showing locations of streamflow-measurement sites in Cortland study area 27
15. Maps showing extent of trichloroethylene plume and contours of equal trichloroethylene concentration in Cortland study area:
A. April 3-5, 1990 30
B. September 17-20, 1990 31
C. April 27, 1993 32
16. Diagrams showing vertical distribution of TCE in ground water at two well sites: A. Well 341, 4,000 feet northeast of TCE source, July 19, 1990. B. Well 381, 750 feet from TCE source, September 23-26,1992 33
17. Graphs showing trichloroethylene concentration at three wells: A. Well 350, November 4, 1986-May 20, 1993. B. Well 347, December 12, 1986-May 20, 1993. C. Well 364, December 12, 1986-April 29, 1993 34
18. Diagram showing physical, chemical, and biological processes that affect the fate and distribution of trichloroethylene in the unconfined aquifer at Cortland 36
19. Diagram showing transformation pathways of trichloroethylene under anaerobic conditions 37
20. Graph showing dissolved chloride concentrations in water from wells at the City of Cortland well field for 1943-76, 1980, and 1990 41
21. Map showing distribution of dissolved chloride concentration in the unconfined aquifer in the Cortland area, April 1990 41
22. Boxplots showing concentration of alkalinity, dissolved calcium, nitrite plus nitrate, and dissolved chloride from selected wells in the Cortland, study area in 1976, 1980, and 1990:
A. By year. B. By land use 44
23. Geohydrologic section showing conceptual model of ground-water flow in the glacial-aquifer system in the Cortland study area 46
24. Maps showing location of active and inactive grid boundaries in layers 1-3 of the three-dimensional ground-water flow model in the Cortland study area 47
25. Maps showing simulated head for in model layers 1-3 during steady-state simulations:
A. high-recharge conditions 53
B. average-recharge conditions 54
C. low-recharge conditions 55
26. Graph showing results of sensitivity analyses for hydraulic head in the glacial-aquifer system in Cortland study area 56
27. Graphs showing results of sensitivity analyses for ground-water discharge to major streams during average recharge conditions in the glacial aquifer system in the Cortland study area:
A. West Branch Tioughnioga River B. Reaches A and B of Tioughnioga River 57
28. Maps showing flowpaths and traveltimes of ground water from two sources of contamination in Cortland study area during (A) high-, (B) average-, and (C) low-recharge conditions 60

TABLES

1. Land use in the Otter Creek-Dry Creek basin, Cortland County, N.Y., 1992 8
2. Results of aquifer tests in the glacial-aquifer system in the Cortland, N.Y. study area 20
3. Streamflow losses and gains in tributary streams in the Cortland study area, 1990-91 23
4. Ground-water discharge to West Branch Tioughnioga River, Tioughnioga River, and to Otter Creek during average- and low-flow conditions, 1991 25

5. Ground-water withdrawals from the Cortland study area by major pumping wells during low-, average-, and high-recharge conditions, 1990-91 . . . 27
6. Range of half-lives for trichloroethylene and its degradation products . . . 38
7. Minimum, maximum, mean, median, and interquartile range of concentration or value for selected constituents or properties of ground-water samples collected from the glacial aquifer in the Cortland study area during April and September 1990 . . . 39
8. Minimum, maximum, mean, median, and interquartile range of concentration or value for selected constituents or properties of ground-water samples collected from the glacial aquifer in the Cortland, N.Y. study area during: A. April 1990. B. September 1990 . . . 40
9. Minimum, maximum, mean, median, and interquartile range of concentration or value for selected constituents or properties of ground water sampled during three studies in Cortland, N.Y. study area . . . 43
10. Minimum, maximum, mean, median, and interquartile range of concentration or value for selected constituents or properties of ground water in the Cortland, N.Y. study area, by land use . . . 45
11. Difference between measured and simulated heads at 49 selected wells in the Cortland, N.Y. study area for high-, average-, and low-recharge conditions . . . 51
12. Measured and simulated streamflow gains and losses, for selected stream reaches during high-, average-, and low-recharge conditions in the Cortland, N.Y. study area . . . 52
13. Steady-state water budgets for the glacial-aquifer system at Cortland N.Y, for high-, average-, and low-recharge conditions . . . 52

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To Obtain
	Length	
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Slope	
foot per mile (ft/mi)	0.1894	meter per kilometer
foot per foot (ft/ft)	0.3084	meter per meter
	Area	
square mile (mi^2)	2.590	square kilometer
acre	0.40483	hectare
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
inch per year (in/yr)	25.4	millimeter per year
million gallons per day (Mgal/d)	3.785	cubic meters per day
gallons per minute (gal/min)	0.06309	liter per second
feet per day	0.3084	meter per day
	Temperature	
degrees Fahrenheit (°F)	°C = 5/9 (°F-32)	degrees Celsius

Specific Conductance

microsiemens per centimeter at 25° Celsius (µS/cm)

Equivalent Concentration Terms

milligrams per liter (mg/L) = micrograms per gram (mg/g) = parts per million
micrograms per liter (µg/L) = micrograms per kilogram (µg/kg) = parts per billion

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

Hydrogeology, Water Quality, and Simulation of Ground-Water Flow in a Glacial-Aquifer System, Cortland County, New York

By Todd S. Miller, Donald A. Sherwood, Peter M. Jeffers, and Nancy Mueller

Abstract

The glacial-aquifer system in Cortland County consists of an unconfined sand and gravel aquifer 40 to 80 feet thick, underlain by a lacustrine and till unit 1 to 155 feet thick that, in turn, is underlain by a confined sand and gravel aquifer 1 to 170 feet thick. The two aquifers are hydraulically connected in some places along the valley walls where the confining layer is absent.

Water in the unconfined aquifer generally moves from areas of recharge along the valley walls toward the center of the valley, then flows northeastward down the Otter Creek-Dry Creek valley and discharges to pumping wells, the West Branch Tioughnioga River, and the Tioughnioga River. Water is pumped from the unconfined aquifer at municipal and industrial wells at a rate of 6.76 to 7.20 million gallons per day.

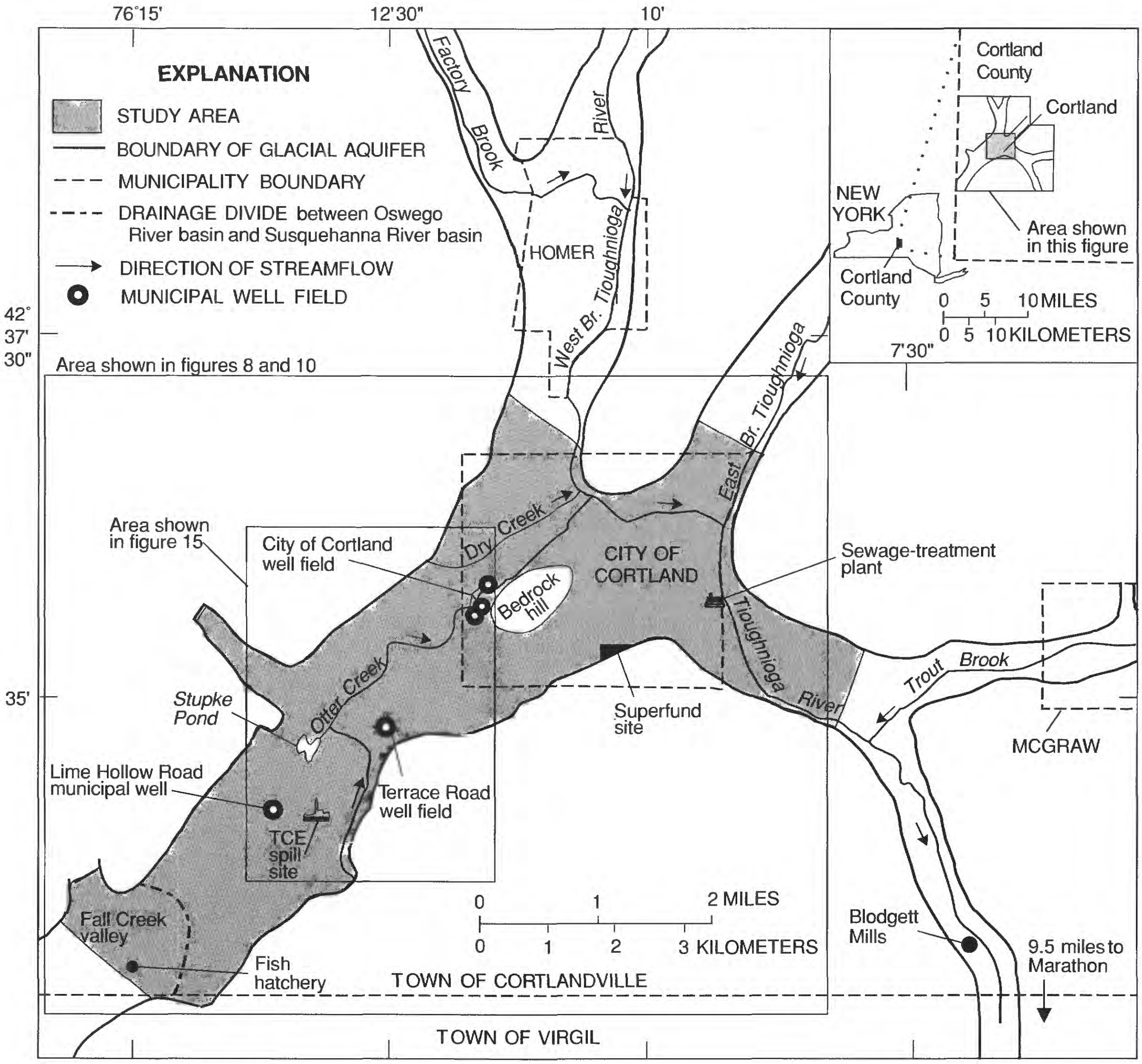
Trichloroethylene (TCE) that was detected in water samples from several wells in 1986 was considered a threat to municipal-water supplies. Results of ground-water sampling in April and September 1990 and in April 1993 indicated that a TCE plume, as defined by concentrations equal to or greater than 5 micrograms per liter, had migrated 1.25 miles northeastward in the unconfined aquifer from a spill area at a typewriter production plant in the west-central part of the aquifer. The extent of the plume was the same in all three sampling periods, indicating that steady-state conditions had been reached. TCE concentrations were below the U.S. Environmental Protection Agency's "Maximum Contaminant Level" of 5 micrograms per liter 1 mile upgradient from the City of Cortland municipal wells, which are 2.25 miles downgradient (northeast) of the spill area. Inorganic- and organic-chemical analyses of ground-water samples collected during April and September 1990 indicate that water generally meets New York State drinking-water standards except in the part of the unconfined aquifer that is contaminated by TCE.

A ground-water flow model (MODFLOW) was used to simulate high-, average-, and low-recharge conditions in the aquifer system, and a particle-tracking routine (MODPATH) was used with output from the flow model to estimate the area contributing water to municipal wells and to delineate flowpaths of ground water from two sources of contamination. The simulated water budgets indicate that the largest source of recharge to the aquifer system (55 to 58 percent of total recharge) is from the uplands; this recharge includes seepage losses from upland streams that flow onto the aquifer, and unchanneled runoff and ground-water inflow from the uplands. The second-largest source of recharge is precipitation (33 to 39 percent of total recharge) that directly falls over the aquifer. Most ground-water discharge (57 to 71 percent of total) occurs as seepage from the aquifer system into streams, and some (26 to 40 percent of the total) occurs as discharge to pumping wells. Results of particle-tracking analyses indicate that the contributing areas are U-shaped and extend over most of the aquifer upgradient from the pumping wells. The largest contributing areas were obtained in the simulation of low-recharge conditions, and the smallest areas were obtained in the simulation of high-recharge conditions. Ground-water flowpaths from sources of contamination shifted southward in the low-recharge simulation in response to changes in the distribution of recharge.

INTRODUCTION

Glacial aquifers are the principal sources of water for many communities in upstate New York, but the high permeability and shallow depth to the water table in these aquifers make them highly susceptible to contamination. Potential contamination sources can include leaking petroleum-product storage tanks, leachate from landfills and septic systems, road-deicing salts, agricultural pesticides and fertilizers, and chemical spills (such as solvents and degreasers) at commercial and industrial facilities. Protection of these aquifers from contamination is critical in areas where ground-water use is great and alternative sources of drinking water are not readily available. Water managers need information on (1) the size and location of the areas that contribute recharge to their public-supply wells, and (2) the direction and rate of flow of ground water from known or potential sources of contamination, to protect the quality of the water.

The City of Cortland and surrounding communities obtain water supplies from a highly productive glacial aquifer system (fig. 1). This system has been designated as a "Primary Aquifer" by the New York



Base from U.S.Geological Survey
1:62,500 series: Cortland (1903) and Groton (1903)

Figure 1. Location and principal geographic features of study area, Cortland County, N.Y.

State Department of Environmental Conservation and as a "Sole Source Aquifer" by the U.S. Environmental Protection Agency (EPA) under the Safe Drinking Water Act.

Several parts of the glacial-aquifer system have been contaminated by: (1) solvents and degreasers, including trichloroethylene (TCE), trichloroethane (TCA), and dichloroethylene (DCE); (2) gasoline that leaked from tanks from at least two service stations; (3) bacteria from failing septic systems; and (4) leachate from inactive hazardous-waste sites. Concentrations of chloride and nitrate in the aquifer generally meet State standards for drinking water but have been steadily increasing since the 1950's as a result of road salt, lawn and garden fertilizers, and leachate from septic systems (Buller and others, 1978).

A study of ground-water contamination (O'Brien and Gere Engineers, Inc., 1987) at a typewriter-production plant in the western part of the aquifer, at which solvents and degreasers were found, resulted in a legal settlement that included funds to study the hydrogeologic framework of the aquifer, the migration of contaminants from the site, and the investigation of other possible sources of offsite contamination. In 1989, the U.S. Geological Survey (USGS), in cooperation with the Cortland County Departments of Health and Planning, began a 3 1/2-year hydrogeologic, water-quality, and numerical modeling study of the glacial-aquifer system in Cortland County. Major objectives of the study were to increase knowledge on how the aquifer system works; provide a numerical ground-water flow model to help manage the ground-water resource; and to determine (a) the extent of a TCE plume, (b) the current ground-water quality in the aquifer, (c) changes (if any) in water quality during the 15-year period since wells were sampled by Buller and others (1978), and (d) whether the ground water meets New York State drinking-water standards.

Purpose and Scope

This report describes the hydrogeology of the glacial-aquifer system including (1) the geologic framework; (2) the ground-water flow system, including ground-water and surface-water interaction, water levels, and water budgets; (3) the water quality, with an emphasis on the extent, trends, and fate of TCE; and (4) results of model simulations of ground-water flow for high-, average-, and low-recharge conditions, including (a) the estimation of recharge areas to municipal wells, and (b) the advective flowpaths of contaminants migrating from sources of contamination. Also included are (1) geologic sections; (2) maps and diagrams depicting well locations, geology, ground-water levels, and direction of ground-water flow for measured and simulated high-, average-, and low-recharge conditions; recharge areas to public water supplies, concentrations of TCE and several other selected chemical constituents, and flowpaths and traveltimes of contaminants; and (3) tables of climate and land-use data, well records, a water budget, and data on hydraulic properties of the aquifers and on water quality.

Previous Investigations

USGS investigations of glacial aquifers in Cortland County began when Asselstine (1946) identified sources of ground-water supplies and collected well and water-quality data. Randall (1972) collected well and test-boring records in the study area. Buller and others (1978) and Miller and others (1981) studied surficial geology, movement of ground water, and water quality in the Otter Creek-Dry Creek valley. Cosner and Harsh (1978) constructed a two-dimensional ground-water model of the glacial aquifer in the Otter Creek-Dry Creek valley; this model was later modified by Reynolds (1985).

Several hydrogeological and engineering consultants conducted site-specific studies at chemical-spill sites in the study area. O'Brien and Gere Engineers, Inc. (1987 and 1990) studied the hydrogeology and organic-chemical contamination in ground water at the typewriter-production plant in the western part of the study area. Blasland, Bouck and Lee, Engineers (1992) investigated the hydrogeology and extent of chemical contamination of an EPA-designated "Superfund site," locally known as the Rosen Superfund Site, in the southeastern part of the study area (pl. 1). Apfel (1967) studied the availability of ground water at a machine-tool plant in the southwestern part of the study area, and Galson Technical Services, Inc., (1988) investigated the hydrogeology and extent of a petroleum-product spill at that site. Resource Engineering (1987) investigated the hydrogeology and extent of contamination from paint-stripping activities at a center for the handicapped in the northern part of the study area.

Methods of Investigation

Hydrogeologic data were collected from several sources, including published reports by the USGS consulting firms, and data in files of local drillers and government agencies. USGS fieldwork during this study included a well inventory, test drilling, leveling, an aquifer test, water-level measurements, streamflow measurements, two seismic-refraction surveys, and three rounds of ground-water sampling.

Well Inventory, Test Drilling, Levels, Water-level Measurements, and Aquifer Test

Records of 215 wells were collected and compiled (appendix 1). The well inventory was augmented by test drilling in which 20 observation wells and 4 test holes were installed by auger, cable-tool, and air-rotary rigs to obtain data on stratigraphy, hydraulic properties, water quality, and water levels in the aquifers.

Leveling was done to about 100 wells to determine the elevations of water-level-measuring points, which were mostly the tops of the well casings. These elevations were determined by standard surveying methods (Kennedy, 1990) and are generally accurate to within 0.01 ft. Levels were also run to determine channel profiles of major streams that flow over the aquifer. The stream-channel elevations were used in the stream-routing package for the ground-water models.

Water levels were measured monthly in 50 wells from July 1989 through October 1991 and during three synoptic rounds in more than 100 wells during March 28-29, 1990 (high-recharge conditions), May 28-June 4, 1991 (average-recharge conditions), and October 7-9, 1991 (low-recharge conditions). These water-level data were contoured to show the potentiometric surfaces (pls. 2 through 4) for high-, average-, and low-recharge conditions and were used to calibrate the models.

An aquifer test was conducted July 16, 1991 at the Town of Cortlandville municipal well at Lime Hollow Road (fig. 1) to calculate the hydraulic conductivity of the aquifer materials. Drawdown data were analyzed through a curve-fitting procedure that uses type curves developed by Nueman (1974) for partially penetrating wells in an unconfined aquifer.

Streamflow Measurements

Streamflow was measured by current meters in several reaches of most streams in the study area during each of the three recharge conditions that were modeled; techniques are described by Buchanan and Somers (1969). Streamflow measurements were used to identify the location and the amount of gain or loss in streams.

Seismic-Refraction Surveys

Seismic-refraction surveys were conducted at two sites (pl. 1) to supplement data from test drilling. These surveys obtained continuous records on depth to water table and to bedrock. Seismic-refraction techniques used in this study are described by Haeni (1988). A series of 12 geophones spaced 100 ft apart were laid on the ground, and arrival times of compressional waves generated by explosives were recorded and plotted as a function of source-to-geophone distances. A three-layer (unsaturated unconsolidated sediments, saturated unconsolidated sediments, and top of bedrock) boundary-formula computer analysis (Scott and others, 1972) was used to calculate depths to water table and to bedrock.

Water Sampling and Analysis

Water samples were collected from wells and streams in April 1990, September 1990, and April 1993. The main purpose of the two 1990 sampling rounds was to map the extent of TCE migrating from the former typewriter-manufacturing plant in the western part of the aquifer under high- and low-recharge conditions and to define the general chemical quality of ground water throughout the study area. The purpose of the April 1993 sampling was to evaluate what effects remedial practices used at the typewriter plant were having on concentrations of TCE in ground water.

Selection of purging techniques to remove standing water from well casings before sample collection depended on well construction and water-yielding capacity of the well. At least three volumes of water were pumped or bailed from monitoring wells with good yield prior to sample collection. Monitoring wells with low yield were pumped dry, then allowed to partly recover before they were sampled. Large wells (6-in. diameter and larger) were purged with a stainless-steel submersible pump or a 4-in. diameter bailer; wells of 2-in. diameter and smaller were purged either by a Teflon[1] bladder pump, a peristaltic pump (with Tygon tubing), or a stainless-steel bailer. The pumps of domestic wells were turned on for 10 to 15 minutes (the estimated time for evacuation of three volumes of standing water in the casing) before sample was

[1] Use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

collected. All sampling and purging equipment were thoroughly cleaned between sampling.

The Chemistry Department at State University of New York (SUNY) College at Cortland analyzed the water samples collected in April 1990 for (1) pH, specific conductance, and total alkalinity; (2) common ions (calcium, chloride, magnesium, sodium, and potassium; nitrate as nitrogen); and (3) volatile organic compounds (VOCs). Temperature and specific conductance of water was measured in the field at the time samples were collected.

The SUNY Chemistry Department also analyzed water samples collected in September 1990 and June 1993 for VOCs. The USGS National Water-Quality Laboratory in Denver, Co., analyzed water samples collected in September 1990 for nutrients, metals and common anions. VOC analyses were done by purge-and-trap/gas chromatograph methods, modified from USEPA 501 methods (U.S. Environmental Protection Agency, 1979).

Quality-control procedures for samples collected during April 1990 consisted of analyses of duplicate samples, replicate samples, and field and laboratory spikes of inorganic constituents. Two samples that were to be analyzed for VOCs were split and spiked; one set consisting of two samples was sent to the USGS National Water Quality Laboratory, and one set was sent to the Chemistry Department at SUNY College at Cortland. Analytical results and recoveries reported by the two laboratories compared favorably.

Simulation Models

A three-dimensional, finite-difference, ground-water flow model, MODFLOW (McDonald and Harbaugh, 1988), was developed to represent the glacial aquifer system and was used for steady-state simulation of three recharge conditions (high, average, and low). The models were used to compute water levels and water budgets. Particle-tracking postprocessing programs, MODPATH and MODPATH-PLOT (Pollock, 1989), were used to estimate the recharge areas of municipal wells, the flowpaths of the advective phase of chemical migration, and traveltime of the advective phase of contaminants migrating from chemical-spill sites to discharge areas.

Description of Study Area

The study area, in the Otter Creek-Dry Creek valley and in parts of West Branch, East Branch, and Tioughnioga River valleys (fig. 1), forms a rectangle 6 mi long by 2 mi wide in the Town of Cortlandville, in the southwestern part of Cortland County (fig. 1). The City of Cortland lies within the study area and within the Town of Cortlandville. The population of the Cortland area increased about 7 percent during 1970-90 and, in 1990, was about 24,100 (U.S. Bureau of Census, 1990).

Physiography and Bedrock Geology

The study area is in the glaciated part of the Allegheny Plateau (fig. 2). The rocks of the plateau consist of gently folded layers of shale with some siltstone, sandstone, and limestone that dip to the south at 40 ft/mi. These rocks are part of the "Catskill Delta" complex (Woodrow and Sevon, 1985) and were deposited in marine seas during late Devonian time (fig. 3). The rocks were then uplifted above sea level millions of years later and then eroded to a nearly flat plain by the middle of the Cenozoic (Isachsen and others, 1991). The rocks were again uplifted during Late Cenozoic time to form the Allegheny Plateau, which was dissected by streams to form a hilly terrain.

Bedrock in the study area is far less permeable than the overlying glacial sand and gravel aquifers. Bedrock forms the bottom of the aquifer system in the study area. Relief in the study area is about 720 ft, and summits are as high as 1,800 ft above sea level. The lowest elevation, about 1,080 ft, is the channel of Tioughnioga River, in the eastern part of the study area. The bedrock surface has a relief of about 1,000 ft in areas where it is more than 300 ft below the flood plain. Uplands have moderately sloping hillsides ranging from 9 to 18 percent.

Muller (1970) described the drainage pattern at Cortland as "the hub of five valleys that converge from the north, northeast, east, south, and southwest" (fig. 1). All five valleys drain into the Tioughnioga River in the eastern part of the study area. Most of the study area is drained by Otter Creek and Dry Creek, which flow northeastward and drain into the West Branch Tioughnioga River in the north-central part of the study area. The western part of the study area contains several kettle ponds, some with bottom sediments of marl that have been mined in the past. Most of the ponds are dry during late summer and fall. Stupke

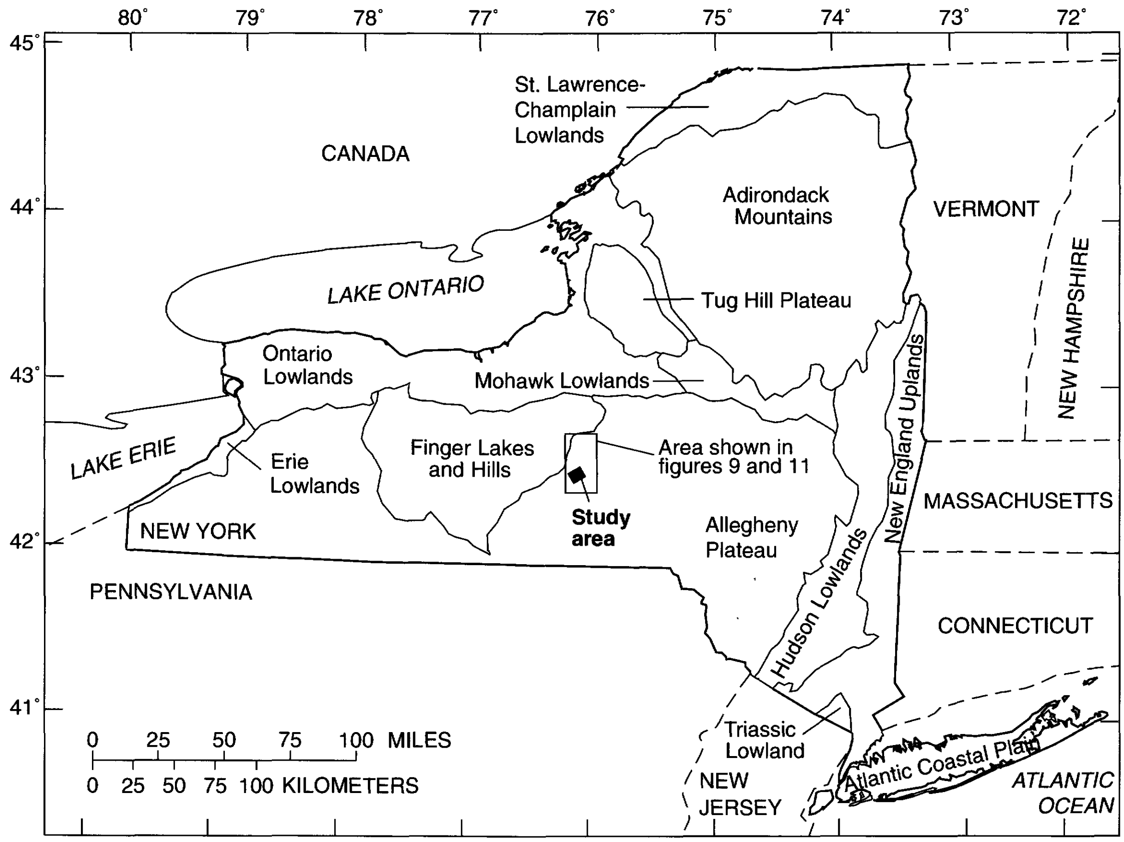


Figure 2. Physiographic features of New York. (Modified from Cressey, 1966, fig. 9, p. 26.)

pond (fig. 1) is a large kettle pond that has no inlet; its outlet is a headwater tributary of Otter Creek.

Climate

Two types of air masses provide the dominant weather characteristics of Cortland—cold, dry airmasses from the northern interior of the continent, which prevail during the cold half of the year, and warm, humid airmasses from the Gulf of Mexico and southwestern part of the continent, which are typical during the warm half of the year (Dethier, 1966). A third, but less common type is the marine airmasses, which move along the North Atlantic Coast (northeasters) and produce occasional cool, wet, cloudy conditions. Large bodies of water near Cortland, such as Lake Ontario, 70 mi to the north, tend to moderate air temperatures and supply moisture to the cold, continental airmasses during the cold season.

Mean annual temperature of Cortland is 45.7 °F (National Oceanic and Atmospheric Administration, 1990). Winters are long, cloudy, and cold, with minimum temperatures ranging from 0 to -10 °F for an average of 13 days per winter (National Oceanic and Atmospheric Administration, 1992). Summer has warm daytime temperatures, cool evenings, and occasional periods of high, uncomfortable humidity. Summer daytime temperatures typically range from the mid-70s to mid-80s reach 90 °F or higher on average of 8 days a year (Roffner, 1985).

The annual precipitation at Cortland for 1973-92 is shown in figure 4; the average for the 20-year period was 41.2 in., and the range was from 32.3 in. in 1982 to 50.6 in. in 1977. Monthly precipitation is normally distributed fairly uniformly throughout the year, but from January 1990 to May 1993 it ranged from 1.35 in. in March 1990 to 8.42 in. in July 1992 (fig. 5). Irrigation for agricultural crops is rarely needed. Severe droughts are rare, but minor droughts that occur periodically cause concern about degradation of water quality of streams during extreme low-flow conditions and of fish survival in reaches that are downgradient of sewage discharges.

Snowfall in Cortland averaged 90.9 in. during 1973-92 (National Oceanic and Atmospheric Administration, 1992). Continuous snow cover typically starts in late December and lasts until mid-March. Some snow is a result of the "lake effect," a process whereby an artic cold front from Canada crosses Lake

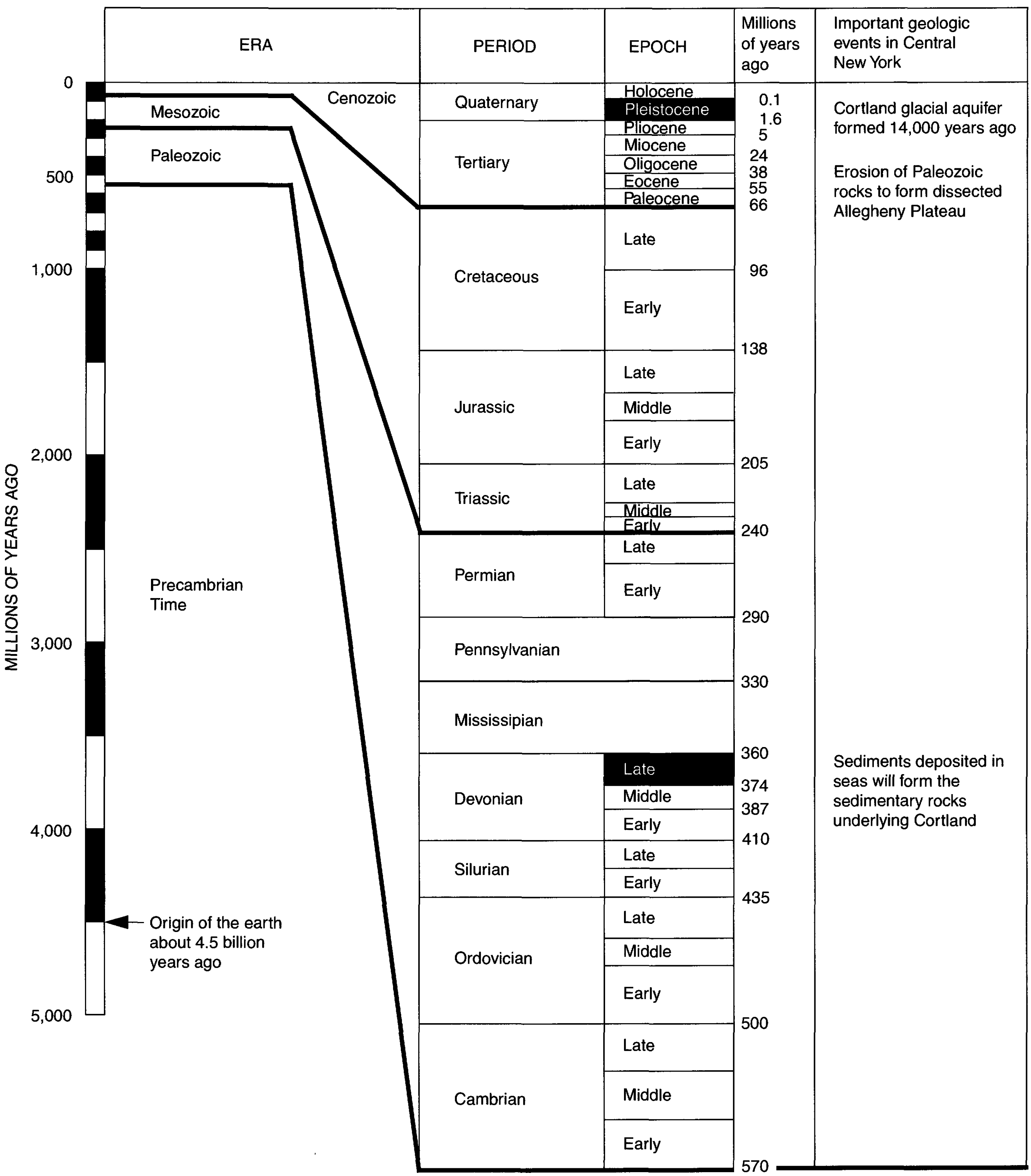


Figure 3. Geologic time scale.

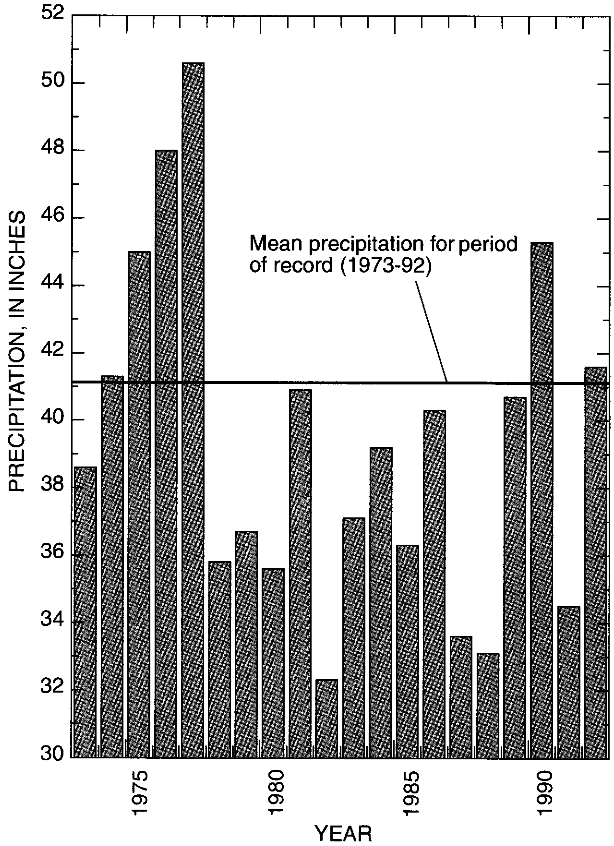


Figure 4. Annual precipitation at Cortland, N.Y., 1973-92. (Data from National Oceanic and Atmospheric Administration, 1992)

Ontario and the Finger Lakes, is warmed in the low elevations and picks up moisture, and then releases some of the moisture as snow as the air rises over the uplands (orographic effects). When the lakes freeze by midwinter,"lake effect" snow becomes infrequent because the ice prevents evaporation off the lake. The heaviest snowfalls, typically 1 to 2 ft, occur when northeasters move inland and cross over or close to Cortland. A severe "northeaster," locally known as the "Blizzard of 93," dumped 3 ft of snow on Cortland during March 13-14, 1993 (National Oceanic and Atmospheric Administration, 1993).

Land Use

Land use in the Otter Creek-Dry Creek basin was inventoried from the 1992 Cortland County Tax Assessment Rolls and from field inspections made in 1992 (table 1).

Agricultural land occupies 35.5 percent of the Otter Creek-Dry Creek drainage basin (5 percent of land over the aquifer). The study area contains three working farms that grow mostly hay and corn. Agricultural land has been decreasing since the 1950's. The prime farmland is in flat outwash valleys, which are also most suitable for urban development; consequently, pressure to convert farmland to residential, commercial, and industrial has increased. The trend of decreasing farm land will probably continue.

Residential, the largest land use, accounts for 29 percent of the Otter Creek-Dry Creek drainage basin. Most of the residential area is within the City of Cortland, and all residential areas within the City of Cortland are sewered. Surrounding the city, in the Town of Cortlandville, are many large suburban housing developments. Most of the residential areas in the Town of Cortlandville are sewered, although residential growth has recently begun to outpace the extension of sewer lines. Most of the residential areas in the bedrock uplands are unsewered.

Commercial land use (8 percent of the Otter Creek-Dry Creek drainage basin) has been continually expanding, especially since 1985, primarily in the form of strip development along major transportation corridors. Most commerce consists of retail sales and services.

Industrial land use also constitutes 8 percent of the Otter Creek-Dry Creek basin. Manufacturing, processing, and warehousing are included in this category. Major products in 1992 were foundation garments, plastic houseware, polystyrene packaging, industrial filters, fishing line, machine tools, and wood products. (The typewriter plant moved to Mexico in 1994.)

Sand and gravel mining constitutes about 2.8 percent of land in the Otter Creek-Dry Creek drainage basin. Most of the gravel is extracted for asphalt production.

Table 1. Land use in the Otter Creek-Dry Creek basin, Cortland County, N.Y., 1992
[Data from Cortland Department of Planning, 1992]

Land use	Percentage of total basin area
Agricultural cropland and pasture	35.5
Residential (sewered)	19
Residential (unsewered)	10
Commercial	8
Industrial	8
Forest and brushland	5
Churches, institutions, and public services	4.4
Parks, athletic fields, and golf courses	3
Sand and gravel mining	2.8
Major transportation corridors	2.0
Water and wetlands	0.9
Other recreational areas	0.8
Cemeteries	0.6

Public land constitutes 7 percent of the Otter Creek-Dry Creek drainage basin. Fortuitously, the City of Cortland owns a 180-acre forested watershed that borders the city's well field; thus, the city's water managers have been able to protect their ground-water supply from contamination, largely by controlling the land use on this property. Other substantial public lands in the study area are the SUNY college campus and a 100-acre fish laboratory owned by the U.S. Fish and Wildlife Service. The campus extends over the aquifer and a bedrock hill (pl. 1). The fish laboratory is on the west side of the ground-water divide in the western part of the aquifer. Other small parcels of public lands include municipal recreational parks and government institution and service sites.

Regulation is the primary means of controlling land use in the study area. Both the City of Cortland and the Town of Cortlandville have zoning ordinances, subdivision controls, and land-use plans. At the County level, the Cortland County Health Department enforces the New York State Sanitary Code, and the Cortland County Planning Board reviews land-use proposals of countywide significance. The Town of Cortlandville adopted an Aquifer Protection District amendment to its zoning ordinance in 1988, to regulate certain land uses over the aquifer.

Acknowledgments

Special thanks are extended to James Feuss, Director of Cortland County Health Department, for providing well and chemical data. Thanks are also extended to Douglas Withey, Superintendent of Cortland County Water Board, for providing pumping data and access for collection of hydrogeologic data in the Waterworks area. Thanks are also extended to Hayne Smith, Town of Cortlandville Engineer, for arranging the aquifer test at the municipal well at Lime Hollow Road.

HYDROGEOLOGY

The glacial aquifer system in the study area, and the ground-water and surface-water flow conditions within it, are the result of glacial processes. Hydrogeologists use concepts and principles of geologic processes and the chronological order in which they

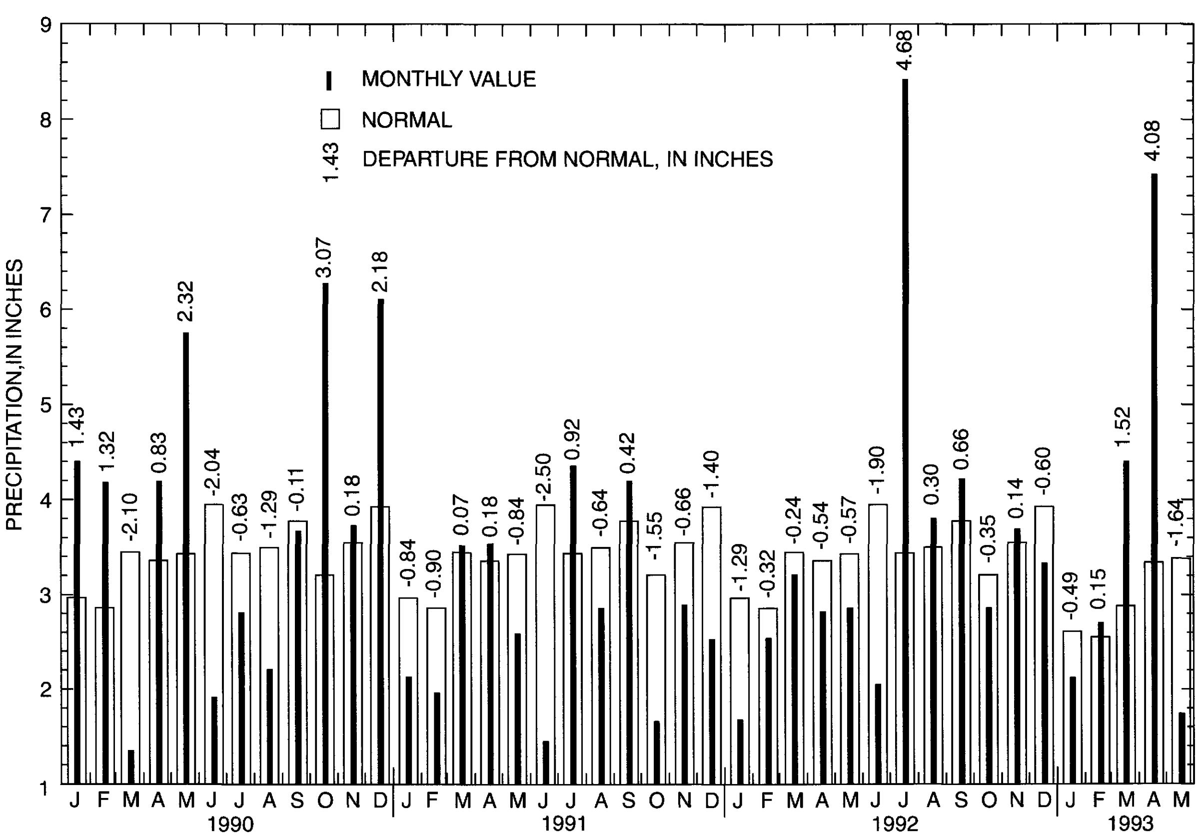


Figure 5. Monthly precipitation and departure from normal at Cortland, N.Y., January 1990 through May 1993. (Data from National Oceanic and Atmospheric Administration.)

have occurred to conceptionalize and interpret the hydrogeologic framework of an aquifer. These processes, when sufficiently understood, form a basis for interpolation and correlation between data points. Glacial processes are highly diverse and have resulted in complex stratigraphy and ground-water flow patterns in the study area; therefore, extensive data are needed for accurate representation of the hydrogeologic system.

Glacial Geology

Erosion by ice and meltwaters during the last glaciation modified the bedrock topography in the study area and removed most of the previously deposited unconsolidated materials (Muller and others, 1988); thus, sediments from the last glaciation (Late Wisconsinan) are prevalent. Some of the sediments that were eroded by ice became entrained in the glacier, or were dragged along its bottom, where they were ground up and later deposited as lodgment till atop bedrock or older glacial deposits. Lodgment till consists of poorly sorted clay, silt, sand, and stones that were compacted by the ice and is a poor aquifer; it is often referred to by drillers and farmers as "hardpan" or "boulder clay"—their testimony to its toughness to drill into or plow.

Valleys in the study area form a dendritic drainage pattern and increase in width to the southwest, indicating that water in the preglacial drainage system in the East and West Branch Tioughnioga River Valleys flowed southward, that Trout Brook flowed westward, and that a stream in the reach of the Tioughnioga River Valley between Polkville and Blodgett Mills flowed northwestward (fig. 6). All four streams converged at Cortland to form a major ancestral river that flowed southwestward in the Otter Creek valley. The southwestward route of the Tioughnioga River was blocked by ice in the Fall Creek valley during Late Wisconsian time and was diverted to the southeast, where it now flows in a narrow valley and exits the study area near Bloggett Mills (fig. 1). The diversion of the Tioughnioga River in the study area resulted in a "separated valley" (Randall and others, 1988), which is a broad valley that is partly filled with stratified drift, is drained by minor streams (Otter Creek and Dry Creek), and abuts a large stream at one end (Tioughnioga River). The small streams in separated valleys are vulnerable to depletion by large ground-water withdrawals, which lower the water table below the streambed and thereby induces water to seep through the streambed into the aquifer.

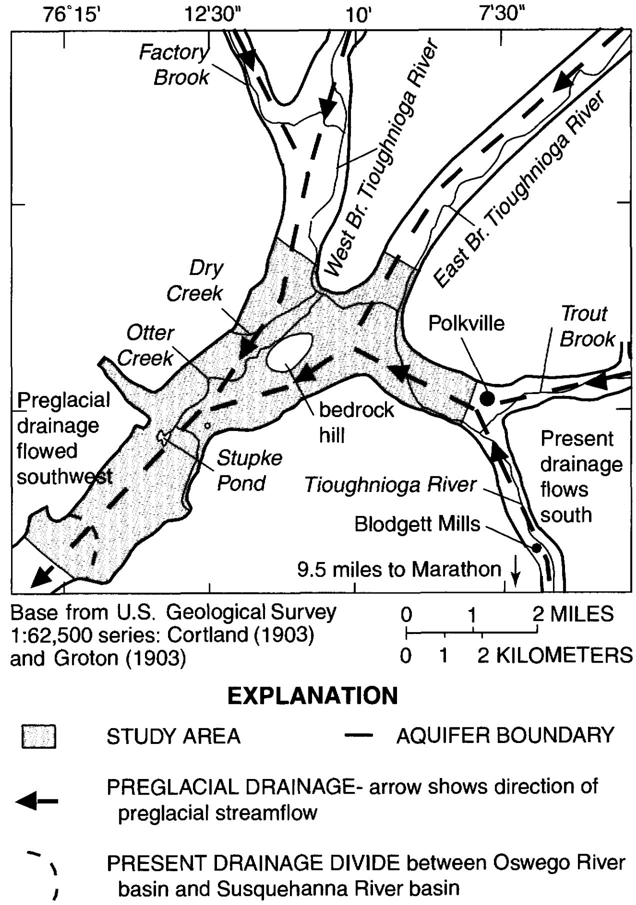


Figure 6. Preglacial drainage in Cortland, N.Y., study area.

Bedrock Scouring

Flowing ice and subglacial meltwaters first removed older unconsolidated deposits, then scoured the underlying Devonian-age shales and siltstones, resulting in widened and deepened bedrock valleys characteristic of glacial terrain. The bedrock valleys are asymmetrical in some places, such as in the Otter Creek Valley near South Cortland (geologic sections A-A′ and B-B′, figs. 7A and 7B), where a buried bedrock bench runs along the northern valley wall, and are nearly symmetrical in other places, such as in the West Branch Tioughnioga River valley (sections C-C′ and D-D′, figs. 7C and 7D).

The longitudinal bedrock profile is nearly flat in the West Branch Tioughnioga River and Otter Creek-Dry Creek valleys, where elevations range from 900 to 950 ft above sea level (figs. 7C and 8). The bedrock floor slopes southward in the East Branch Tioughnioga

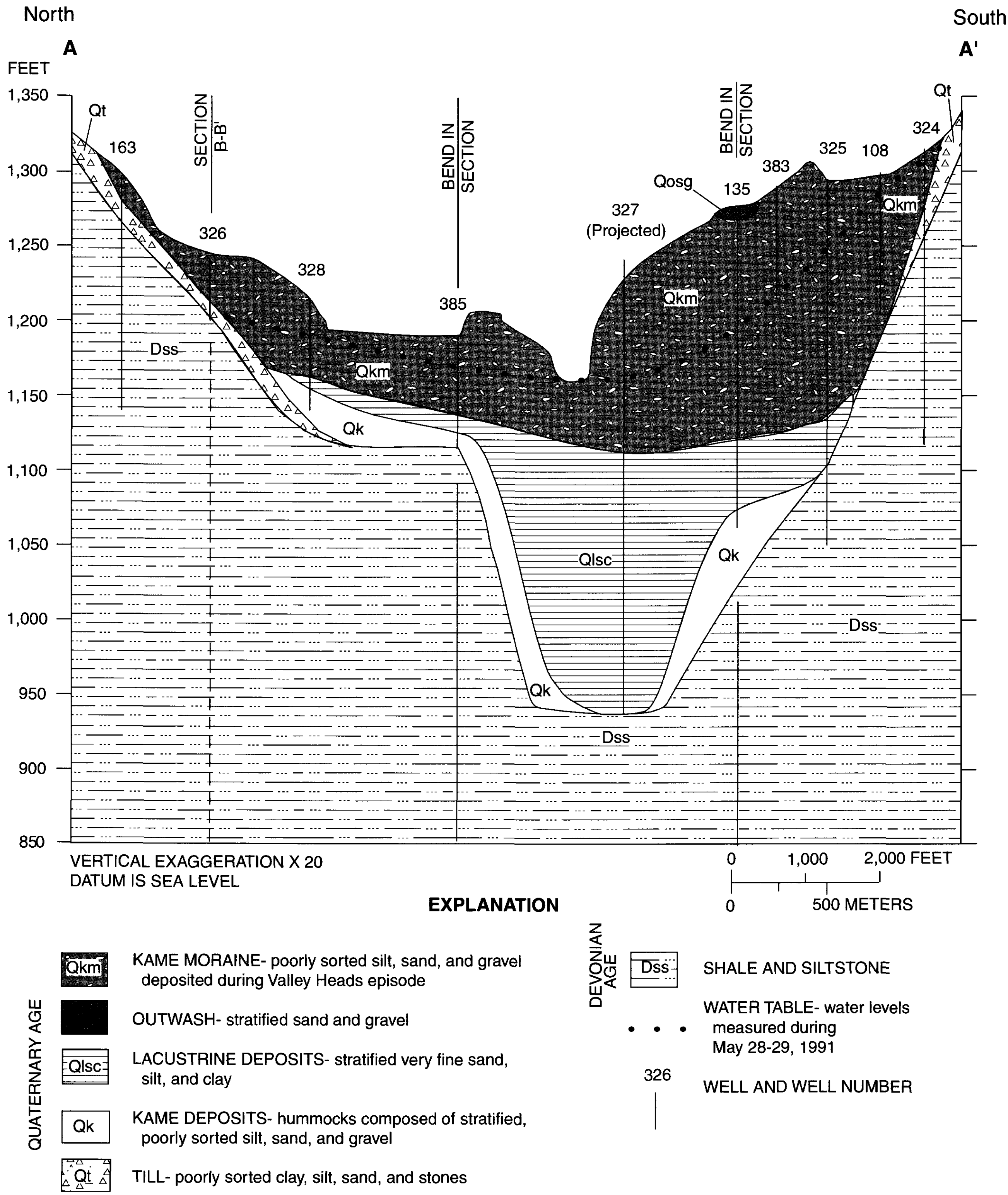


Figure 7A. Hydrogeologic section A-A′. (Line of section and well locations are shown in pl. 1.)

River Valley (Reynolds, 1987) and slopes northwestward in the Tioughnioga River Valley from the col (preglacial divide) near Messengerville to the eastern part of the City of Cortland. A conspicuous depression in the bedrock floor in the eastern part of the city (fig. 8) at well 430 (pl. 1) is the location of the lowest

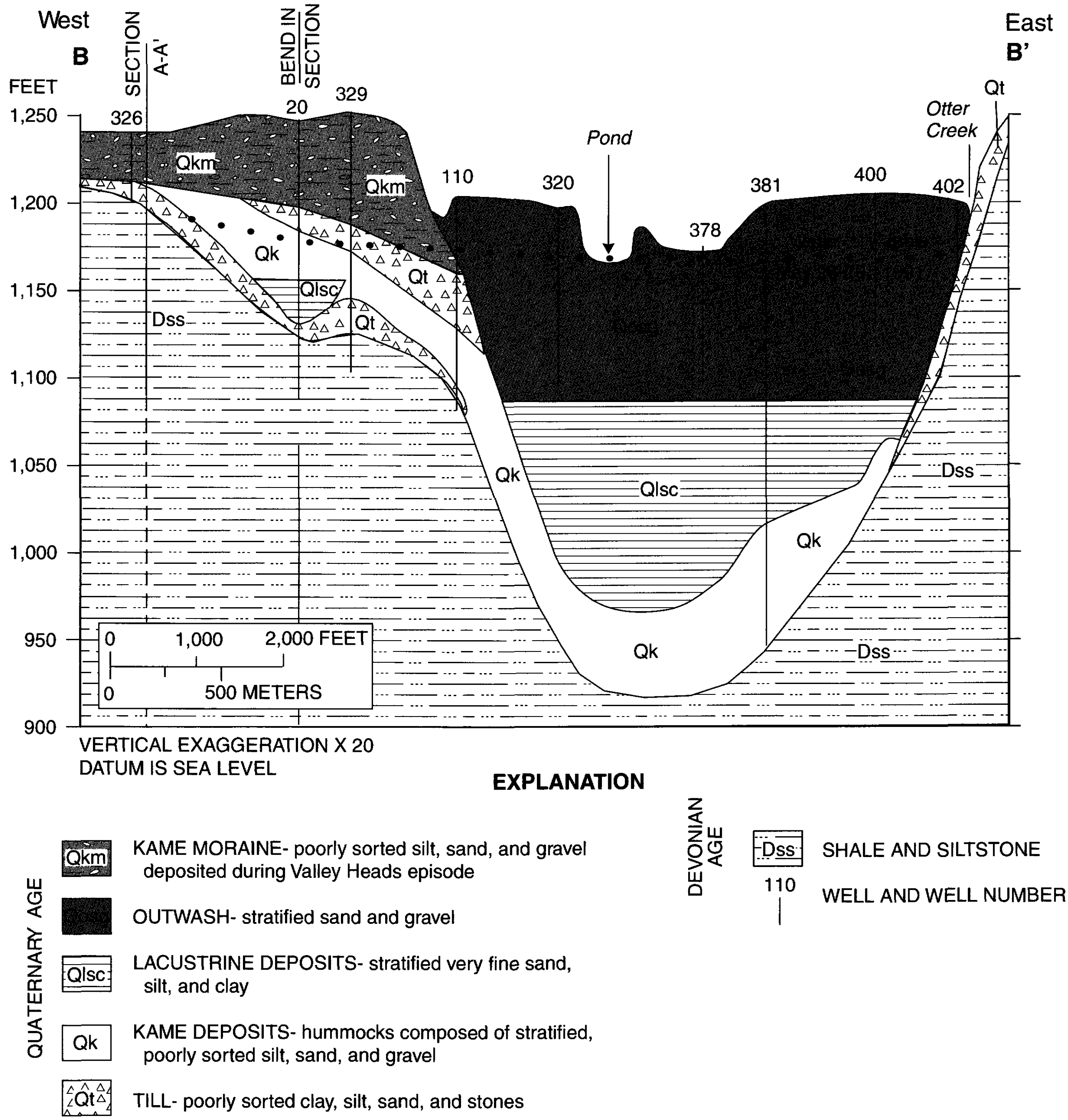


Figure 7B. Hydrogeologic section B-B′. (Line of section and well locations shown in pl. 1.)

elevation of the bedrock surface (801 ft) and the thickest valley fill found in the study area (313 ft thick).

In the center of the city is an isolated, 120-ft-high, egg-shaped (from top view) bedrock hill (fig. 1) that is surrounded by valley-fill deposits more than 200 ft thick. This landform is known as an umlaufberg (Muller, 1970), which formed when meltwaters deposited outwash around the hill and buried a preglacial bedrock spur between the northeast side of the hill and the bedrock massif hills to the north. The SUNY campus is on this hill.

Kames and Kame Terraces

As the glacier began to retreat from its maximum extent in northern New Jersey about 19,000 years before present (Late Wisconsinan time) it took about 5,000 years for the ice front to recede northward and give ground to the Cortland area (Muller and Calkin, 1993). As the glacier receded from the study area (between 14,000 and 15,000 years before present), the uplands emerged first because the ice was thinner there than in the valleys. Meltwater and upland streams that

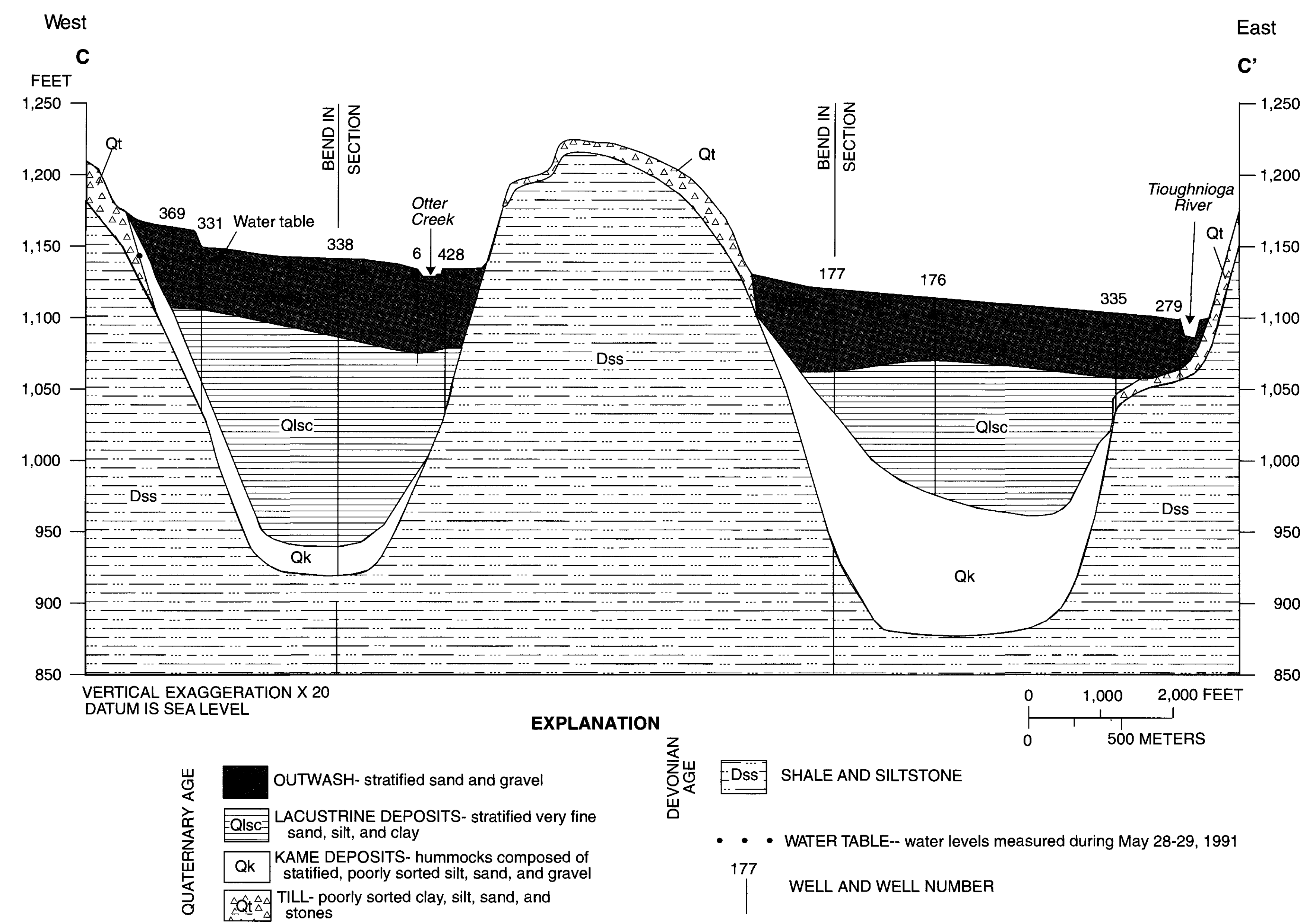


Figure 7C. Hydrogeologic section C-C′. (Line of section and well locations are shown on pl. 1.)

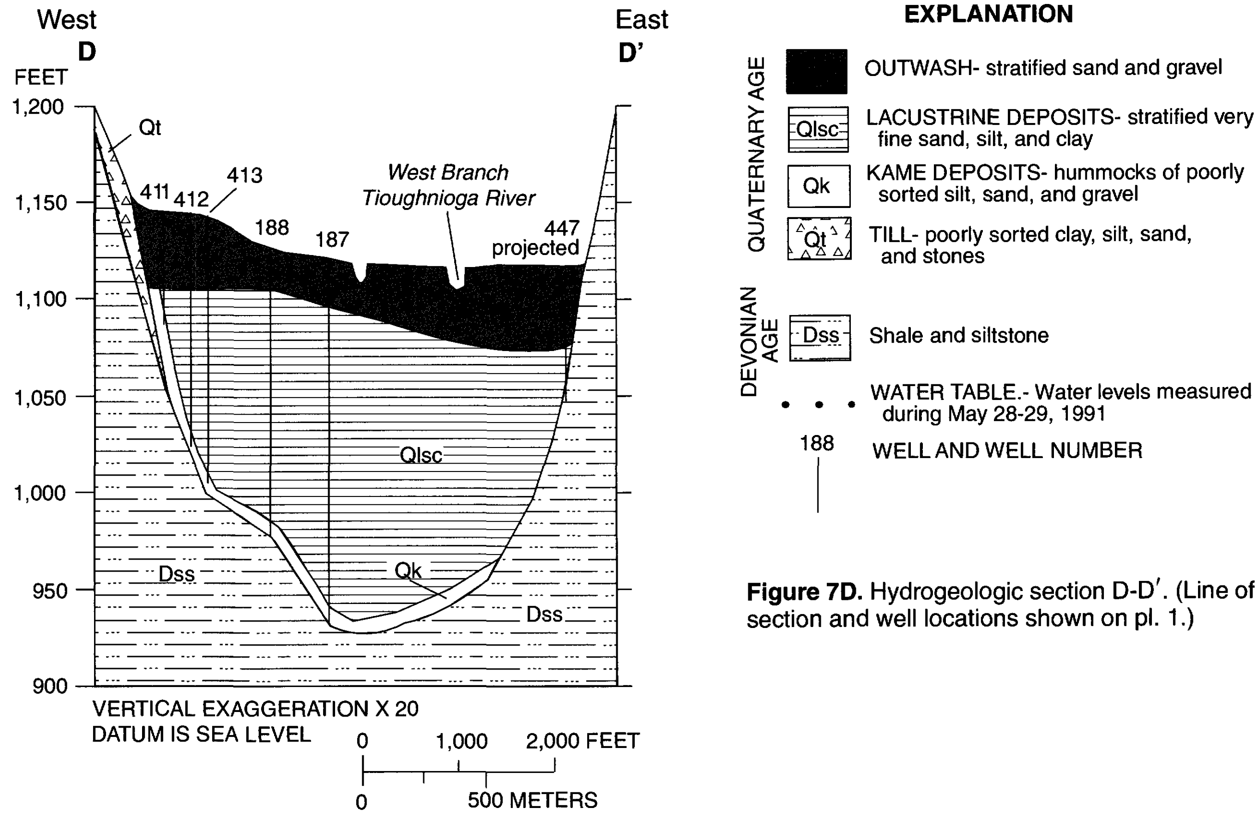


Figure 7D. Hydrogeologic section D-D′. (Line of section and well locations shown on pl. 1.)

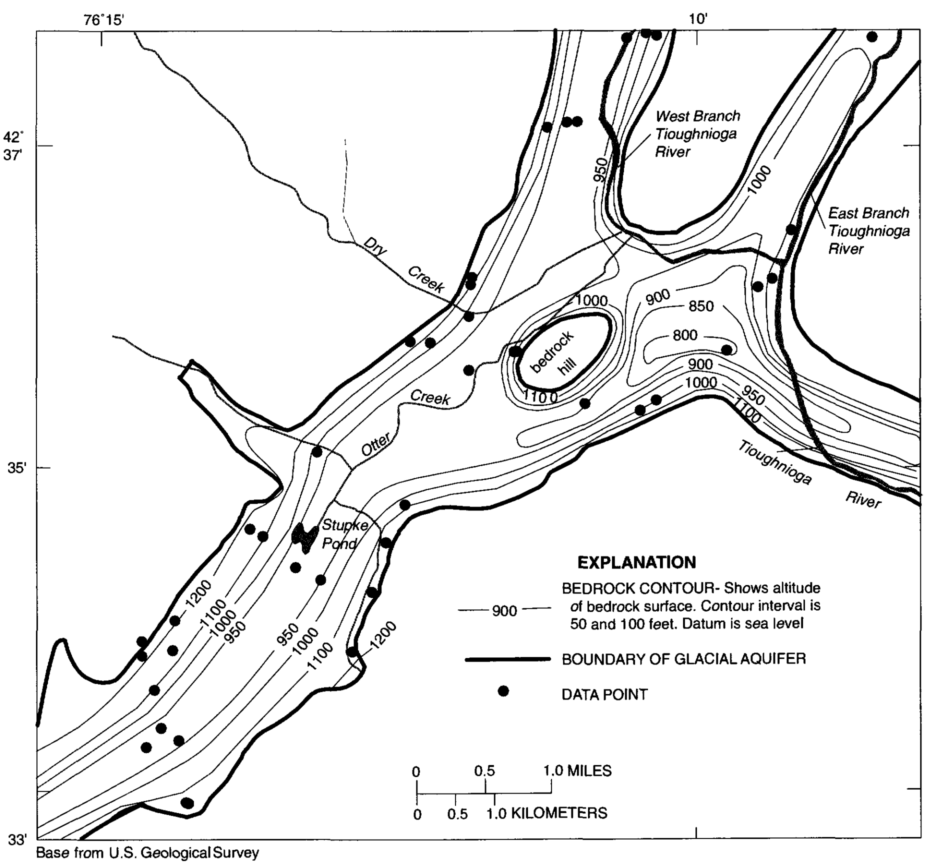
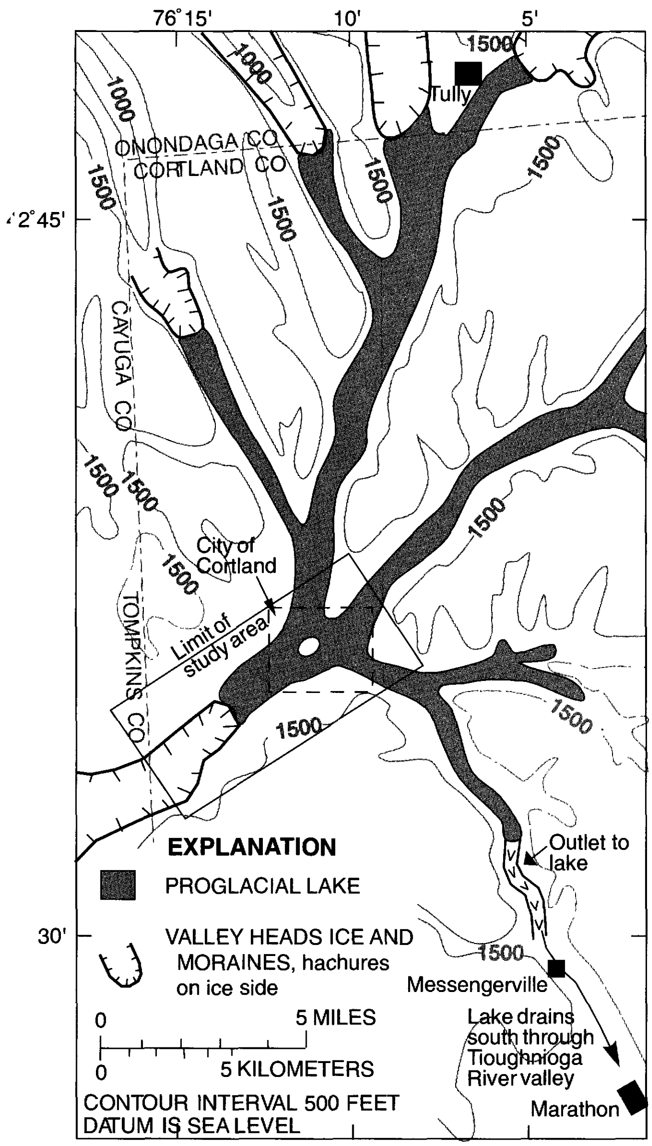


Figure 8. Bedrock-surface altitude in Cortland, N.Y., study area.

drained into the valleys deposited sand and gravel, silt, and clay on the remaining ice and between the ice and the bedrock hillside. When the ice melted, the sediments atop and next to it collapsed, forming hummocky mounds of ice-contact deposits known as kames and kame terraces. Kames typically consist of poorly sorted silty sand and gravel of moderate permeability, but discontinuous zones of well-sorted, highly permeable, coarse sand and gravel are found in some places. Large areas of kames are found on hillsides at Cortland High School in the southeast part of the study area, South Cortland, and in the East Branch Tioughnioga River Valley (pl. 1).



Base from U.S. Geological Survey, 1954, 1:250,000

Figure 9. Location of Valley Heads ice and moraines that dammed drainage in valleys of the Tioghnioga River basin. (Location is shown in fig. 2.)

Kame deposits on hillsides are typically 10 to 80 ft thick and form minor aquifers where they are saturated; in some places, however, kame deposits may be only seasonally saturated. Kame deposits in the central parts of the valley form confined aquifers where they are overlain by lacustrine very fine sand, silt, and clay. Buried kame deposits are typically 60 to 170 ft thick in the western and eastern parts of the study area (figs. 7B, 7C), and 2 to 30 ft thick in the West Branch Tioughnioga River Valley (fig. 7D). Kame deposits in areas where the confining layer is absent, or pinches out before extending to the edges of the valley, are overlain by outwash sand and gravel (fig. 7C) and form a continuous unconfined aquifer.

Valley Heads Moraine System

A major standstill of the ice front in the northern part of the Allegheny Plateau of central New York between 14,000 and 14,900 years ago resulted in deposition of large amounts of sediment that formed the Valley Heads Moraine system (Muller and Calkin, 1993). A Valley Heads Moraine formed in the western part of the study area and in valleys north of it (fig. 9). This moraine is called "Valley Heads" because it formed a drainage divide between, and headwater areas of, the southward draining Susquehanna River basin and the northward draining St. Lawrence River basin.

The crest of the Valley Heads Moraine in the western part of the study area is characterized by kame and kettle topography (pl. 1). Kettles formed where blocks of ice melted, leaving depressions. The ice side (southwest side) of the moraine is relatively steep and hummocky, whereas the northeast side grades from hummocky terrain to a moderately sloping, pitted outwash plain that, in turn, grades to a slightly sloping, smooth outwash plain. The moraine deposits consist of heterogeneous sediments including coarse kamic sand and gravel in the upper part, and fine-grained sediments, such as till and lacustrine material, in the lower part.

Proglacial Lakes and Lacustrine Deposits in Valleys

Glaciers were imposing obstructions to streams in northward draining valleys—the ice formed dams that impounded water in valleys. These impoundments are known as proglacial lakes. During the retreat of Late Wisconsinan ice in central New York, proglacial lakes occupied large parts of valley systems, including the Tioughnioga River drainage system (fig. 9).

Upland streams and meltwaters from the glacier transported and deposited gravel, sand, silt, and clay into proglacial lakes. The coarse-grained, heavy sediments carried by these streams (sand and gravel) were deposited nearshore to form deltas, whereas the fine, light sediments (very fine sand, silt, and clay) were carried further out into the lake, were they settled to form a lake-bottom deposit (lacustrine unit). This lacustrine unit is found throughout the valley in the study area except where it thins and pinches out along the valley edges (fig. 10). It is as much as 90 ft thick in the eastern part of the study area, 15 ft thick in the northern and central parts, and 170 ft thick in the southwestern part. This unit underlies the upper outwash aquifer and overlies the confined aquifer.

A delta was found at the well 341 site (pl. 1), on McLean Road in the central part of the aquifer. The well penetrated a sequence of coarse sediments that graded with increasing depth to fine sediments from 0 to 83 ft below land surface. The sequence is interpreted as coarse outwash from land surface to 37 ft below land surface that overlies deltaic sediments from 37 to 83 ft below land surface. This sequence, in turn, overlies fine-grained lacustrine sediment.

The proglacial-lake outlet was south of Messengerville (fig. 9). Elevations of proglacial-lake outlets are useful because they indicate the maximum lake level and, thus, the maximum elevation at which lacustrine deposits can be found. The exact elevation of this outlet is uncertain, however, because the Tioughnioga River eroded much of the sediment plug that formed the outlet channel. The lake's water level can be estimated from other evidence, however. For example, the absence of beaches and hanging deltas that would be expected to flank hillsides along the valleys suggest that the highest water level was lower than the present valley-floor elevation (about 1,100 ft). The highest elevation at which lacustrine deposits were found at drilling sites in the study was 1,090 ft (penetrated by well 429 in the southern part of the city); therefore, the maximum lake level was probably between 1,090 and 1,100 ft.

Glaciofluvial Sediments (Outwash) of the Valley Heads Episode

As the sediment plug that dammed the proglacial lake at Messingerville (fig. 9) was eroded, allowing the proglacial lake to drain to the south in the Tioughnioga River valley, meltwater from retreating Valley Heads ice throughout the area developed a braided-stream system that deposited large amounts of glaciofluvial sediments (outwash) on top of the lacustrine sediments. The outwash forms a wedge-shaped deposit that is more than 100 ft thick near the head of outwash in the western part of the study area (fig. 7B, geologic section B-B′) and thins eastward to 35 to 45 ft thick in the southern and eastern parts of Cortland (fig. 7C, geologic sectionC-C′). Outwash in the study area grades from coarse boulder gravel at the head of outwash in the southwestern part to coarse cobble and pebbly, sand and gravel in distal reaches in the central and eastern parts of the study area. The outwash, along with local deltaic deposits, forms most of the highly permeable unconfined aquifer in the study area (fig. 11). Drilling with percussion-tool and air-rotary drilling rigs is difficult near the head of outwash, where boulder gravel is present, and augering is nearly impossible. The large amount of very coarse sediments that form the outwash in the study area indicate that large discharges of fast-flowing meltwaters characterized the period of the Valley Heads standstill.

Ice Readvance and Drainage of Proglacial Lake During Late Stages of Deglaciation

A discontinuous 10- to 20-ft-thick layer of till that overlies the morainal and outwash deposits in the western part of the study area indicates that ice readvanced or surged northeastward to about Stupke Pond during the late stages of the Valley Heads episode. The till is typically found 10 to 30 ft below land surface and is overlain by 10 to 30 ft of sand and gravel deposited by subsequent meltwater.

The final glacial event to affect the study area was the draining of a proglacial lake that formed in the Fall Creek valley between the retreating ice front and the western side of the Valley Heads Moraine. The lake drained eastward through an outlet on the moraine at an elevation of about 1,195 ft and eroded a 200-ft-wide, 10- to 20-ft deep channel in the moraine and created a widening swath through the outwash in the western and central parts of the study area (pl. 1). This erosion of outwash left 10- to 20-ft-high cutbanks (pl. 1) along the channel, and outwash terraces above it. Test boring 345, in the middle of the channel, encountered boulders the size of bowling balls to depth of 20 ft below land surface, indicating that large volumes of fast-moving water had flowed through the channel.

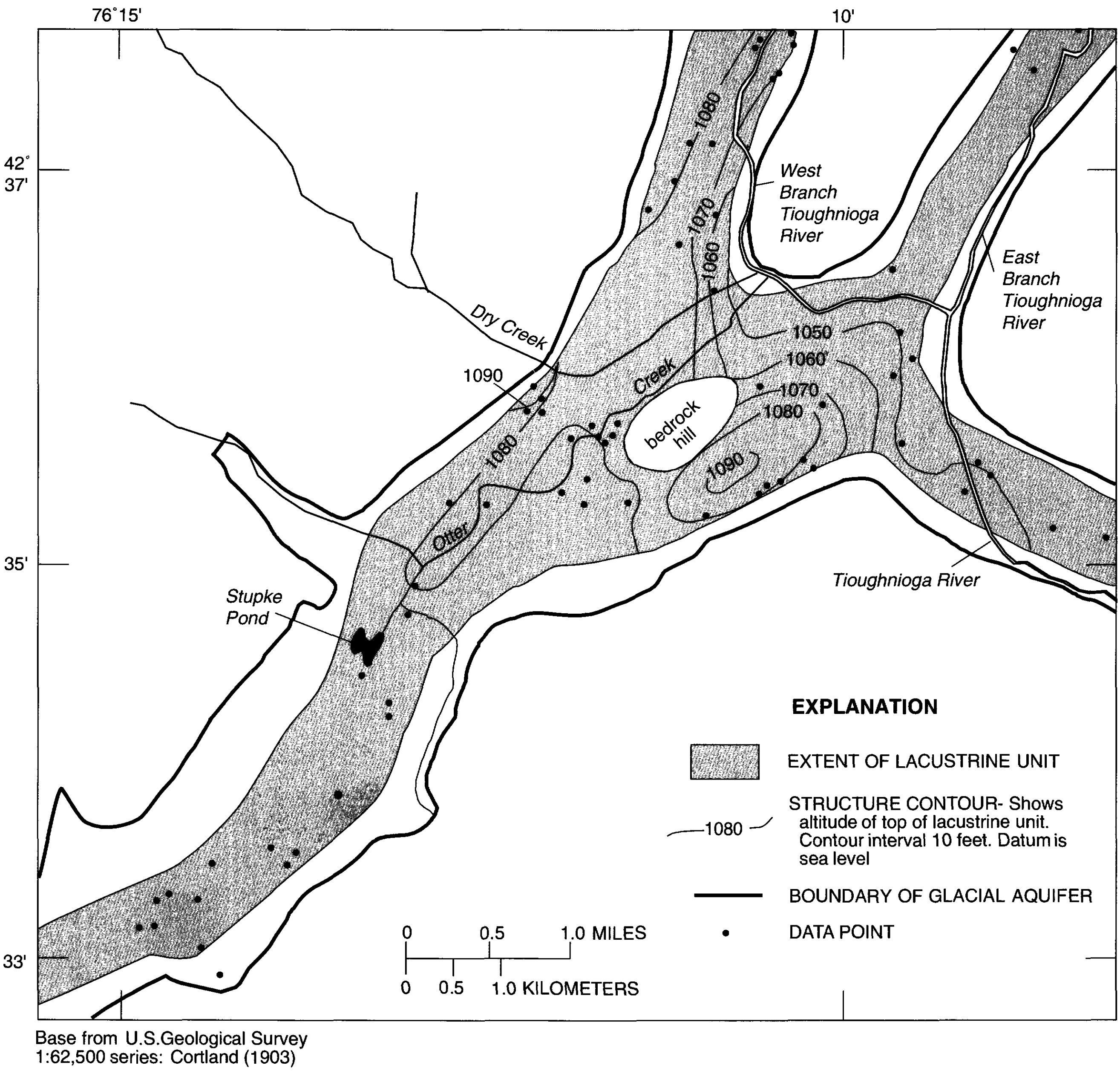
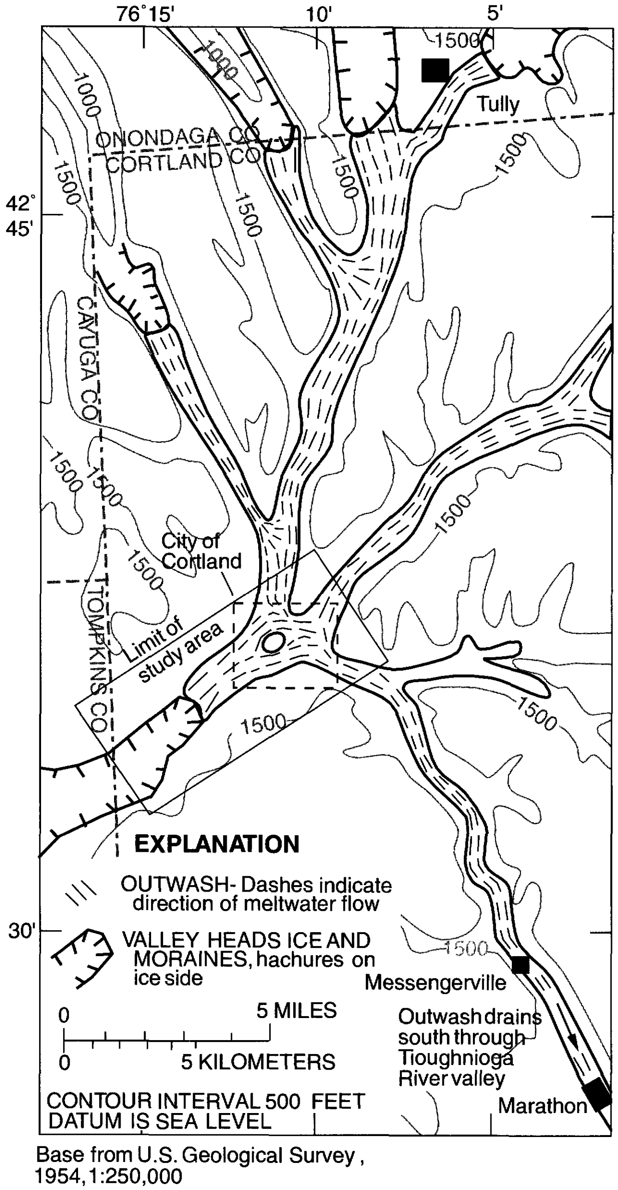


Figure 10. Upper surface altitude of lacustrine unit in Cortland, N.Y., study area.

Hydrology of the Glacial-Aquifer System

The aquifer system in the study area is part of a large regional glacial-aquifer system that occupies major valleys in the Tioughnioga River basin (fig. 11). The regional aquifer system is bounded laterally by till-covered bedrock hillsides (pl. 1) and beneath by the bedrock valley floor. The aquifer system in the study area consists of a 40-to 80-ft-thick unconfined sand and gravel aquifer that overlies a 1- to 155-ft-thick lacustrine confining layer that, in turn, overlies a 1- to 170-ft-thick confined sand and gravel aquifer (fig. 12). The base of the confined aquifer is the till and bedrock. Although the confining unit impedes ground-water movement between the upper and lower aquifers in the middle of the valley, the two aquifers are in hydraulic contact where the confining layer is absent in many places along the valley walls. The unconfined sand and gravel aquifer in the study area is one of the most productive aquifers in New York State and has been designated as a "Primary Aquifer" by the New York State Department of Environmental Conservation, and as a "Sole Source Aquifer" by the U.S. Environmental Protection Agency.



Base from U.S. Geological Survey, 1954, 1:250,000

Figure 11. Positions of Valley Heads ice, and of outwash that was deposited in valleys of the Tioughnioga River basin. (Location is shown in fig. 9.)

Geometry of Aquifers and Confining Unit

The unconfined aquifer forms a wedge-shaped deposit that thins and slopes downward to the northeast. The saturated thickness of the unconfined aquifer (from the water table to the top of the underlying lacustrine confining unit) is as much as 80 ft in the western part of the study area and thins northeastward to about 40 ft at the Tioughnioga River in the eastern part. The unconfined aquifer is underlain in most places by the lacustrine unit, which has a flat or gently northeastward sloping surface.

The lacustrine unit, which forms a confining unit that separates the unconfined aquifer from the confined aquifer (fig. 7, geologic sections A-A′, B-B′, C-C′, and D-D′), is an extensive lens-shaped deposit that consists of interbedded very fine sand, silt, and clay. It is typically 60 to 140 ft thick but is much as 155 ft thick in the middle of the valley. It thins toward the valley walls, where it pinches out. It typically lies 100 to 130 ft below land surface in the western part of the study area, 55 to 85 ft in the central part, and 35 to 65 ft in the eastern part. This unit extends beyond the study area in all valleys (fig. 10).

Beneath the confining unit is the confined sand and gravel aquifer, which is found everywhere except in the middle of the valley in the western part of the study area, where several well records indicate the lacustrine deposit to lie directly over bedrock. The bottom of the confined aquifer is the bedrock valley floor or, in some places, the top of till that overlies bedrock. The top of the confined aquifer has an undulating surface that is typical of hummocky kames and(or) bead-shaped glaciofluvial deltas that form the aquifer. The confined aquifer ranges from 1 to 170 ft thick.

Hydraulic Conductivity

Hydraulic conductivity is a measure of the ability of deposits to transmit water. Well-sorted, coarse-grained sediments have high hydraulic conductivity because they have many large interconnected pore spaces through which water can flow, whereas fine-grained sediments have low hydraulic conductivity because they have fewer and smaller interconnected pore spaces. Although clay may be well sorted and can have high porosity, it has the lowest hydraulic conductivity because the pores are so small that molecular attraction between clay particles and water prevents significant movement of water. Hydraulic conductivity of well-sorted sand and gravel typically exceeds 500 ft/d; that of medium to coarse sand and moderately sorted, fine sandy gravel typically ranges from 25 to 500 ft/d; that of fine sand and poorly sorted silty gravel typically ranges from 1 to 25 ft/d; and that of silt, clay, and till typically is less than 1 ft/d (Heath, 1983).

Hydraulic conductivity of outwash can differ widely from place to place because the complex depositional processes in meltwater environments resulted in a heterogeneous mixture of particle sizes. As stream channels were abandoned, buried, moved laterally, aggraded, or downcut, the outwash materials became mixed; the particle size in a channel reflects the flow velocity of meltwater discharging from the ice and also the place of deposition within the channel, such as, inside a meander bend, where the velocity is much lower than along the outside of the bend.

Wells that pump large amounts of water are preferred for aquifer tests because tests at these wells affect a relatively large volume of the aquifer and tend to average the effects of local anomalies within the aquifer, whereas slug tests and aquifer tests that remove only small amounts of water affect a relatively small volume of aquifer and are, therefore, more likely to tap a zone that might not be representative of the aquifer. Hydraulic-conductivity values of aquifers in the study area, as determined from aquifer tests that used large pumping rates, are given in table 2.

Unconfined Aquifer

Hydraulic-conductivity values of the unconfined aquifer in the study area, as determined from aquifer tests that used large pumping rates, ranged from 85 to 1,150 ft/d (table 2). The largest values (880 to 1,150 ft/d) were in the unconfined outwash deposits in the western and central parts of the study area, which were close to the ice front during the Valley Heads standstill, where fast-flowing meltwater deposited well-sorted coarse gravel and washed away most of the fine-grained sediment, and redeposited it in more distal reaches. Moderately high values (220 to 380 ft/d) were measured in distal reaches of unconfined outwash aquifer in the eastern part of the study area, where meltwater velocity was lower than that near the ice front and resulted in deposition of finer, less sorted sand and gravel. A moderately low value

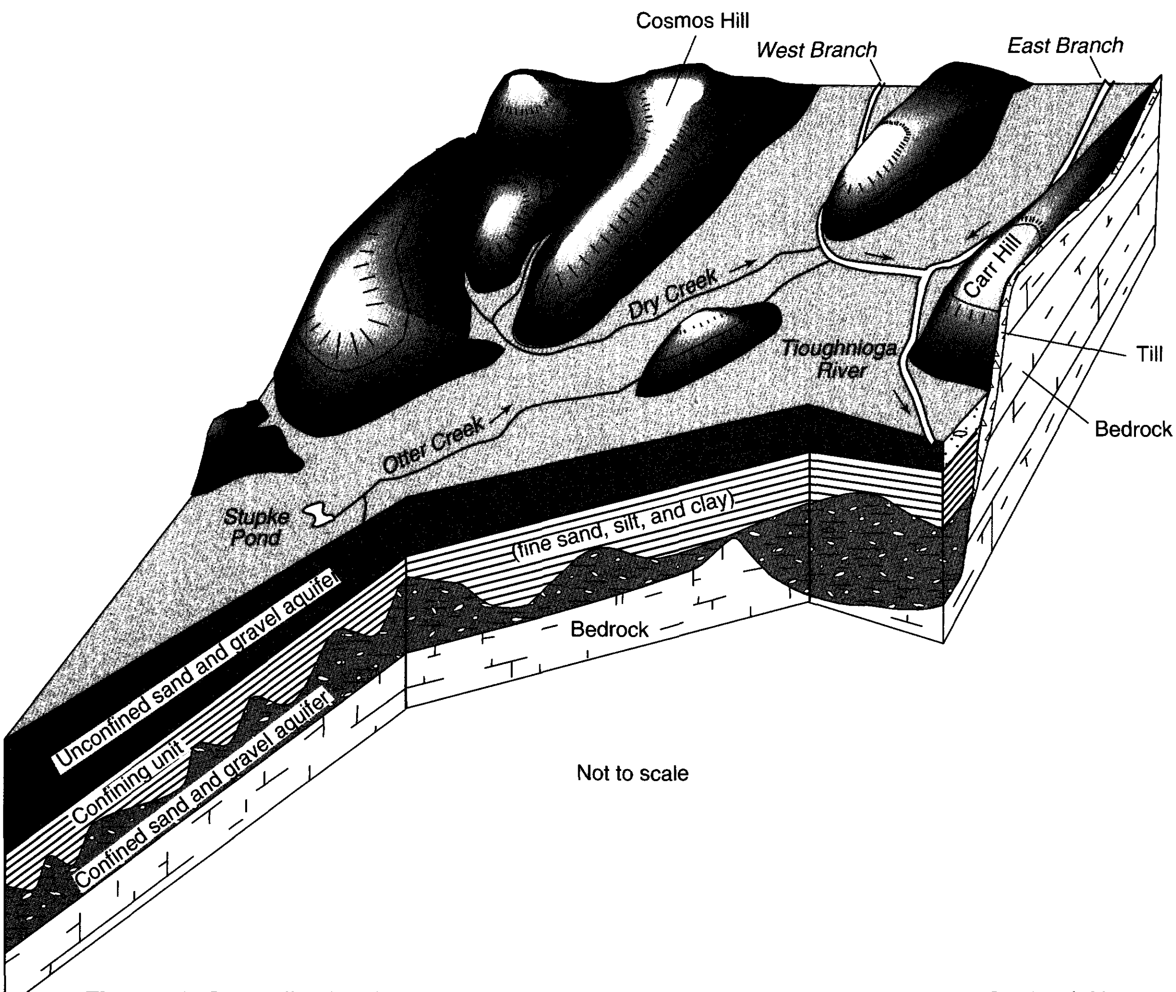


Figure 12. Generalized hydrogeologic framework of the glacial-aquifer system in the Cortland, N.Y., study area.

Table 2. Results of aquifer tests in the glacial-aquifer system in the Cortland, N.Y. study area.

[Well locations are shown in pl. 1, gal/min = gallons per minute, ft/d = feet per day.]

USGS well number	Location	Date	Aquifer	Average pumping rate (gal/min)	Average hydraulic conductivity (ft/d)
317	City of Cortland	9-12-75	Unconfined (outwash)	3,000	1,150[a]
11	Barry School	4-26-76	Unconfined (outwash)	1,200	1,050[a]
355	Town of Cortlandville (Terrace Road)	3-15-76	Unconfined (outwash)	630	950[a]
432	Town of Cortlandville (Lime Hollow Road)	7-16-91	Unconfined (outwash)	1,430	880[b]
434	Smith Corona Corporation	12-26-90	Unconfined (outwash)	975	900[c]
386	ETL Testing Laboratories	9-11-80	Unconfined (outwash)	350	350[d]
447	Rosen Superfund site	1-19-95	Unconfined (outwash)	80	220[e]
435	Monarch Tool Corporation	8-4-67	Unconfined (kame)	150	85[f]
151	Tunison Fish Hatchery	3-12-68	Confined (kame)	125	60[a]
409	Tunison Fish Hatchery	8-14-62	Confined (kame)	82	65[a]

a Cosner and Harsh, 1978
b Determined during this study
c O'Brien and Gere Engineers, Inc., 1990
d Reynolds, 1985
e Blasland, Bouck and Lee, Engineers, 1992
f Apfel, 1967

(85 ft/d) was determined from an aquifer test at an industrial well installed in unconfined kame deposits in the western part of the unconfined aquifer; this reflects the poorly sorted silty sand and gravel that is typical of kame material.

The gradation from high hydraulic conductivity in the western part of the study area to moderately high values in the eastern part is consistent with the observed northeastward decrease in grain size of sediment samples collected during test drilling. Coarse cobble gravel predominates in the western and central parts, whereas coarse sand and gravel is common in the eastern part. The northeastward fining of sediments reflects the increasing distance from the source of sediments at the ice front, and the decrease in the gradients of meltwater channels (from 40 ft/mi in the western part to 20 ft/mi in the eastern part). It also reflects a decrease in bedload particle-size through mechanical erosion during transport.

Moderately high hydraulic conductivity values (260 to 380 ft/d) were determined by three diffusivity analyses (transmissivity divided by storage coefficient), and one specific capacity analysis, in the unconfined outwash deposits along the Tioughnioga River in the eastern part of the study area by Reynolds (1985, 1987). Low to moderately low values (3.4 to 140 ft/d) were obtained by slug tests in small-diameter monitoring wells installed in the unconfined aquifer near the valley wall at the Rosen Superfund site (pl. 1) (Blasland, Bouck and Lee, Engineers, 1992). These low values probably result from the mixing along the valley walls of poorly sorted, silty sand and gravel inwash from uplands with well-sorted outwash.

Confined Aquifer

Low- to moderately low hydraulic conductivity values (16 to 65 ft/d) were obtained for the confined aquifer from two aquifer tests at the fish hatchery in the southwestern part of the study area and one slug test at the Rosen Superfund site (fig. 1). Hydraulic conductivity values determined from aquifer tests at the fish hatchery ranged from 60 to 65 ft/d, and the value determined by a slug test at the Rosen Superfund site was 16 ft/d. These aquifer tests probably represented poorly sorted kame deposits.

Confining Unit

A hydraulic conductivity value of 2.0 ft/d was obtained from analysis of a slug test of a 2-in.-diameter monitoring well installed in the confining unit at the Rosen Superfund site (Blasland, Bouck and Lee, Engineers, 1992). Hydraulic conductivity values of the confining layer were estimated in other locations from grain-size characteristics observed in split-spoon samples and from air-rotary and cable-tool drill cuttings. A value of 2.0 ft/d was estimated for the confining unit where it consists of very fine to fine sand and silt; this value also was estimated for a similar fine-grained deposit in New Hampshire

(Tepper and others, 1990). A value of 0.1 ft/d is estimated for areas where the confining layer consists of silt and clay.

Ground-Water Levels and Flowpaths

Water-level measurements can be used to define the slope of the water table in the unconfined aquifer and of the potentiometric surface in the confined aquifer. The slope determines the direction of ground-water flow. Water levels in about 100 wells were measured during March 28-29, 1990; from May 28-June 4, 1991; and October 7-9, 1991, to obtain values representing periods of high, average, and low recharge, respectively (pl. 2-4). These measurements were used to calibrate the ground-water flow model, as discussed further on. Ground-water levels also were measured monthly in about 50 wells from July 1989 through October 1991 to determine annual water-level fluctuations. The water-level measurements made during this study indicated a hydraulic head loss of about 100 ft over the 6-mi length of the study area, from the ground-water divide in the western part to the Tioughnioga River in the east.

Ground water moves from areas of high head to areas of low head, and the directions of flow depend on local factors such as aquifer geometry, distribution of recharge, and location of discharge areas (streams, ponds, wetlands, and pumping wells). These factors also determine the altitude and slope of the water table (or of the potentiometric surface in a confined aquifer). Ground water flows roughly perpendicular to the potentiometric contours (lines of equal head), as shown in plates 2-4.

Unconfined Aquifer

Water in the unconfined aquifer generally moves laterally from the edges of the valley toward the center, then northeastward along the axis of the Otter Creek-Dry Creek valley and discharges to pumping wells and to the West Branch Tioughnioga and the Tioughnioga Rivers. The study area contains four major pumping centers: (1) the City of Cortland well field, (2) the well field for the Town of Cortlandville on Terrace Road, (3) a well for the Town of Cortlandville on Lime Hollow Road, and (4) the purge well at the typewriter plant in the western part of the study area (pl. 2-4).

The hydraulic gradient in the unconfined aquifer in the middle of the valley typically ranges from 0.0027 ft/ft during periods of low water levels to 0.0037 ft/ft during periods of high water levels. The steeper hydraulic gradients along the edges of the valley in some areas than in the middle probably result from kame deposits of low hydraulic conductivity and(or) proximity to major recharge areas, such as where upland streams flow onto the aquifer and lose water to the coarse sediments.

Ground-water flowpaths during periods of high, average, and low recharge shift with the magnitude and distribution of recharge. For example, water infiltrating from upland tributary streams that flow onto the Otter Creek-Dry Creek valley forms a fan-shaped ground-water mound within the unconfined aquifer. Water spreads from the apex of the mound (where the stream enters the edge of the valley) toward middle of the valley where, in effect, it "pushes" the flowpath of ground water in the middle of the valley (the water is moving down the axis of the valley) toward the opposite side of the valley.

The extent of the "push effect" depends upon the local geology, the size of the upland tributary basin, and recharge conditions at the opposite valley wall. The median annual-minimum streamflow is highly dependent on the size of a drainage basin and the amount of sand and gravel in it (Thomas, 1966). Drainage basins that are underlain by significant amounts of sand and gravel (more than 20 percent of the basin) have significantly higher streamflow during low-flow periods than basins underlain entirely by till or bedrock. During low-recharge conditions, streamflow in small upland till and bedrock basins and on unchanneled hillsides is minimal or absent and would provide little or no recharge to the main valley from these streams. Streams in large upland tributary basins that contain significant amounts of sand and gravel tend to be perennial, however, and provide a continuous amount of recharge to the aquifer (Thomas, 1966).

Confined Aquifer

The study area contains only 15 wells that tap the confined aquifer because the unconfined aquifer has adequate yields in most places, making more costly deep wells unnecessary. Therefore, the inferred directions of ground-water movement in the confined aquifer are less certain than those in the unconfined aquifer, which are based on water-level measurements in more than 100 wells.

The direction of ground-water flow in the confined aquifer, as inferred from water-level measurements made in 15 wells finished in the confined aquifer, generally follows that in the unconfined aquifer; that is, from the edges of the Otter Creek-Dry Creek valley toward the center, then northeastward down the valley axis. Ground water in the West Branch and East Branch Tioughnioga River valleys flows southward and southwestward, respectively, then, southeastward as underflow down the Tioughnioga River valley at the confluence with the Otter Creek-Dry Creek valley.

Vertical (downward) gradients were measured in some nested piezometers along the edges of the valley where the confining unit is absent. These areas are where water in the unconfined aquifer flows vertically downward to the confined aquifer.

Conceptually, water in the confined aquifer may move up into the unconfined aquifer along the edges of the valley in the eastern part of the study area, as indicated by ground-water-flow simulations (discussed in the modeling section). Monitoring wells would need to be installed along the edges of the valley in this area to determine whether such upward flow actually occurs.

Sources of Recharge

The aquifer system receives recharge from three sources under natural (nonpumping) conditions— (1) infiltration of precipitation on the aquifer, (2) upland sources, such as runoff from unchanneled hillsides and seepage from bedrock that border the aquifer, and (3) seepage from tributary streams that flow onto the aquifer (fig. 13). The unconfined aquifer receives additional recharge from (1) infiltration beneath recharge basins at an industrial site in the western part of the aquifer, and (2) induced infiltration from streams and ponds near the major pumping wells.

Direct Infiltration of Precipitation on the Valley

Part of the precipitation that falls on surficial sand and gravel is returned to the atmosphere by evapotranspiration; the remainder infiltrates and recharges the aquifer. Thus, the amount of recharge by infiltration (R_i) equals precipitation (P) minus evapotranspiration (ET), assuming that ground-water evapotranspiration is negligible:

$$R_i = P - ET \quad (1)$$

Rates of recharge from precipitation vary seasonally. Most of the precipitation that falls during the dormant period of vegetation (typically from mid-October through the end of April) infiltrates into the aquifer, but little reaches the aquifer during the growing season (May through September) because it is lost through evapotranspiration.

In the Northeast, evapotranspiration in any year can be estimated as the long-term average annual precipitation minus long-term average annual stream runoff (Lyford and Cohen, 1987). Average annual runoff for 53 years (1939-91) in the Tioughnioga River basin, measured at a streamflow gage at Cortland (USGS station 01509000, pls. 2-4) was 23.0 in. (Campbell and others, 1992); thus, the average annual evapotranspiration would equal 18.2 in. (long-term average annual precipitation of 41.2 in. minus long-term average annual runoff of 23.0 in.), and the long-term average annual recharge would be 23.0 in. (long-term average annual precipitation of 41.2 in. minus average annual evapotranspiration of 18.2 in.).

Upland Sources

Although direct infiltration of precipitation on the valley has been considered the chief source of recharge to sand and gravel aquifers, recent studies in the glaciated Northeast indicate that, in regions of moderate to high topographic relief (where hills rise more than 500 ft above the adjacent valley floor), more than half of the natural recharge to surficial stratified-drift aquifers in the valleys can be derived from upland runoff (Morrissey and others, 1987). For example, 58 percent or more of the recharge in two glacial aquifers in valleys in central New York was derived from (1) unchanneled runoff from hillsides that border the valley-fill aquifer, and (2) seepage loss from upland tributary streams that flow over the aquifer (Randall and others, 1988).

Recharge to valley-fill aquifers from adjacent unchanneled hillsides include surface runoff and the lateral movement of ground water (within upland till, sand and gravel, and bedrock) that flows toward the valley and seeps into the aquifer along the its edges (fig. 13). All precipitation that is not lost through evapotranspiration in the unchanneled drainage areas in the uplands is assumed to become either runoff or ground water that will eventually reach the valley and infiltrate into the aquifer. If a stream is at the base of the hill, however, runoff and ground water from the hillside will discharge into the stream rather than to the aquifer.

The amount of recharge from runoff from adjacent unchanneled hillsides annually can be calculated by the following equation:

$$R = P - ET \times DA \qquad (2)$$

where R = recharge from runoff from unchanneled hillsides
P = precipitation
ET = evapotranspiration
DA = drainage area of hillside

Tributary streams (channeled flow) that drain till-and-bedrock basins in the uplands are major sources of aquifer recharge where they enter and flow over the permeable surficial sand and gravel in the main valley. Small tributaries that flow onto the aquifer typically go dry, especially during the summer, when flow in streams is small and the water table in the valley-fill aquifer falls below the streambed, allowing water in the stream to seep below the channel. The rate of recharge from losing tributaries is controlled largely by the vertical hydraulic conductivity and thickness of the streambed and by the hydraulic heads in the stream and aquifer. Rates of recharge from tributaries were calculated from several sets of streamflow measurements made during periods of high, average, and low recharge in 1990-91 in most tributary streams that flow onto the aquifer (table 3). Discharges at the measuring sites are shown in plates 2 through 4. Most tributary streams in the study area lose water to the aquifer where they flow onto the valley; an exception is Otter Creek, which can be divided into three reaches that have two flow regimes; these are (1) the reach from the point where Otter Creek enters the valley to where it joins the outlet to Stupke Pond, (2) the reach from Stupke Pond to the umlaufberg, and (3) the reach where Otter Creek flows north of the umlaufberg to its mouth. Reaches 1 and 3 lose water during the entire year; and reach 2 typically gains water during high-recharge conditions but loses water during periods of average and low recharge. Reach 3 is hydraulically connected to the aquifer during most of the year, except when the water table is lower than the streambed in the summer, causing Otter Creek to dry up. Otter Creek can be considered the main trunk stream in the Otter Creek-Dry Creek valley because it has the only reach in the valley that gains water, even though for only part of the year.

Only part of the water in upland tributaries recharges the aquifer during periods of high streamflow (during spring and during large storms throughout the year); the remainder flows over the aquifer and discharges into the West Branch Tioughnioga and Tioughnioga Rivers. During average- and low-flow conditions (summer, fall, and winter), however, all of the water in most tributary streams recharges the aquifer, except in Dry Creek, which goes dry only during extended droughts. As the water table declines through the summer, losing streams typically dry up in the upstream direction, starting at the mouth, whereas gaining streams typically dry up in the downstream direction, starting at the headwaters.

Table 3. Streamflow losses and gains in tributary streams above unconfined aquifer in the Cortland study area, 1990-91.

[Values are in cubic feet per second; location of tributaries and streamflow-measurement sites are shown in pls. 2-4.]

Tributary stream	Streamflow loss (-) or gain (+) between measurement sites near valley wall and near mouth, or where streams dry up		
	March 29,1990 (high recharge)	May 30-June 4, 1991 (average recharge)	October 9, 1991 (low recharge)
UPPER REACH OF OTTER CREEK (from valley wall to outlet to Stupke Pond)	-1.20	-0.41	Dry at valley wall
Dry Creek	-0.81	-0.54	-0.37
Perplexity Creek	-0.65	-0.20	Dry at valley wall
Tributary A	-0.95	-0.12	Dry at valley wall
Tributary B	-0.40	-0.12	Dry at valley wall
Tributary C	-0.41	Dry at valley wall	Dry at valley wall
Tributary D	-2.10	-0.23	Dry at valley wall
Tributary E	-1.22	-0.11	Dry at valley wall
Estimated loss from other tributaries not measured	-0.50	-0.05	Dry at valley wall
Sum of tributary losses	-8.24	-2.73	-0.37
LOWER REACH OF OTTER CREEK (Stupke Pond to mouth)	+8.60	-0.42	Entire reach was dry

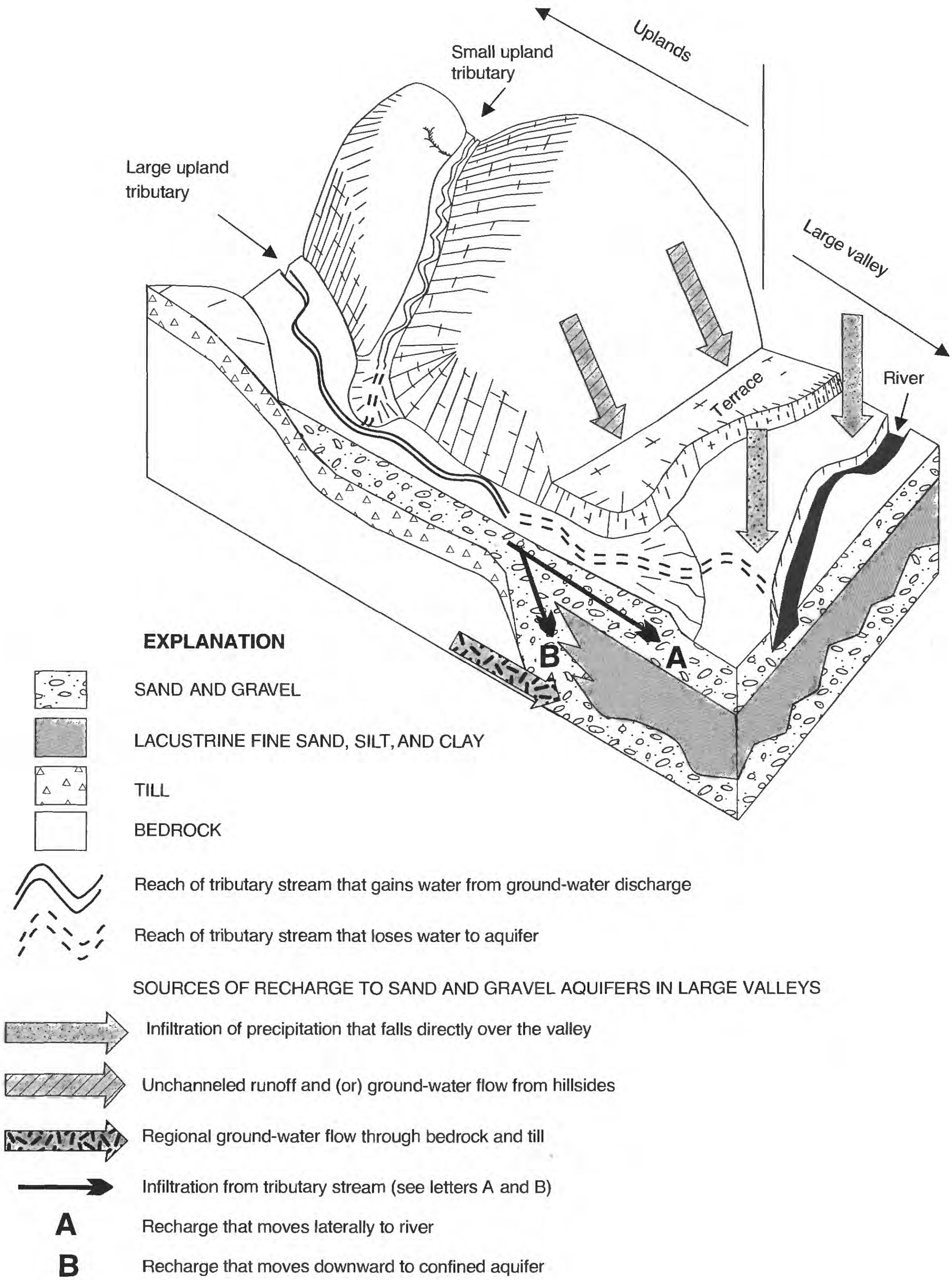


Figure 13. Sources of recharge to stratified drift in valleys in the glaciated Northeast. (Modified from Morrissey and others, 1987, fig. 1.)

Induced Infiltration by Ground-Water Withdrawals

Pumping affects Otter Creek where it flows through the City of Cortland well field because that reach of the creek is hydraulically connected to the aquifer (pl. 2-4). Pumping lowers the water table beneath the stream surface and thereby induces infiltration from the stream to the aquifer. Pumping of a City of Cortland municipal well during low-flow conditions once caused a nearby reach of Otter Creek to dry up, and when the pump was turned off, water reappeared in the creek (James Roberts, former manager of Cortland Water Department, oral commun., 1990). The rate of induced infiltration for a pumping rate of 4.29 Mgal/d, as estimated from results of numerical model simulation of average-conditions, is 0.6 ft^3/s. No induced infiltration can occur when Otter Creek dries up.

The municipal well for the Town of Cortlandville on Lime Hollow Road may induce some infiltration from a pond 400 ft south of the well. The similarity of water levels in the pond to those in the municipal well suggests that the pond is hydraulically connected to the aquifer.

Infiltration From Recharge Basins

A recovery well (well 434, pl. 1) at the typewriter plant in the western part of the study area is pumped at a rate of about 980 gal/min. The water is routed through an air stripper, where most volatile-organic chemicals are removed, then discharged to recharge basins about 750 ft north of the plant (pl. 2-4), where it infiltrates back to the aquifer.

Ground-Water Discharge

Water in the unconfined aquifer discharges (1) as seepage into major streams and, seasonally, to some reaches of Otter Creek; (2) to pumping wells; and (3) as seepage to springs that are headwaters to the Fall Creek valley in the western part of the study area. Most of the water pumped from municipal wells is eventually piped to the sewage-treatment plant as wastewater, where it is treated and discharged into the Tioughnioga River in the eastern part of the study area (pl. 2). Most water in the confined aquifer leaves the study area as underflow in the Tioughnioga River valley in the southeastern part of the study area.

Seepage to Streams

Most of the ground water that discharges to streams enters the West Branch Tioughnioga and Tioughnioga Rivers; lesser amounts enter the reach of Otter Creek from the Stupke Pond outlet to the umlaufberg in the central part of the study area. The confining unit prevents most water in the confined aquifer from flowing upward into the unconfined aquifer and into the streams.

Measurements of streamflow in the West Branch Tioughnioga and Tioughnioga Rivers and in Otter Creek (fig. 14) indicate that total ground-water discharge to these streams was 17.8 ft^3/s for average-recharge conditions and 8.4 ft^3/s for low-recharge conditions (table 4); measurements in these large streams during periods of high recharge were impractical (for safety reasons).

Table 4. Ground-water discharge to West Branch Tioughnioga River, Tioughnioga River, and Otter Creek during average- and low-flow conditions, 1991.

[All values are in cubic feet per second. Location of measurement sites and reaches shown in fig. 14].

Reach	Site no.	Average-flow conditions: Measured discharge	Average-flow conditions: Net gain within reach (upstream value minus downstream value)	Low-flow conditions: Measured discharge	Low-flow conditions: Net gain within reach (upstream value minus downstream value)
A. West Branch Tioughnioga River	1	31.4		12.8	
	2	40.6	9.2	18.7	5.9
A and B. Tioughnioga River	1	83.2		53.3	
	3	99.2		64.4	
minus discharge from sewage		-8.4	7.6	-8.6	
treatment pland	subtotal	90.8		55.7	2.5
B-E. Otter Creek	3	1.4		0.0	
	7	2.4	1.0	0.0	0.0
		TOTALS	17.8		8.4

Municipal and Industrial Withdrawals

Total ground-water withdrawal from the glacial-aquifer system by municipal and industrial wells ranges from 6.76 to 7.20 Mgal/d (table 5), most of which is from the unconfined aquifer. The largest user is the City of Cortland, which, during 1984-92, pumped 3.9 to 4.3 Mgal/d (data from records at the Cortland Water Department). Substantial leaks in the distribution system (Douglas Withey, manager of Cortland Water Department, oral commun., 1994) result in conveyance losses that return some of the water to the aquifer; therefore, actual discharge from pumping is somewhat less than the reported values.

The Town of Cortlandville pumped from 0.65 to 0.99 Mgal/d of water from its two well fields during 1990-91 (Hayne Smith, Town of Cortlandville Engineer, oral commun., 1992). A purge well at the typewriter plant pumped at a rate of 0.69 Mgal/d from December 1989 through October 1990, and at a rate of 1.43 Mgal/d from October 1990 to at least December 1994. All pumped water from the purge well is returned to the aquifer through recharge basins 750 ft north of the plant. When the purge well was pumped continuously (since October 1990),the other production wells for the plant were not used.

Underflow From the Study Area

Within the confined aquifer, water that is northeast of the ground-water divide in the western part of the study area flows northeastward and leaves the study area as underflow through the Tioughnioga River valley at an estimated rate of 40,500 ft^3/d (0.5 ft^3/s), as calculated from Darcy's equation for one-dimensional flow in a prism of porous material:

$$Q = \frac{KA(h_2 - h_1)}{L} \qquad (3)$$

where Q = flow (L^3t^{-1})

K = hydraulic conductivity of the aquifer (Lt^{-1});

A = cross-sectional area perpendicular to flow (L^2);

h_2-h_1 = head difference across the prism of flow (L);

L = length of flowpath (L).

The following hydraulic values were used to calculate underflow (Q) out of the Tioughnioga River valley:

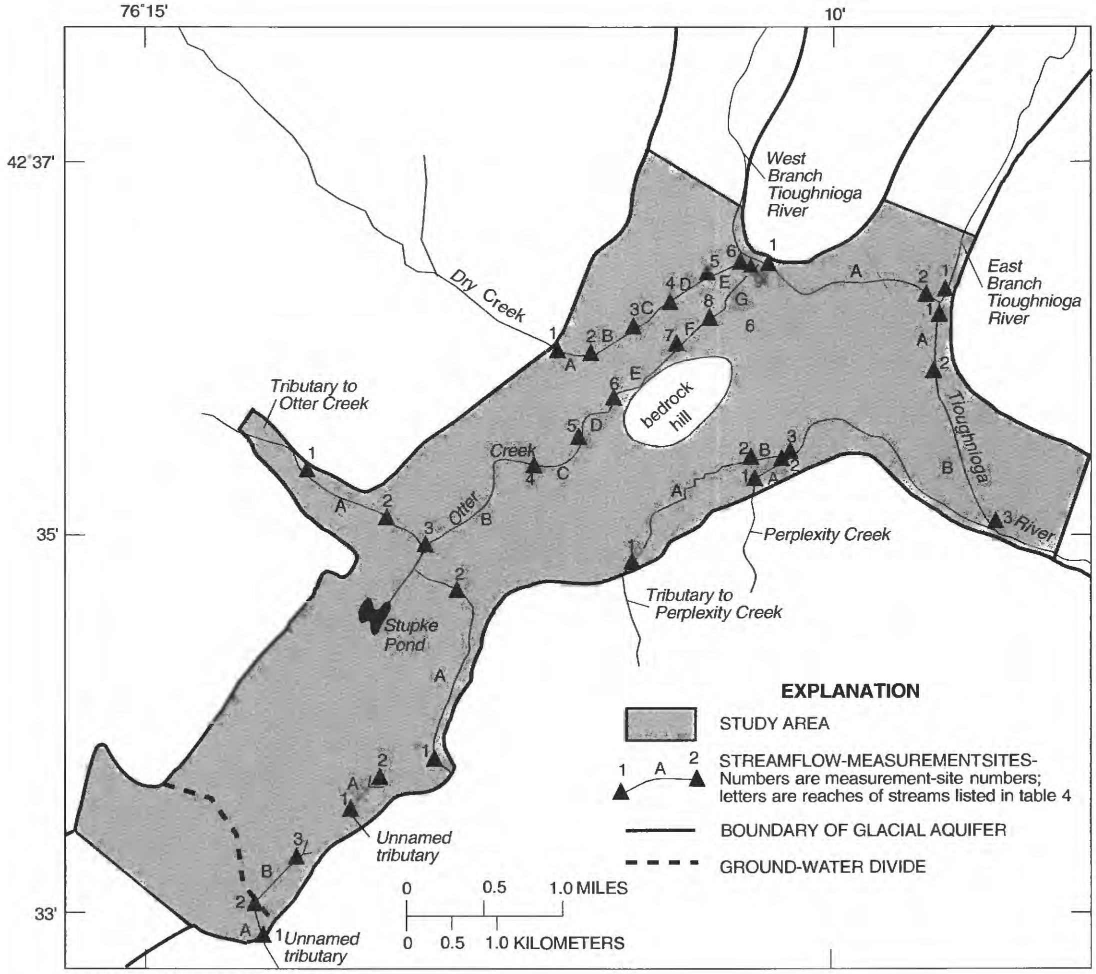
hydraulic conductivity (K)	150 ft/d
cross-sectional area (A) of valley	135,000 ft^2
head difference (h^2-h^1)	0.002 ft
length (L)	1 ft.

Ground water that is west of the divide in the western part of the study area flows southwestward and leaves the study area as underflow to the Fall Creek valley, also at an estimated rate of about 40,500 ft^3/d, or 0.5 ft^3/s.

WATER QUALITY

Water from 15 wells was sampled about monthly by the Cortland State College and Cortland County Department of Planning during 1987-93. In addition, the USGS and these two groups conducted three synoptic rounds of sampling to (1) define the extent of a trichloroethylene (TCE) plume that resulted from a spill at the typewriter plant in the western part of the study area; (2) assess the contamination-remediation efforts at the source (the plant site); and (3) compare current concentrations of common ions, metals, and nutrients in ground water throughout the study area with historical data to detect changes or trends in water quality over time. TCE was used at the typewriter plant for degreasing mechanical parts from 1958 through October 1986 (O'Brien and Gere Engineers, Inc., 1987). Results of chemical analyses are given in appendix 3.

The first round of sampling (April 4-5, 1990, a high-recharge period), entailed collection of samples from 60 wells (31 observation wells, 26 private wells, and 3 municipal wells). All samples were analyzed for common ions, metals, nutrients, and volatile-organic compounds (VOC's). The second round (September 17-20, 1990, a low-recharge period), entailed collection of samples from 31 of the 60 wells sampled previously to verify results from the first sampling, and from an additional 9 observation wells that were installed after the first sampling to obtain data needed to define the extent of the TCE plume. Of the 40 samples collected during the second round, all were analyzed for nutrients, and 30 were analyzed for common ions, metals, and VOCs. The third round of sampling, 3 years later (April 27, 1993), entailed collection and analysis of samples from 18 wells for TCE and its degradation products to determine whether remedial efforts at the typewriter plant site had improved water quality downgradient of the site.



Base from U.S.Geological Survey
1:62,500 series: Cortland (1903)

Figure 14. Location of streamflow-measurement sites in Cortland, N.Y., study area.

Table 5. Ground-water withdrawals from the Cortland, N.Y. study area by major pumping wells during low-, average-, and high-recharge conditions, 1990-91.

[All values are in millions of gallons per day. Locations of wells are shown on pl. 1.]

Well number	Owner	Recharge conditions and dates of measurement: Low recharge (Oct 7-9, 1991)	Average recharge (May 28-June 4, 1991)	High recharge (Mar. 28-29, 1990)
317	City of Cortland	4.09	4.28	4.41
354, 355	Town of Cortlandville, Terrace Road	0.56	0.40	0.65
432	Town of Cortlandville, Lime Hollow Road	.16	.59	Not pumping
434	Smith Corona Corp., recovery well	1.43	.69	.69
392	Smith Corona Corp., production wells	Not pumping	.48	.36
386	ETL Testing Labs	.22	.22	.22
373	Cortland Hospital	Not pumping	.18	.18
140, 139	Tunison Fish Hatchery	.20	.20	.20
138	Tunison Fish Hatchery	.10	.10	.10
	TOTALS	6.76	7.14	7.20

Volatile Organic Compounds

The U.S. chemical industry produces large amounts of volatile organic compounds (VOCs) that are used extensively by industries and by homeowners. Large-scale production and use of VOCs has resulted in many instances of soil- and ground-water contamination, most of which has resulted from leaks or spills at manufacturing plants, petroleum-product storage tanks, and chemical-waste disposal sites (Plumb, 1991). VOCs are low-molecular-weight hydrocarbons having very low (less than 2 percent) solubility in water, and rapid volatization. VOCs on the USEPA list of "Priority Pollutants" (U.S. Environmental Protection Agency, 1991) include trichloroethylene (TCE), benzene, 1,1,1-trichloroethane, and *cis*-1,2-dichloroethylene. Each is toxic to some degree, and most, including TCE, are believed to be carcinogenic (National Academy of Sciences, 1977). The USEPA "Maximum Contaminant Levels" (MCLs) for drinking water supplied by municipal water systems is 5 µg/L for TCE and benzene; 200 µg/L for 1,1,1-trichloroethane, and 70 µg/L for *cis*-1,2-dichloroethylene (U.S. Environmental Protection Agency, 1991). The MCL is an enforceable, health-based regulation set by the USEPA.

Many VOCs, including many of the chlorinated hydrocarbons (CHCs), are solvents used in degreasers and cleaners for metal and electronic parts, and also in paint removers, dry-cleaning fluids, drain cleaners, spot removers, and septic-tank cleaners. Other VOCs, such as benzene and toluene, are used in fuels. TCE is a CHC and a common industrial solvent that has been in commercial use for about 40 years. CHCs are persistent in the environment because they resist chemical and biological degradation; the average half-life for abiotic CHC transformations range from 2 months to 10^{10} years, and CHC half-lives for biodegradation range from 2 weeks to 8 months (Barbee, 1994). Anaerobic reductive dehalogenation (typically dechlorination) of CHCs is the primary biodegradation process in ground water; for example, *cis*-1,2-dichloroethylene is a reductive dechlorination product of TCE (Barrio-Lage and others, 1986; Wilson and others, 1991).

Extent and Migration of Trichloroethylene Contamination in the Unconfined Aquifer

The Chemistry Department at SUNY College at Cortland detected TCE in samples from a well in the central part of the unconfined aquifer in 1986. The well is 0.25 mi north of the Cortlandville municipal well field and 1.25 mi southwest and upgradient of the Cortland well field, and City and Town water managers and Cortland County health officials were concerned that the TCE could migrate to drinking-water supplies. In December 1986, samples were taken from about 23 observation wells and domestic wells by the college Chemistry Department and the Cortland County Department of Health to determine the extent and source of VOC contamination. Most of these wells were resampled about monthly during 1986-93. Most samples were analyzed by the college Chemistry Department; the rest were analyzed by the USGS laboratory in Denver, Co., and Buck Laboratory in Cortland.

From December 1986 through 1993, TCE was found in concentrations above the MCL of 5 µg/L at many wells in the central part of the unconfined aquifer. The highest TCE concentration found beyond the typewriter plant was 222 µg/L, in well 350 (owner Pace) on Pheasant Run (pl. 1) on April 9, 1987. This well 350 is 1,000 ft downgradient from the TCE source area at the plant. *cis*-1,2-Dichloroethylene, a solvent and reductive dehalogenation product of TCE, was also found in offsite wells where TCE was detected, but concentrations were below the MCL of 70 µg/L.

Horizontal Migration

Analyses of samples collected offsite by the Cortland County Department of Health and the college Chemistry Department, and of samples collected on the typewriter plant site by O'Brien and Gere Engineers, Inc. (1987), indicated that TCE in ground water was migrating northeastward. Hydrogeological consultants working for the plant found much higher concentrations of TCE and *cis*-1,2-dichloroethylene in wells at the plant site than in offsite wells and identified TCE-contaminated soils near the northwest side of the main plant building (O'Brien and Gere Engineers, Inc., 1987). The highest TCE concentrations found were at well site 448 (local well no. MW-7), installed by the consultants along the northwest perimeter of the main plant building (pl. 1), where TCE and *cis*-1,2-dichloroethylene concentrations of 10,000 and 7,600 µg/L, respectively, were found on August 3, 1989. TCE concentrations that day in 19 other wells on the site ranged from <1 to 270 µg/L, and *cis*-1,2-dichloroethylene concentrations ranged from <1.0 to 1,700 µg/L (O'Brien and Gere Engineers, Inc., 1990).

The extent of the TCE plume during the three rounds of sampling is shown in figures 15A, B, and C, respectively; the plume is defined where concentrations exceeded the MCL of 5 µg/L. The extent of the plume was roughly the same during all three sampling rounds, indicating that steady-state conditions probably had been reached. The plume extends 1.25 mi northeast from the plant and follows head gradients and the direction of ground-water flow.

Vertical Migration

The vertical distribution of TCE in the unconfined aquifer at wells 341 and 381 is plotted in figure 16. The TCE concentrations at well 341 (fig. 16A), which is 4,000 ft northeast of the TCE source at the plant, are higher in the middle zone than in the lower and upper zones of the unconfined aquifer, but the TCE concentration at well 381, which is 750 ft northeast of the TCE source, was uniformly distributed with depth (fig. 16B). The vertical distribution of TCE at well 341 (fig. 16A) is likely the result of (1) vertical dispersion of TCE with increasing distance from the source; (2) the vertical distribution of hydraulic conductivity in the aquifer, and (3) dilution by recharge (from precipitation). Coarse-grained sediments that form the top and middle zones of the aquifer and have high hydraulic conductivity provide a preferred pathway for ground-water flow and dissolved contaminants, but the fine-grained sediments of lower hydraulic conductivity in the lower zone retard downward ground-water movement and are a less preferred pathway. Little or no TCE was detected in the confined aquifer, which is protected by the lacustrine confining unit, which prevents the movement of water in the unconfined aquifer into the confined aquifer.

Effects of Remediation Efforts

A recovery well was installed at the typewriter plant as part of a "pump and treat" method for onsite remediation. Contaminated water is pumped from the aquifer and routed through an air stripper, where VOCs are volatilized and released into the atmosphere. The treated water is then piped 750 ft north of the plant and discharged into recharge basins, where it infiltrates to the water table. The return of pumped water to the aquifer causes little or no net loss of ground water. A cone of depression that has formed around the recovery well, and a ground-water mound that has formed beneath the recharge basins, alters the ground-water flow paths in the vicinity of the plant.

The effects of pumping by the TCE-recovery well and the rate of ground-water flow are essential considerations in evaluations of TCE concentrations in the plume. If the pump-and-treat system keeps the contaminated water from leaving the site, concentrations of VOCs will decrease over time through degradation and dispersion, and through downvalley movement of the tail of the plume that developed before pumping .

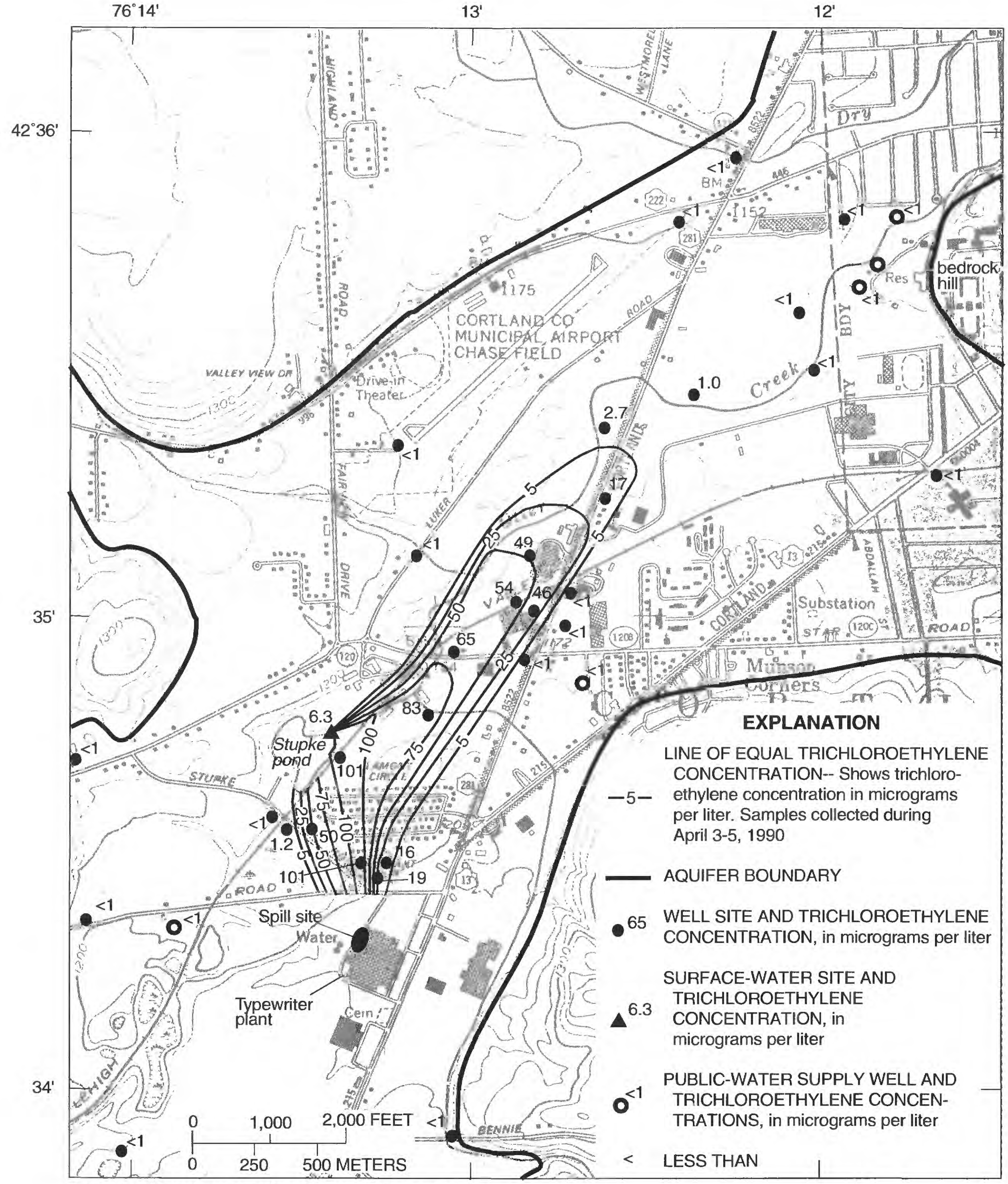
The recovery well was pumped intermittently from December 1989 through October 1990 at a rate of about 980 gal/min for 12 to 18 hours daily and continuously at this rate since October 1990. The TCE concentrations in most wells that were sampled in April 1990 (110 days after the beginning of intermittent pumping) were probably not significantly affected by the pumping because all wells that were sampled, except for well 22 (local well number CT-22), were more than 1,000 ft from the source of TCE– the distance ground water would move in 110 days at a velocity of 9 ft/d (velocity = hydraulic conductivity of 1,000 ft/d, divided by porosity of 0.3, times the hydraulic gradient of 0.0027 ft/ft).

The highest TCE concentrations found during the April 1990 sampling were just above 100 µg/L at well 350 (owner Pace) and well 121 (local well number CT-21), which are 1,000 and 2,400 ft northeast of the source of TCE, respectively (fig. 15A and pl. 1). These two wells have had the highest TCE concentrations of any offsite wells.

Pumping of the recovery well might have affected TCE concentrations at wells as far as 0.5 mi (2,640 ft) northeast of the source by the time of the second sampling round (September 17-20, 1990), as calculated for a pumping duration of 288 days (9.5 months) and a ground-water flow rate of 9 ft/d. TCE concentrations beyond this distance from the source were probably not affected yet.

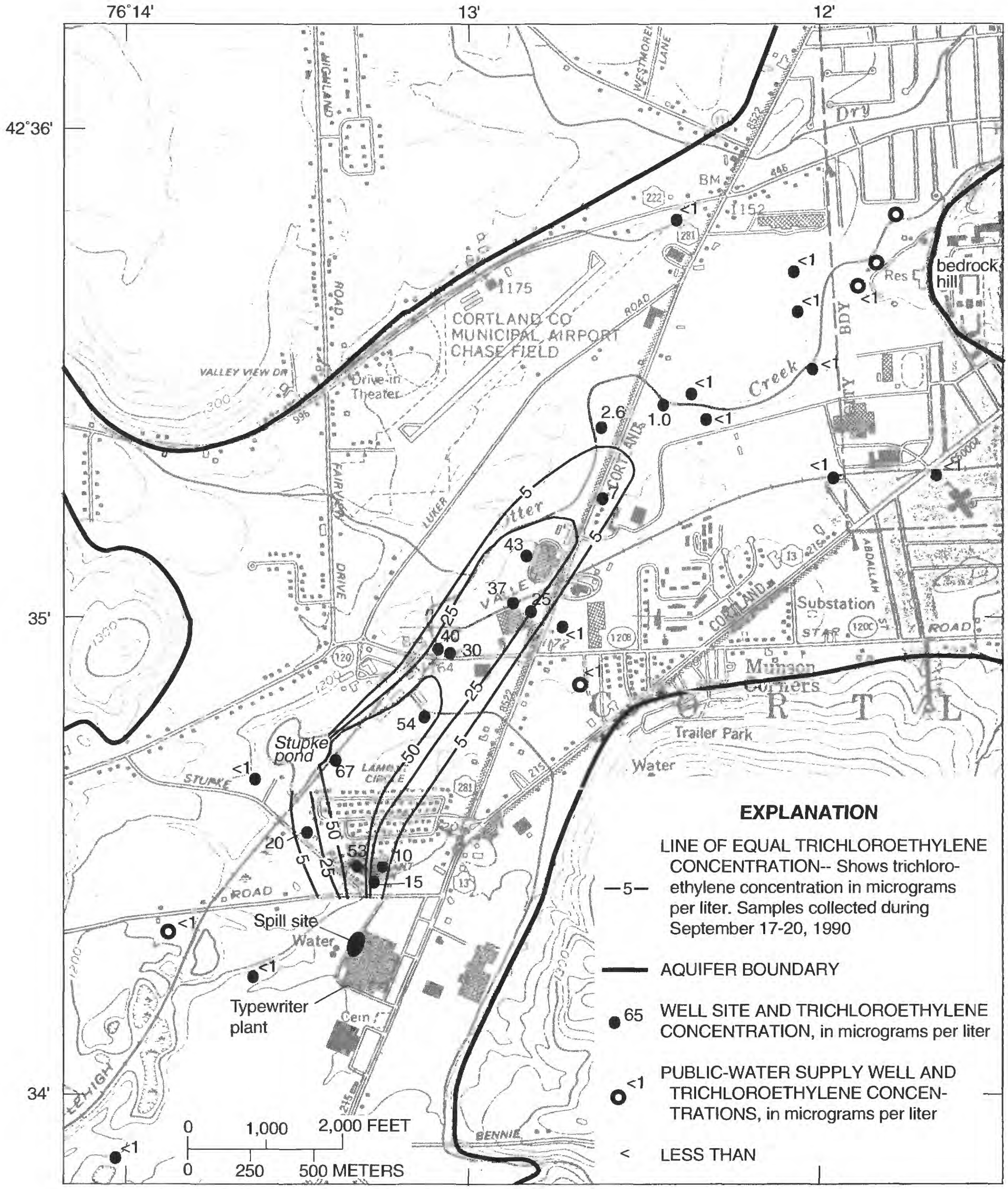
The extent of the TCE plume in September 1990 was about the same as in April 1990, but TCE concentrations were typically 30 to 50 percent lower; this could partly reflect the tendency of TCE concentrations at wells not yet affected by the recovery well to be lower during low-recharge periods (summer and fall) than during high-recharge periods (spring), as explained further on.

By the time of the third sampling round, 3 years later (in April 1993), the recovery well had been operating for 1,186 days (3.25 years), the last 2.5 years of which it had pumped continuously. During those 2.5



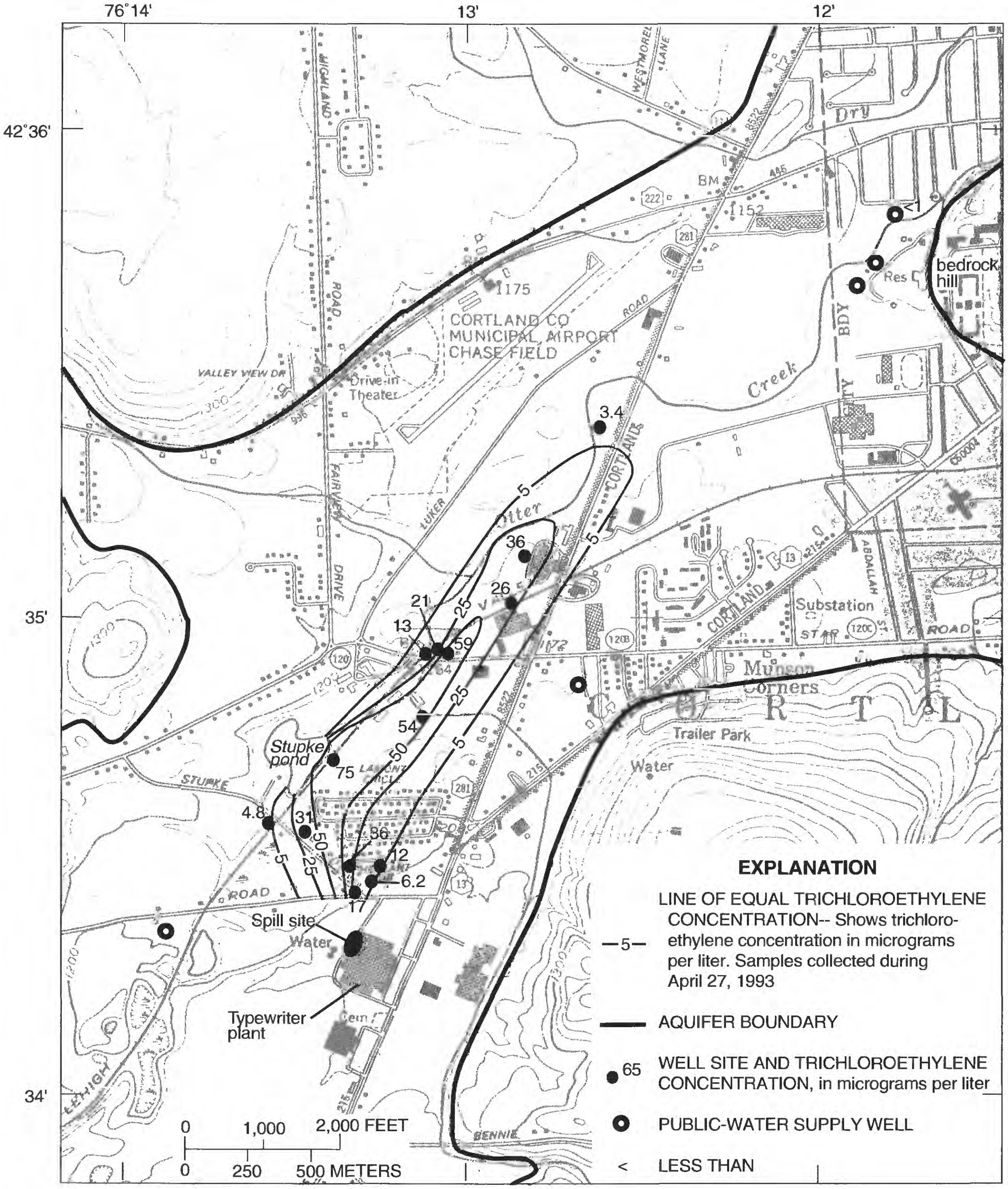
Base from New York State Department of Transportation
1:24,000 series: Cortland, New York (1980)

Figure 15A. Extent of trichloroethylene plume and lines of equal trichloroethylene concentration in study area, April 3-5, 1990.



Base from New York State Department of Transportation
1:24,000 series: Cortland, New York (1980)

Figure 15B. Extent of trichloroethylene plume and lines of equal trichloroethylene concentration in study area, September 17-20, 1990.



Base from New York State Department of Transportation
1:24,000 series: Cortland, New York (1980)

Figure 15C. Extent of trichloroethylene plume and lines of equal trichloroethylene concentration in study area, April 27, 1993.

years, ground water would had moved more than 1.5 mi from the source–a distance greater than the length of the plume (about 1.25 mi). Therefore, water at all wells sampled during April 1993 would have been affected by the recovery-well operation.

The "pump and treat" remedial program was expected to capture all contaminated ground water on the site; TCE concentrations at the site were expected to decline rapidly, and those offsite were expected to decline significantly. These expectations were bolstered by analyses of several random samples collected in the fall of 1992, which showed that TCE concentrations had decreased significantly, some to the lowest values since December 1986 (fig. 17). These decreases prior to the April 1993 sampling suggested that the pump-and-treat system at the plant site was effective. A large amount of recharge in the winter and spring of 1993 (fig. 5), which included the blizzard of 1993, reversed this trend of improvement, however.

Results of the April 1993 sampling indicated that TCE concentrations at most wells in the middle and distal parts of the plume (figs. 15C, 17B, 17C) had increased significantly since the preceding fall and were nearly as high as those detected during April 1990 (fig. 15A) and September 1990 (fig. 14B). These elevated concentrations could not have been due to additional TCE emanating from the plant area because the ground-water traveltime from there to the middle and distal parts of the plume is from 1.5 to 2.5 years. The elevated TCE concentrations can be explained, however, by desorption of TCE that had previously sorbed onto sediments in the unsaturated zone. The above-normal recharge of March and April 1993 raised the water table to its highest level in at least 10 years and resaturated upper parts of the aquifer that had been

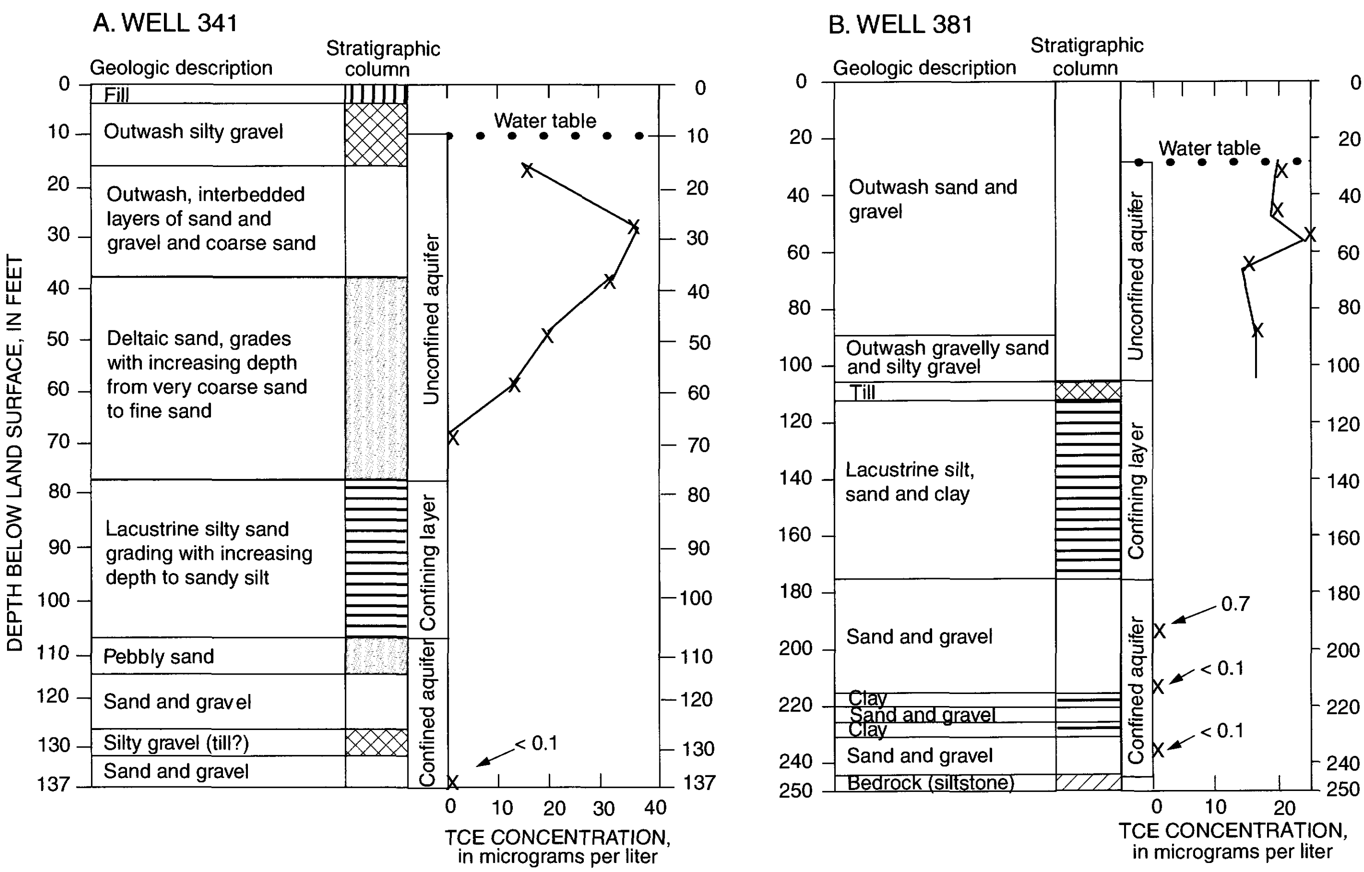


Figure 16. Vertical distribution of trichloroethylene (TCE) in ground water at two wells in Cortland, N.Y., study area: A. Well 341, 4,000 feet northeast of typewriter plant site, July 19, 1990. B. Well 381, 750 feet northeast of plant site, September 23-26, 1992. (Well locations shown on pl. 1.)

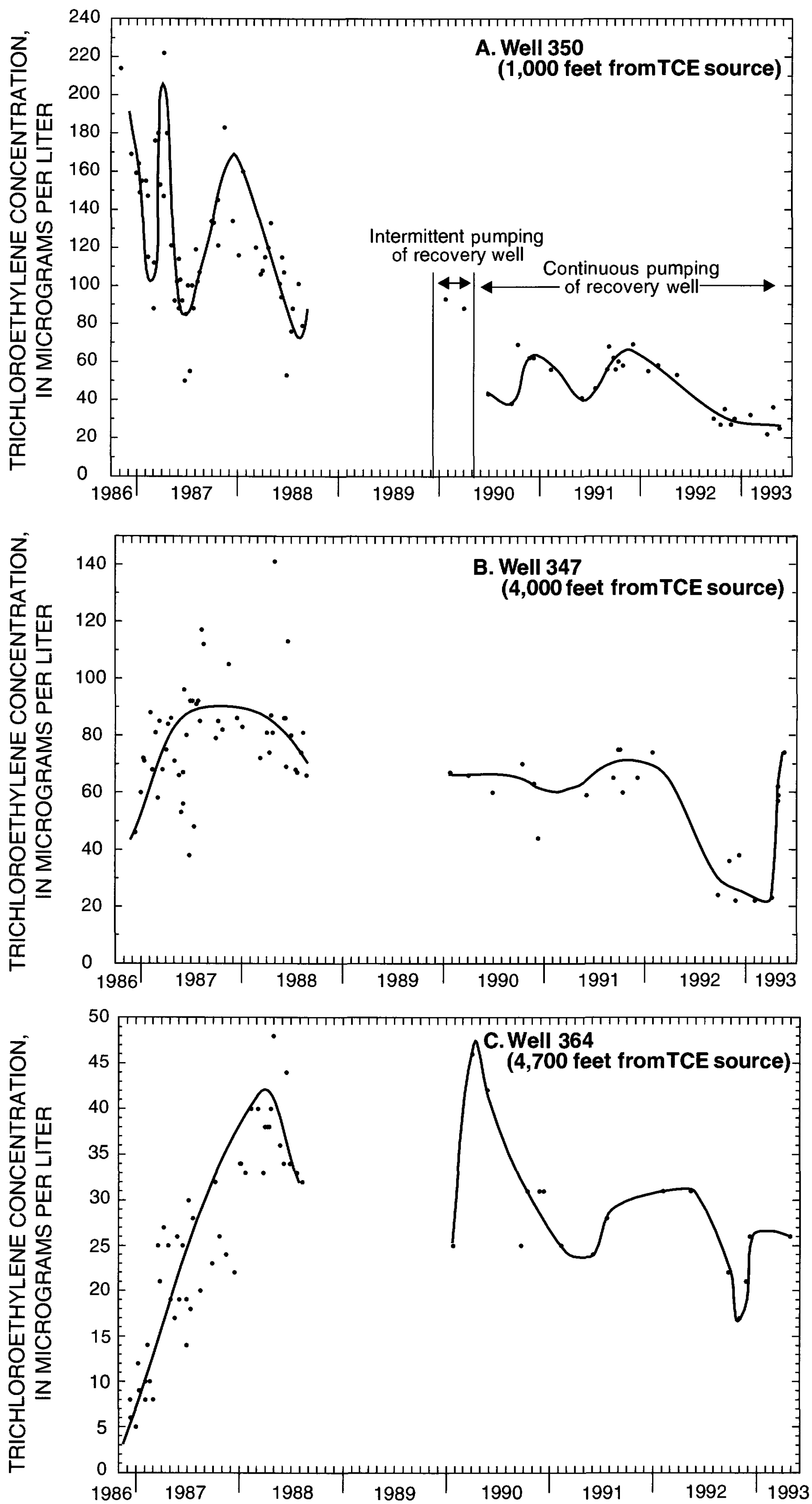


Figure 17. Trichloroethylene concentration at wells 350, 347, and 364 from November 1986 through May 1993. (Locations shown on pl. 1.)

unsaturated and that contained TCE that had not been thoroughly flushed by precipitation.

Results of the April 1993 sampling indicated that TCE concentrations had increased in the middle and distal wells but had declined significantly at some wells near the source, such as well 350 (owner Pace, fig. 17A), and at other wells on Pheasant Run (pl. 1) that had the highest TCE concentrations of the offsite wells. The lowered TCE concentrations at these wells could be explained by changes of ground-water flow paths near the plant site as a result of pumping by the recovery well and infiltration of the pumped water in recharge basins.

Long-Term Trends In TCE Concentrations

The year in which the TCE spill occurred was estimated from the arrival of the front of the plume at well 364 early in 1987 (fig. 17C) and from results of a particle-tracking program (MODPATH) in the back-tracking mode. The program calculated the ground-water traveltime to range from 21 months for high-recharge conditions to 23 months for low-recharge conditions. Subtracting 21 to 23 months from the time when the front of the TCE plume reached well 364 (early in 1987) indicates the time of the spill to be as early 1985. After the front of the plume reached well 364 in early 1987, the TCE concentrations at this well fluctuated only slightly through late 1992 (fig. 17C).

The highest concentrations of TCE in most offsite wells since the first sampling began in 1986 were found during 1987-88. Concentrations decreased slightly thereafter from 1989 through mid-1992, then decreased sharply at the end of the 1992, probably in response to (1) removal of contaminated soil, and (2) capture of contaminated ground water by the recovery well. These decreases were followed in the spring of 1993 by increases to about the same levels as those during 1989-91, however. As explained previously, the simultaneous increases of TCE concentrations in middle and distal parts of the plume suggest local releases of TCE to the aquifer, such as through desorption from a diffuse TCE source in the previously unsaturated zone of the aquifer, rather than to new TCE migrating from the source area at the typewriter plant. Desorption of TCE in the unsaturated zone can occur when (1) precipitation infiltrates the soil, and (2) a rising water table saturates the previously unsaturated zone.

TCE concentrations at wells within 1,500 ft of the typewriter plant, such as well 350 (fig. 17A), showed seasonal fluctuations. TCE concentrations were highest during the spring and lowest during the summer and fall. Hydrogeologic consultants (O'Brien and Gere, Engineers., 1990) also reported seasonal TCE fluctuations in wells at the plant. TCE concentrations at wells more than 1,500 ft from the plant showed little fluctuation, however (for example, well 364, about 4,500 ft downgradient of the plant, fig. 17C and pl. 1), indicating that seasonal fluctuations of TCE concentrations decrease with increasing distance from the TCE source.

Fate and Migration of Trichloroethylene

The fate and migration of TCE through an aquifer system are affected by physical, chemical, and biological processes. Physical processes include advection, dispersion, and nonaqueous-phase flow; chemical processes include volatilization, sorption, and dissolution; and biological processes include aerobic and anaerobic biotransformations (MacKay and others, 1985). Some of these processes are illustrated in figure 18.

The physical processes of advection, dispersion, and nonaqueous-phase flow affect the transport of TCE in the study area. The advective phase of TCE plume generally follows the direction of ground-water flow as it moves northeastward from the typewriter plant and either discharges into Stupke Pond and Otter Creek or remains in the central part of the aquifer. Physical dispersion of TCE results from differing rates of ground-water flow that result from varying lengths of flowpaths (some flowpaths follow a more circuitous route than others) and local variations in the hydraulic conductivity of the aquifer.

The relatively constant TCE concentrations that were found in most offsite wells before operation of the recovery well (1987 through the end of 1990) suggest a slow desorption of TCE from contaminated aquifer sediments and (or) dissolution of a dense, nonaqueous-phase liquid (DNAPL) in the aquifer. DNAPLs migrate downward under gravitational force in the unsaturated zone, where they may disperse, dissolve, degrade, or be removed by pumping or excavation.

DNAPL's in the unsaturated zone tend to partition into a gaseous phase and migrate as volatilized constituents. Most soil-gas TCE will diffuse upward in response to natural concentration gradients and will eventually escape into the atmosphere, but some will be adsorbed onto sediments in the unsaturated zone (Cho, and others, 1991) by one or more of the following sorption mechanisms: (1) mineral-surface absorption, (2) partitioning into natural organic matter, (3) partitioning into water that coats the surface of sediments, and (4) adsorption into micropores. The amount of natural organic matter already on the unsaturated sediments is reported as the dominant factor for absorption of CHCs onto sediments, but where the organic content of the sediment is low, absorption in micropores may contribute significantly to sorbate uptake (Farrell and Reinhard, 1994).

Where a spilled DNAPL exceeds the retaining capacity of the unsaturated zone, it seeps to the water table and sinks downward within the aquifer (fig. 18), where some of it becomes trapped in pore spaces, some dissolves in the ground water, and the rest continues downward (DNAPL is denser than water) until it encounters a stratigraphic layer of low permeability (such as at the bottom of the aquifer), where it will accumulate as a pool. Continuous dissolution and dispersion of DNAPL's within the pore spaces of the saturated sediments and in the pool at the bottom of the aquifer then provides a constant release of contaminants (Barbee, 1994). DNAPL pools have been difficult to locate because they are relatively small and commonly migrate downslope along the bottom of aquifer and accumulate in local depressions. No such pools have been found in the study area to date; they may have dispersed or migrated elsewhere, or they could have eluded detection by the few test wells that extend to the bottom of the aquifer.

The rate and extent of chemical and microbial transformation of TCE in the subsurface are controlled by the physiochemical properties of TCE, by chemical properties of soil and water, and the microbial population in the soil (Barbee, 1994). The three major isomers formed by reductive dehalogenation of TCE

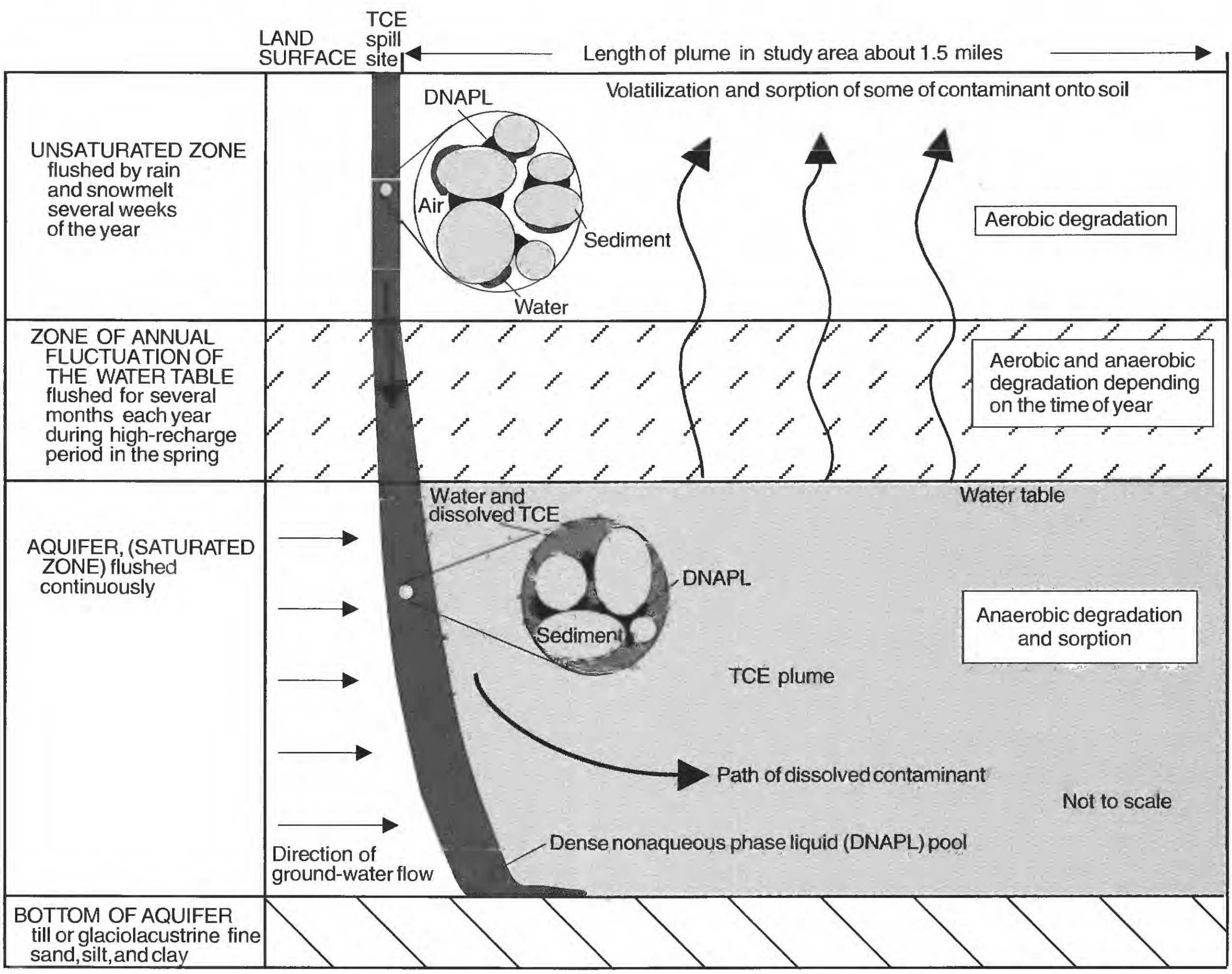


Figure 18. Physical, chemical, and biological processes that affect the fate and distribution of trichloroethylene (TCE) in and above the unconfined aquifer at Cortland, N.Y.

under methanogenic conditions by anaerobic soil microorganisms are *cis*-1,2-DCE, *trans*-1,2-DCE and 1,1-DCE (Ehlke and others, 1991; Imbrigiotta and others, 1991; Davis and Olsen, 1990). *Cis*-1,2-DCE is by far the most common transformation product in ground water in the study area, as well as in most other parts in the United States. The ratio of the *cis* form to the *trans* form of 1,2-DCE in laboratory experiments is about 30:1 (Davis and Olsen, 1990). Primary and secondary chemical and microbiological transformation pathways of TCE under anaerobic conditions are depicted in figure 19.

Anaerobic mechanisms such as hydrolysis and dehalogenation are the primary abiotic transformation pathways of TCE breakdown in typically reduced subsurface environments, but reactivity ranges over 10 orders of magnitude (Barbee, 1994). Under typical ground-water conditions, chlorinated ethenes such as TCE are relatively nonreactive; and 1,2-DCE is the least reactive product. Only under strongly basic conditions will chlorinated ethenes hydrolyze (Jeffers and others, 1989).

Biological transformation of CHCs can occur under a wide range of environmental conditions. The most significant process in the subsurface is microbially mediated dehalogenation (McCarty, 1991). The bacterial process, called cometabolism, involves an inducer/substrate (such as methane) that activates as an enzyme pathway that, in turn, oxidizes the substrate to generate carbon and energy for bacterial growth, while also oxidizing CHCs, such as TCE (McCarty, 1991). The cometabolic reductive dehalogenation process results in degradation products of halogenated and nonhalogenated aliphatic hydrocarbons (fig. 19) that can serve as primary substrates for further biodegra dation of CHCs (Barbee, 1994). The biotransformation of TCE may produce degradation products that are persistent in the environment (such as *cis*-1,2-DCE and *trans*-1,2-DCE), and that are greater health threats than TCE, (such as vinyl chloride, which is carcinogenic to humans). The half-lives for TCE and its chlorinated degradation products are given in table 6.

Further transformation of *cis*-1,2-DCE is uncertain. The half-life of *cis*-1,2-DCE through abiotic hydrolysis is at least 85 million years (table 6); thus, the likelihood of detecting the products of further degradation would be small–only on rare occasions and in trace amounts was 1,2-DCA detected. Other possible transformation compounds, such as vinyl chloride, were not detected. The ultimate transformation products of TCE are carbon dioxide, water, and chloride (fig. 19).

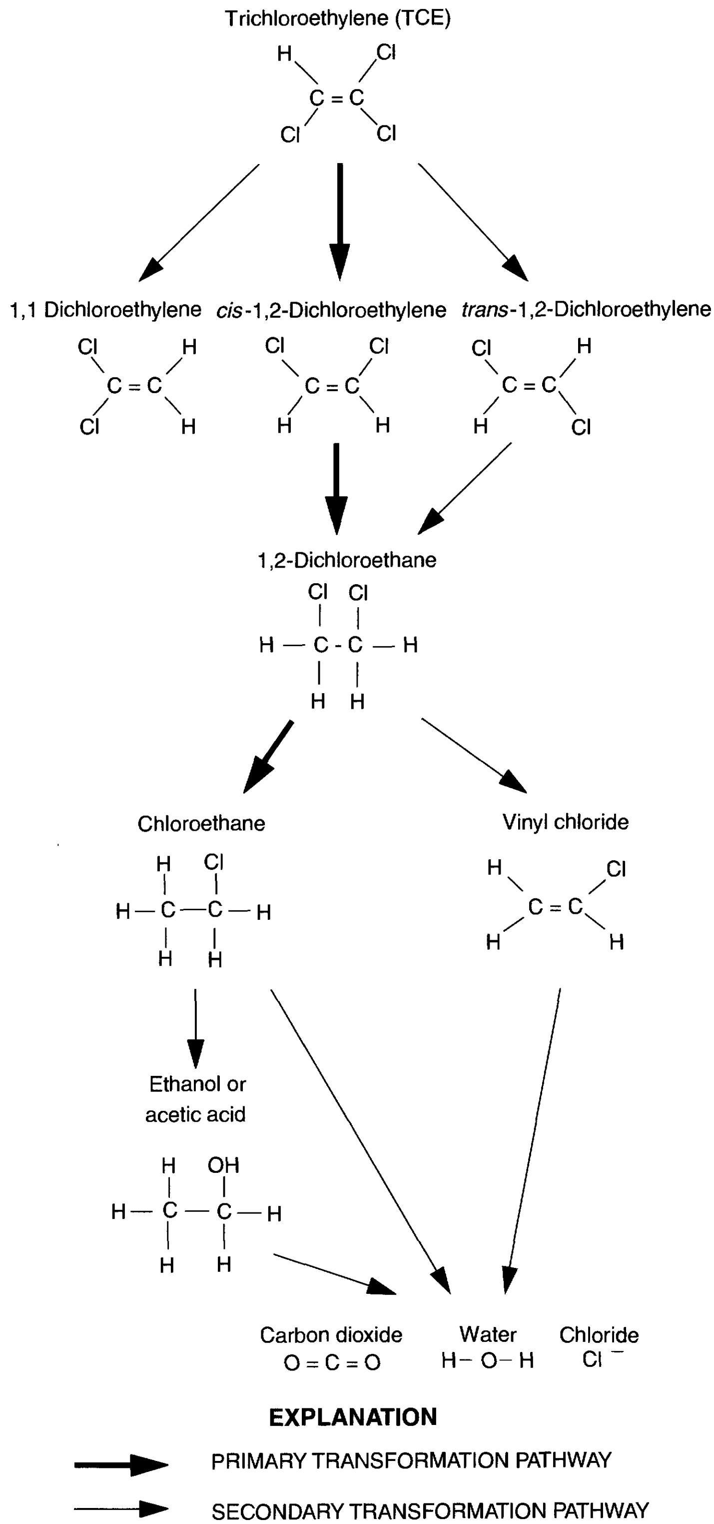


Figure 19. Transformation pathways of trichloroethylene under anaerobic conditions. (Modified from Davis and Olsen, 1990, fig. 1.)

Table 6. Range of half-lives for trichloroethylene and its degradation products.

[> = greater than, data from Barbee, 1994]

Chlorinated hydrocarbon	Half-life process	
	Abiotic hydrolysis or dehalogenation half-life (years)	Anaerobic biodegradation half-life (days)
Trichloroethylene	0.42 - 1.1	33 - 320
cis-1,2-dichloro-ethlene	8.5×10^7 - 2.1×10^{10}	88 - 339
trans-1,2-dichloro-ethylene	8.5×10^9 - 2.1×10^{10}	53 - 147
1,1-Dichloroethylene	4.7×10^7 - 1.2×10^8	81 - 173
1,2-Dichloroethane	24 - 61	>60
Vinyl chloride	>10	>60

Inorganic Chemical Constituents and Physical Characteristics

Chemical quality of ground water is generally affected by several factors: (1) the chemical composition of precipitation that recharges the aquifer; (2) chemical reactions with the soil as the recharge passes through the unsaturated zone; (3) chemical reactions between the aquifer material and ground water in the aquifer; (4) residence time of water within the matrix, and (5) land use above the aquifer.

Chemical analyses of ground-water samples collected during April and September 1990 (table 7) in parts of the unconfined part of the aquifer that are not contaminated by TCE indicate that the quality of ground water in the study area generally meets New York State drinking-water standards. Concentrations of some constituents at some wells slightly exceeded the drinking-water standards, however.

Specific Conductance, pH, and Alkalinity

Specific conductance is a measure of the capacity of water to conduct an electrical current and is related to the type and concentration of ions in solution. Specific conductance is affected by precipitation and by chemical and physical reactions such as adsorption, ion exchange, oxidation, and reduction. Specific conductance of water samples collected during April 1990 ranged from 257 to 1,440 μS/cm, with a median value of 544 μS/cm (table 8A), and values in September 1990 ranged from 288 to 3,850 μS/cm, with a median of 612 μS/cm (table 8B). Median specific conductance values for the April samples did not differ significantly from the September values, nor from the median value of 440 μS/cm for samples collected in 1976 (Buller and others, 1978). Median values for the 1990 sampling from Cortland aquifer seemed to be slightly higher than those for other aquifers in upstate New York, however (Miller and others, 1988).

The pH of a solution is a measure of the effective hydrogen-ion concentration. The primary determinant of pH in ground water is the interaction of soil and rock molecules with gaseous and dissolved carbon dioxide, bicarbonate, and carbonate ions. The pH of ground water in the study area ranged from 7.2 to 8.4 with a median value of 7.6 for the April 1990 sampling, and from 6.9 to 8.9 with a median value of 7.7 for the September 1990 sampling. These median values indicate that the water in the study area is slightly basic.

Alkalinity is a measure of the capacity of water to neutralize an acid by chemical buffering; most alkalinity results from bicarbonate (HCO_3) and carbonate (CO_3) ions. Median values for alkalinity in the study area were 190 mg/L during the April 1990 sampling and 202 mg/L for those collected in the September 1990 sampling. These values are within the range of most ground water in the State.

Chloride and Sodium

Potential sources of chloride and sodium in ground water include road-deicing salts, septic-tank effluents, and sodium-bearing minerals within the aquifer. In some places, elevated concentrations of these ions can result from the discharge of mineralized water in bedrock into sand and gravel aquifers.

Elevated concentrations of chloride were generally found in ground water near major roads that are heavily salted. Median concentrations of chloride for the April and September 1990 samplings were 37 and 39 mg/L, respectively. The chloride concentration of 274 mg/L at the Cortland County office building during April 1990 exceeded the New York State drinking-water standard of 250 mg/L (well 177, pl. 1).

Chloride concentrations in ground water at the City of Cortland well field have been increasing since the early 1940's (Buller and others 1978) (fig. 20). Although still well below the New York State drinking-water standards, chloride concentrations there are significantly higher (at the 95-percent confidence level) than in 1976.

Chloride has migrated downward to some degree throughout the study area. The median concentration of samples from depths greater than 22.5 ft below the water table was 30 mg/L, and the median concentration of samples from depths less than that was 39 mg/L. The chloride concentration of a sample from well 306, which is 255 ft deep, was 28 mg/L. Chloride concentrations during the April 1990 sampling were generally less than 40 mg/L in the western part of the study area, except at the north end of the municipal airport, where the concentration at well 330 was 80 mg/L. Concentrations in the central part of the aquifer ranged from 40 to 80 mg/L, and those in the eastern part ranged from 40 mg/L to 120 mg/L (fig. 21).

Dissolved sodium concentrations in the study area ranged from 4.8 mg/L to 530 mg/L, with a median value of 28 mg/L. Although no standard has been established for sodium, the USEPA (1976) recommends less than 20 mg/L in drinking water for people on sodium-restricted diets. Of the 30 wells that were sampled during September 1990, 20 had sodium concentrations above the 20-mg/L limit.

Trace Elements (Iron and Manganese)

Trace elements generally occur naturally in ground water in extremely low concentrations, but industrial processes and urbanization tend to increase their abundance within the hydrologic system and thereby can seriously degrade water quality. Except for iron and manganese, trace elements detected in ground water in the study area did not exceed drinking-water standards. Iron and manganese concentrations are generally considered together; State drinking-water standards specify a combined maximum limit of 300 µg/L. Concentrations of iron and manganese exceeded the 300-µg/L limit at 7 of the wells sampled during September 1990; the median concentration of iron and manganese at each was 16 µg/L. Extremely high concentrations of iron and manganese (7,900 µg/L and 3,600 µg/L, respectively) were found in water from well 365 (pl. 1), in the eastern part of the study area. This well is at an abandoned gasoline station on the edge of the TCE plume, and dissolution of old under-

Table 7. Minimum, maximum, mean, median, and interquartile range of concentrations for selected constituents or properties of ground-water samples collected from the glacial aquifer in the Cortland, N.Y. study area during April and September 1990.

[Values are in milligrams per liter, mg/L, unless otherwise noted, µS/cm, microsiemens per centimeter; µg/L, micrograms per liter]

Constituent or property	Number of samples	Minimum	Maximum	Mean	Median	Interquartile range 25th	Interquartile range 75th
Well depth, in feet	86	14	255	55	47	34	67
Alkalinity (as $CaCO_3$)	101	62	312	191	196	167	220
pH	60	6.9	8.9	7.7	7.7	7.6	7.8
Specific conductance, µS/cm	60	257	3,850	673	592	513	705
Phosphorus, total as PO_4	59	.01	1.29	.44	.43	.12	.68
Nitrate as N	59	<.01	12	4.1	4.3	2.4	5.6
Chloride	69	5.0	270	52	38	28	61
Sodium	89	4.8	530	37	23	15	39
Potassium	40	.2	8.3	1.7	1.4	1.0	2.0
Calcium	30	.1	780	94	79	72	89
Nitrite + nitrate as N	40	.10	9.9	4.4	4.6	3.4	5.6
Magnesium	30	6.0	39	15	14	14	16
Sulfate	30	17	25	22	23	21	24
Silica	30	.55	14	7.2	7.4	6.7	7.9
Barium (µg/L)	30	29	290	77	62	50	74
Berylium (µg/L)	30	.50	1.5	.55	.50	.50	.50
Cadmium (µg/L)	30	< 1	3.0	1.1	< 1	< 1	< 1
Chromium (µg/L)	30	< 5	15	5.3	< 5	< 5	< 5
Cobalt (µg/L)	30	< 3	9	3.3	< 3	< 3	< 3
Copper (µg/L)	30	< 10	50	13	< 10	< 10	< 10
Iron (µg/L)	30	< 3	7,900	334	16	10	38
Lead (µg/L)	30	10	30	11	10	10	10
Manganese (µg/L)	30	< 1	3,600	206	16	4	72

Table 8. Minimum, maximum, mean, median, and interquartile range of concentration or value for selected constituents or properties of ground-water samples collected from the glacial aquifer in the Cortland, N.Y. study area during April 1990 and September 1990.

[Values are in milligrams per liter (mg/L) unless otherwise noted, µS/cm = microseimens per centimeter, ft = feet]

Constituent or property	Number of samples	Minimum	Maximum	Mean	Median	Interquartile range	
						25th	75th
A. April 1990							
Well depth (ft)	43	14	255	55	45	28	67
Depth to water surface (ft)	40	3.3	61.6	15.5	11.5	7.2	18.2
Depth below water table (ft)	32	4.3	247	39.7	27.2	17.6	45.5
Alkalinity (as $CaCO_3$)	59	62	265	182	190	154	212
pH	28	7.2	8.4	7.7	7.6	7.5	7.7
Specific conductance, µS/cm	28	257	1,440	581	544	477	660
Phosphorus, total as P	59	.01	1.3	.44	.43	.12	.68
Nitrate as N	59	.1	12	4.1	4.3	2.4	5.6
Chloride	59	5.0	270	52	37	28	61
Sodium	59	5.0	200	29	22	14	35
Potassium	59	.15	8.3	1.7	1.4	1.02	2.0
B. September 1990							
Well depth (ft)	43	14	217	55	48	34	67
Depth to water surface (ft)	29	5.5	72.8	22.9	17.5	13.1	28.0
Depth below water table (ft)	28	2.5	207.3	33.6	22.4	14.6	35.7
Specific conductance	32	288	3,850	753	612	555	796
pH	32	6.9	8.9	7.7	7.7	7.6	7.8
Alkalinity (as $CaCO_3$)	42	104	312	204	202	187	224
Nitrite + nitrate as N	40	.10	9.9	4.4	4.6	3.4	5.6
Calcium, dissolved	30	13	230	82	79	74	90
Magnesium, dissolved	30	6.0	39	15	14	14	16
Sodium, dissolved	30	4.8	530	54	28	18	47
Chloride, dissolved	10	21	79	47	39	30	70
Sulfate	10	17	25	22	23	21	24
Silica, dissolved	30	.55	14	7	7.4	6.7	7.9
Barium, dissolved (µg/L)	30	29	290	77	62	50	74
Berylium, dissolved (µg/L)	30	.50	1.5	.55	.50	.50	.50
Cadmium, dissolved (µg/L)	30	< 1	3	1.1	< 1	< 1	< 1
Chromium, dissolved (µg/L)	30	< 5	15	5.3	< 5	< 5	< 5
Cobalt, dissolved (µg/L)	30	< 3	9	3.3	< 3	< 3	< 3
Copper, dissolved (µg/L)	30	< 10	50	13	< 10	< 10	< 10
Iron, dissolved (µg/L)	30	< 3	7,900	330	16	10	38
Lead, dissolved (µg/L)	30	10	30	11	10	10	10
Manganese, dissolved (µg/L)	30	< 1	3,600	210	16	4	72

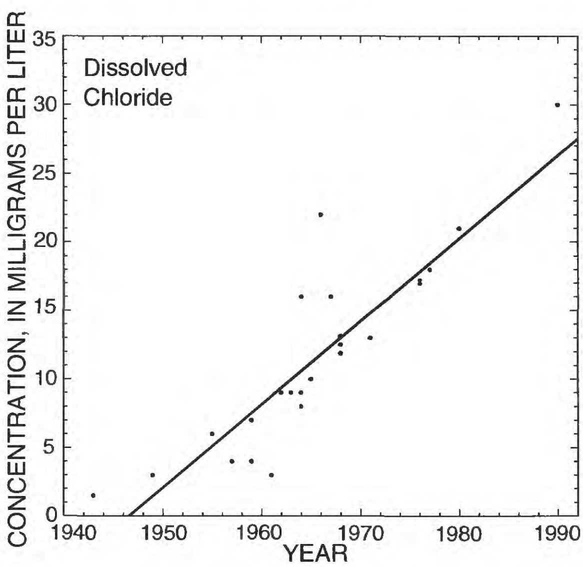


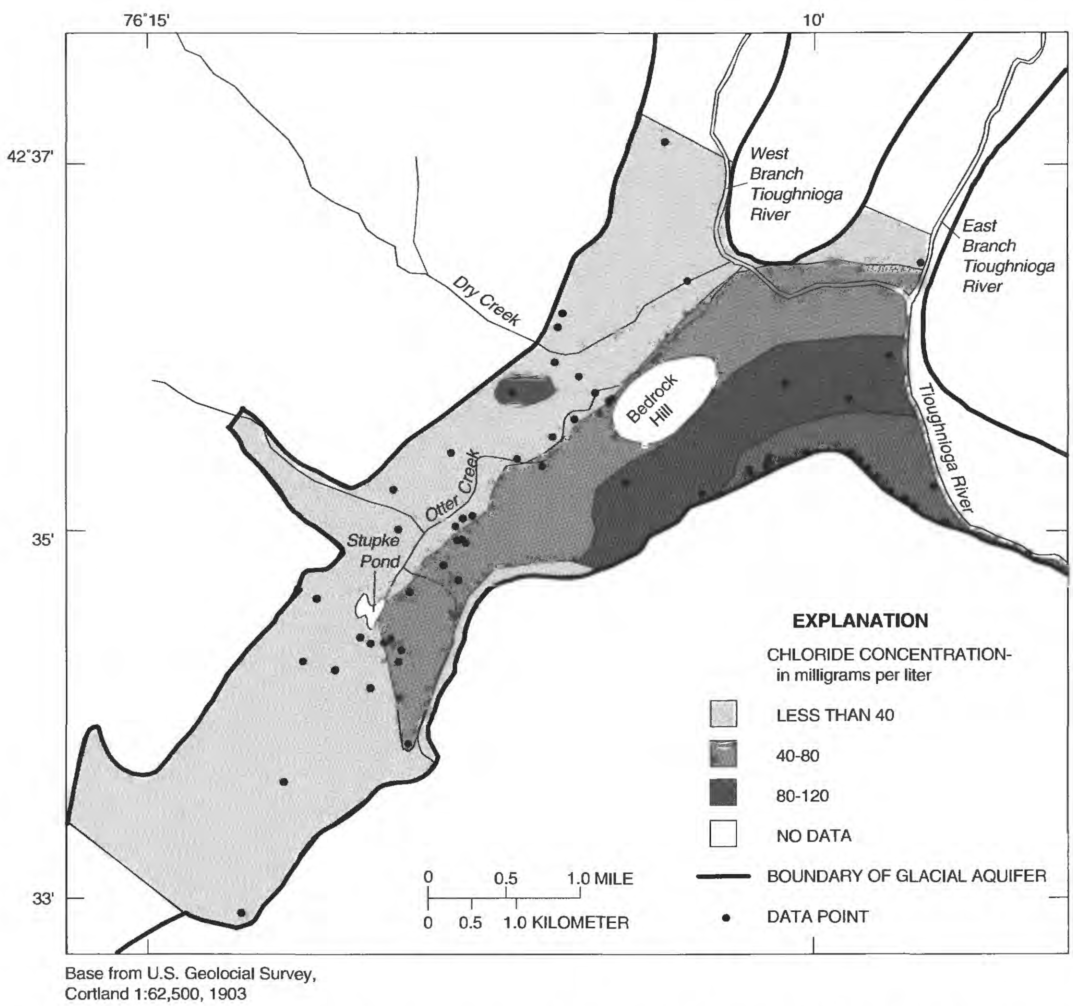
Figure 20. Dissolved chloride concentrations in water from wells at City of Cortland well field, 1943-76, 1980, and 1990. (Modified from Buller and others, 1978, fig. 20.)

ground gasoline-storage tanks may have been the source of the iron and manganese.

Nitrogen

Nitrogen, which constitutes about 80 percent of the atmosphere, generally occurs in nature in combination with other elements and is a common degradation product of organic wastes. Nitrate sources include (1) the decomposition of organic nitrogen that is introduced to the soil by nitrogen-fixing plants and bacteria, (2) human and animal wastes, and (3) organic and inorganic fertilizers.

Total nitrate concentrations (NO_3^- as N) in ground-water samples collected in April 1990 ranged from 0.1 to 12 mg/L, with a median value of 4.3 mg/L. The largest concentrations (12 and 8.6 mg/L) were at wells 304 and 204, respectively, both of which are close to Otter Creek and just downgradient of a large dairy farm.



Base from U.S. Geolocial Survey,
Cortland 1:62,500, 1903

Figure 21. Distribution of chloride concentrations in the unconfined aquifer in Cortland study area, April 1990.

Ground-water samples collected in September 1990 were analyzed for dissolved nitrite plus nitrate (NO_2^-+NO_3^-) as N. Nitrate (NO_3^-) is typically the most common nitrogen species in surface water and ground water, whereas nitrite (NO_2^-) is unstable and usually undergoes nitrification or denitrification and typically occurs in concentrations of less than 0.1 mg/L (Behnke, 1974). Concentrations of nitrite plus nitrate ranged from 0.1 to 9.9 mg/L in September 1990 with a median value of 4.6 mg/L. The highest concentrations were 9.9 mg/L and 8.3 mg/L in wells 5 and 207, respectively, both of which are subject to agricultural influences. Wells 304 and 204, which had the highest nitrate concentrations in April 1990, had concentrations of 4.0 and 4.6 mg/L, respectively, in September 1990. Data from several well pairs (a shallow well and a deep well) indicate that the vertical distribution of nitrogen is fairly uniform throughout the upper part of the unconfined aquifer. Nitrate-concentration data from six wells finished in the confined aquifer indicate that nitrogen is present in that aquifer, but in lower concentrations (median value 2.0 mg/L).

Temporal Changes

Data collected in this study (April and September 1990) were compared with data collected in 1978 by Buller and others (1978), and with data collected from November 1979 through January 1981 by Cortland County, to discern trends in water quality in the glacial-aquifer system. Only wells that also had been sampled in the 1978-81 studies were represented in the comparison. Constituents that were compared were alkalinity, nitrite plus nitrate as N, calcium, chloride, and sulfate. Chloride was the only constituent for which concentrations for all four periods were available. Maximum, minimum, mean, median, and interquartile ranges of the constituents that were compared are shown in table 9.

Nonparametric statistical tests were used to discern year-to-year differences in median values. A 0.05 level of significance (95-percent confidence level) was used for all tests to describe the error probability of falsely detecting differences. Simple descriptive statistics such as boxplots and median and interquartile range were used first to examine the distribution of the sample population of each constituent from the three time periods. Because water-quality data typically do not have a normal distribution, the median and interquartile range provide a better measure of the sample-population distribution than do the mean and the standard deviation. For this reason, a Kruskal-Wallis one-way ANOVA (analysis of variance) was done on ranked data to compare the distribution of concentrations by year (Conover and Iman, 1981). Differences among sample populations (by year) indicated by the Kruskal-Wallis test were further defined by Tukey's multiple-comparison test.

Concentrations of chloride, the only constituent with data from all four time periods, were significantly greater during April and September 1990 than in 1976 or 1980. Median values for April and September 1990 were similar (36 and 38 mg/L, respectively), and the median concentration for 1980 (21 mg/L) was slightly greater than for 1976 (18 mg/L). The increase in chloride concentration over the years (fig. 20) is due to increased use of road salt and, to a lesser extent, leakage from aging septic systems.

Median concentrations of alkalinity were greater in September 1990 (210 mg/L) than in April 1990 (191 mg/L), and the September median was significantly greater than that for 1976 (167 mg/L). Median concentrations of calcium for April and September 1990 where nearly equal (80 and 77 mg/L, respectively) but were significantly higher than in 1976 (63 mg/L). Median concentrations of nitrite plus nitrate differed significantly among sampling periods–September 1990 had the highest, and 1976 had the lowest. The trend of increasing nitrogen concentrations may result from increased application of agricultural and lawn fertilizer, as well as leaking septic systems. The significant difference between nitrate concentrations in April 1990 and those in September 1990 may result from three factors: (1) recharge during this period was fairly large; thus, concentrations may have been diluted; (2) ground-water levels in September had declined by an average of 7.4 ft, decreasing the amount of dilution; and (3) nitrogen from fertilizers applied during late spring and summer probably had reached the water table by September. The distribution of concentration data for alkalinity, nitrite plus nitrate, calcium, and chloride in 1976 and the two 1990 sampling periods are shown by year in figure 22A.

Ground-Water Chemistry and Land Use

The available data allow only generalized comparisons between ground-water quality and land use. Because land use in the study area is heterogeneous, the effects of a particular land use on the quality of water at a particular well or group of wells are impossible to isolate. Most of the 52 wells sampled were in the Cortland municipal area, which contains several land-use categories, including residential, industrial, commercial, recreation, major transportation routes, and other small categories associated with urban areas. The remaining 16 wells were grouped as agricultural. Water from these wells, which were in the southern end of the study area and at its edges, was readily identifiable by characteristics that are associated with agriculture. Thus, ground-water quality was compared simply between two broad categories of land use–urban and agricultural. Six wells that penetrated the confined aquifer were eliminated from the data set prior to analysis of because part of their recharge area is outside the study area.

The distribution of chemical data for the two land-use groups were compared through use of boxplots (fig. 22B). Any statistically significant differences in concentrations reflecting land use were tested with the Kruskal-Wallis one-way ANOVA, which compares the distribution of ranks of concentrations between groups of data to determine whether any of the groups differ significantly from the others. Significance was chosen at 0.05 (95-percent confidence level).

Table 9. Minimum, maximum, mean, median, and interquartile range of concentration or value for selected constituents or properties of ground water sampled during three studies in Cortland County, N.Y. study area

[Values are in milligrams per liter unless otherwise noted, µS/cm, microsiemens per centimeter; dashes indicate no data].

Constituent or property	Sampling date[1]	Number of samples	Minimum	Maximum	Mean	Median	Interquartile range 25th	Interquartile range 75th
Specific conductance (µS/cm)	1976	84	235	700	451	450	405	499
	1980	0	--	--	--	--	--	--
	April 1990	22	236	797	474	470	334	542
	Sept. 1990	6	413	631	545	556	512	584
Alkalinity (as $CaCO_3$)	1976	23	63	231	168	167	152	182
	1980	0	--	--	--	--	--	--
	April 1990	22	62	239	180	191	167	219
	Sept. 1990	12	151	300	209	210	183	224
Nitrate (total as N)	1976	27	1.6	4.9	3.4	3.4	2.8	4.1
	1980	153	.10	5.0	2.4	2.7	1.6	3.3
	April 1990	22	.80	12	4.6	4.6	2.4	6.1
	Sept. 1990	0	--	--	--	--	--	--
Nitrite + nitrate (as N)	1976	84	.55	5.6	3.2	3.4	2.7	4.0
	1980	0	--	--	--	--	--	--
	April 1990	0	--	--	--	--	--	--
	Sept. 1990	12	3.7	9.9	6.0	5.8	4.7	7.3
Calcium	1976	19	31	80	64	63	59	76
	1980	0	--	--	--	--	--	--
	April 1990	22	32	97	78	80	75	87
	Sept. 1990	6	61	87	76	77	72	81
Chloride	1976	85	3.0	78	24	18	12	28
	1980	153	5.0	72	24	21	14	30
	April 1990	22	15	110	45	36	27	61
	Sept. 1990	7	29	79	46	38	30	72
Sulfate (as SO_4)	1976	18	19	26	22	21	20	24
	1980	0	--	--	--	--	--	--
	April 1990	0	--	--	--	--	--	--
	Sept. 1990	7	19	25	23	24	23	25

[1]1976 data from Buller and others (1978). 1980 data provided by Cortland County Department of Health. 1990 data from present study

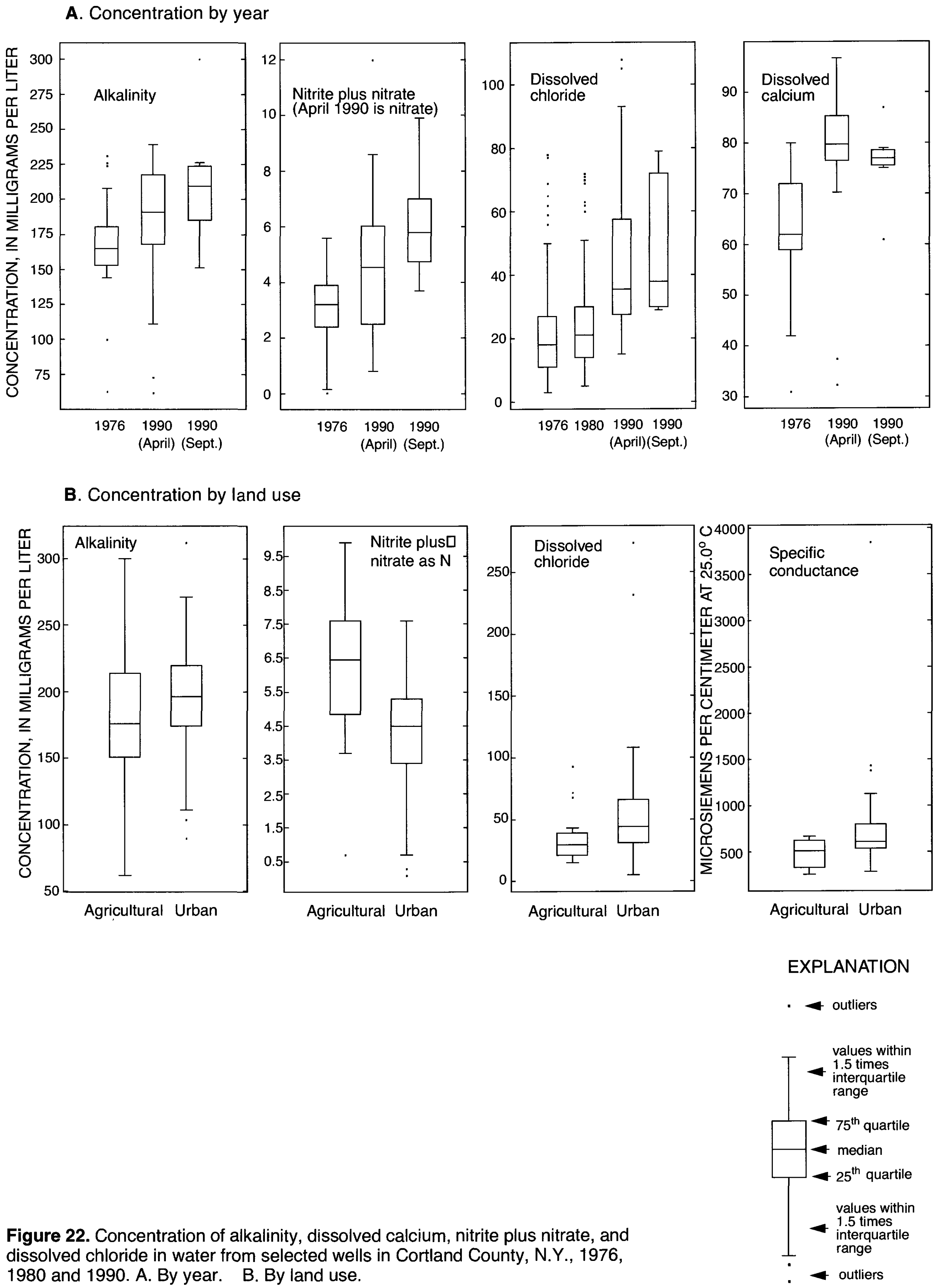


Figure 22. Concentration of alkalinity, dissolved calcium, nitrite plus nitrate, and dissolved chloride in water from selected wells in Cortland County, N.Y., 1976, 1980 and 1990. A. By year. B. By land use.

Only two constituents—specific conductance and chloride—showed a significant difference between the two land-use categories; concentrations of both were significantly higher in the urban area than in the agricultural area. The higher chloride concentrations in the urban area may be attributable to road salt, industrial wastes, and sewage leaked from aging septic and sewer systems, and the significantly greater specific conductance values in the urban area than in the agricultural area are associated with the higher chloride concentrations. The median chloride concentration was 44 mg/L in the urban area and 30 mg/L in the agricultural area, and the median specific conductance values were 610 µS/cm and 516 µS/cm, respectively. Median concentrations of sodium were considerably larger (although not statistically significant) in the urban area than the agricultural area (24 mg/L and 16 mg/L, respectively). Alkalinity was slightly higher in the urban area, and median concentrations of nitrate and calcium were nearly the same in both areas. Concentrations of nitrite plus nitrate were considerably higher in the agricultural area (although not a statistically significant difference) as a result of the agricultural sources of that constituent. Maximum, minimum, median, mean, and interquartile ranges of the selected constituents grouped by land-use categories are in table 10.

SIMULATION OF GROUND-WATER FLOW

A ground-water flow model was constructed to delineate areas that contribute ground water to municipal wells and the flowpaths of ground water migrating from two sources of contamination. Because annual and seasonal fluctuations in the amount of recharge affect flow conditions in the aquifer system, three steady-state ground-water recharge conditions–high, average, and low–were simulated.

Description and Design of Numerical Model

A quasi-three-dimensional, numerical three layer ground-water flow model was constructed to compute hydraulic head and flows in the glacial aquifer system in the study area. Heads in the confining unit were not calculated; instead, resistance to flow in the confining unit is included in terms of vertical conductance between the unconfined and confined aquifers. This approach to simulating flow through a confining layer is called the "quasi-three-dimensional" approach. The model was developed with the computer program MODFLOW (McDonald and Harbaugh, 1988), which is based on block-centered, finite-difference equations that describe the physics of water flowing through a porous medium. The equations relate water levels to geometry and hydraulic properties of the aquifer, such as hydraulic conductivity, and to stresses such as

Table 10. Minimum, maximum, mean, median, and interquartile range of concentrations or values for selected constituents or properties of ground water in Cortland, N.Y. study area, by land use

[Values are in milligrams per liter unless otherwise noted; µS/cm = microsiemens per centimeter, * indicates significant difference at the 95-percent confidence level in constituent concentration between land uses.].

Constituent or property	Land use	Number of obser vations	Minimum	Maximum	Mean	Median	Interquartile range	
							25th	75th
Alkalinity (as $CaCO_3$)	Agricultural	20	62	300	183	180	154	218
	Urban	76	90	312	197	197	177	221
*Specific conductance (µS/cm)	Agricultural	12	257	668	501	516	351	634
	Urban	43	344	3,850	728	610	546	802
Nitrate (as N)	Agricultural	12	.1	8	4.2	4.2	2.3	6.0
	Urban	45	.1	12	4.2	4.5	2.7	5.5
*Chloride (as Cl)	Agricultural	17	15	93	37	30	21	42
	Urban	50	5	270	58	44	31	67
Sodium (as Na)	Agricultural	14	4.8	51	21	16	11	30
	Urban	70	4.8	530	39	24	16	39
Calcium (as Ca)	Agricultural	14	.10	780	150	78	55	88
	Urban	70	47	240	86	79	73	89
Nitrite + nitrate (as N)	Agricultural	6	.70	9.9	5.9	6.4	3.0	8.7
	Urban	31	.30	7.6	4.3	4.6	3.5	5.4

pumping and recharge. The aquifer system is represented by a three-layer grid in which all characteristics of the system, including geometry, hydraulic properties, and stresses, are defined by values specified at the centers of cells, and the model calculates the head at the center of each cell. The process of representing a continuous system with a specified number of discrete points is called discretization.

In the finite-difference method, the discrete points are located along rows and columns, and each point is associated with a cell. Head and flows are calculated only for "active" cells, which represent the aquifers; "inactive" cells are those outside the aquifer boundary and are ignored in the calculations.

The design of the numerical model is based on the conceptualization of the aquifer system as previously discussed in the hydrogeology section and shown schematically in figure 23. The aquifer system is simulated as a quasi-three-dimensional-flow system with three layers, and horizontal flow in the aquifers and vertical flow through the confining unit is assumed. The unconfined aquifer is divided into two layers (layers 1 and 2) to provide adequate vertical resolution and to simulate flowpaths and particles that could flow beneath cells that simulate streams and wells (such cells are known as "weak sinks" because not all flow into a cell is captured by the cell). The confined aquifer is represented by a single layer (layer 3) except where the confining unit is locally absent along the edges of the valley; in these locations an arbitrary elevation that approximates the elevation of the top of the adjacent confining unit was assigned to the top of the layer. In this quasi-three dimensional approach, the confining unit is represented by the vertical conductance between layers 2 and 3. Heads in the confining unit are not calculated, and vertical flow through it is the product of differences in head between layers 2 and 3 and the vertical conductance of the confining unit.

The geometric and hydraulic values that were used as input to the model were based on available data. The values for areas with little or no data were estimated

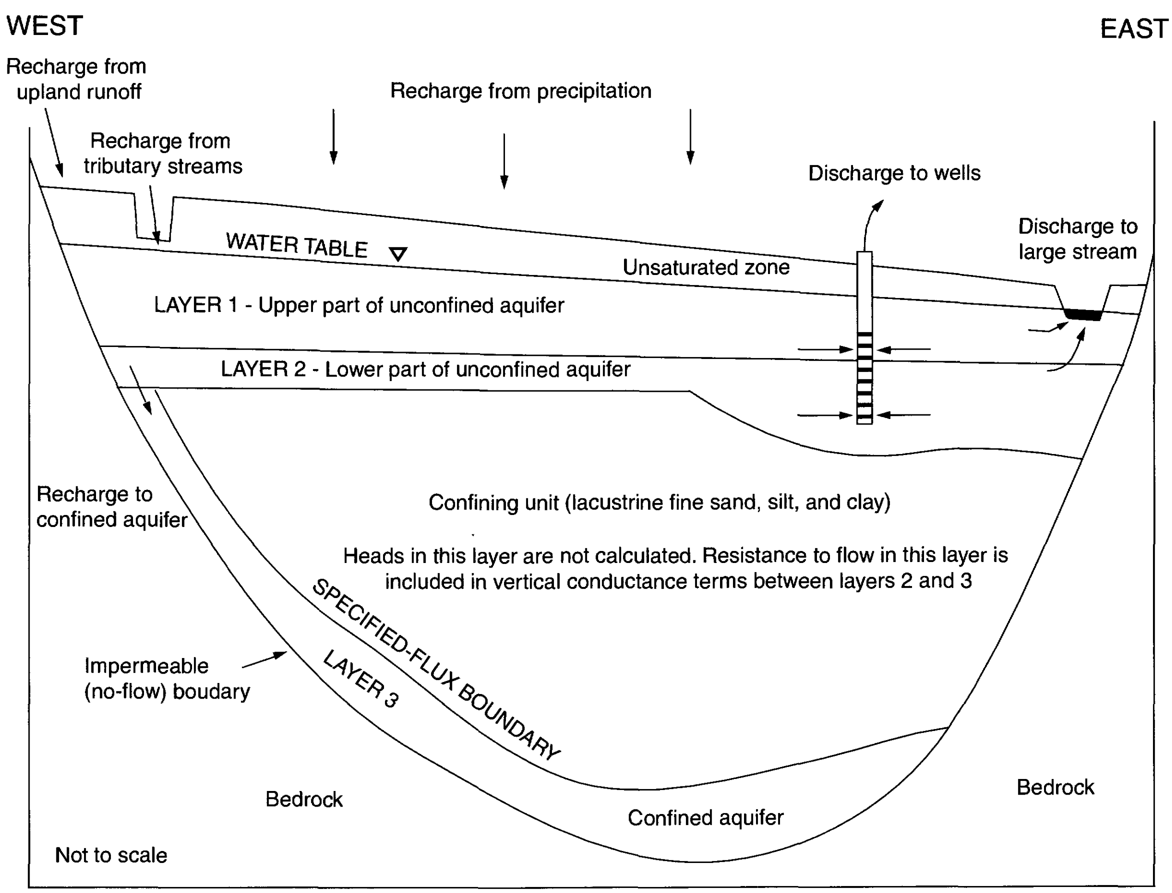


Figure 23. Conceptual model of ground-water flow in glacial-aquifer system in Cortland, N.Y., study area.

and then adjusted, within reasonable limits, during model calibration until the simulated water levels and flows matched the measured values.

Model Grid

A rectangular, finite-difference grid with 66 rows and 119 columns was superimposed on a map of the aquifer system (fig. 24 and pl. 5) to discretize the hydrogeologic conditions of the conceptual model. A uniform cell size of 300 x 300 ft was used because municipal wells, streams, and sources of contamination are distributed throughout the study area. (A grid with cells of uniform size simulates the hydrologic conditions throughout the study area more accurately than a grid with variably sized cells, although the latter provides increased resolution in areas represented by small cells, they may not accurately represent conditions in large-cell areas.

Geometry of Model Layers

A geologic section was drawn for every second row of the model, giving a total of 33 geologic sections. The surface elevations of the bottom of layer 1 and the top and bottom of layers 2 and 3 of the geologic sections were entered as arrays into the model. Corresponding data for intervening rows, for which no geologic sections were constructed, were interpolated, or were determined from records of wells corresponding to those rows. The elevation of the top of layer 1 (water table) was calculated by the model, and the elevation of the bottom of layer 1 (top of layer 2) was arbitrarily assigned to roughly equal to the middle of the unconfined aquifer,

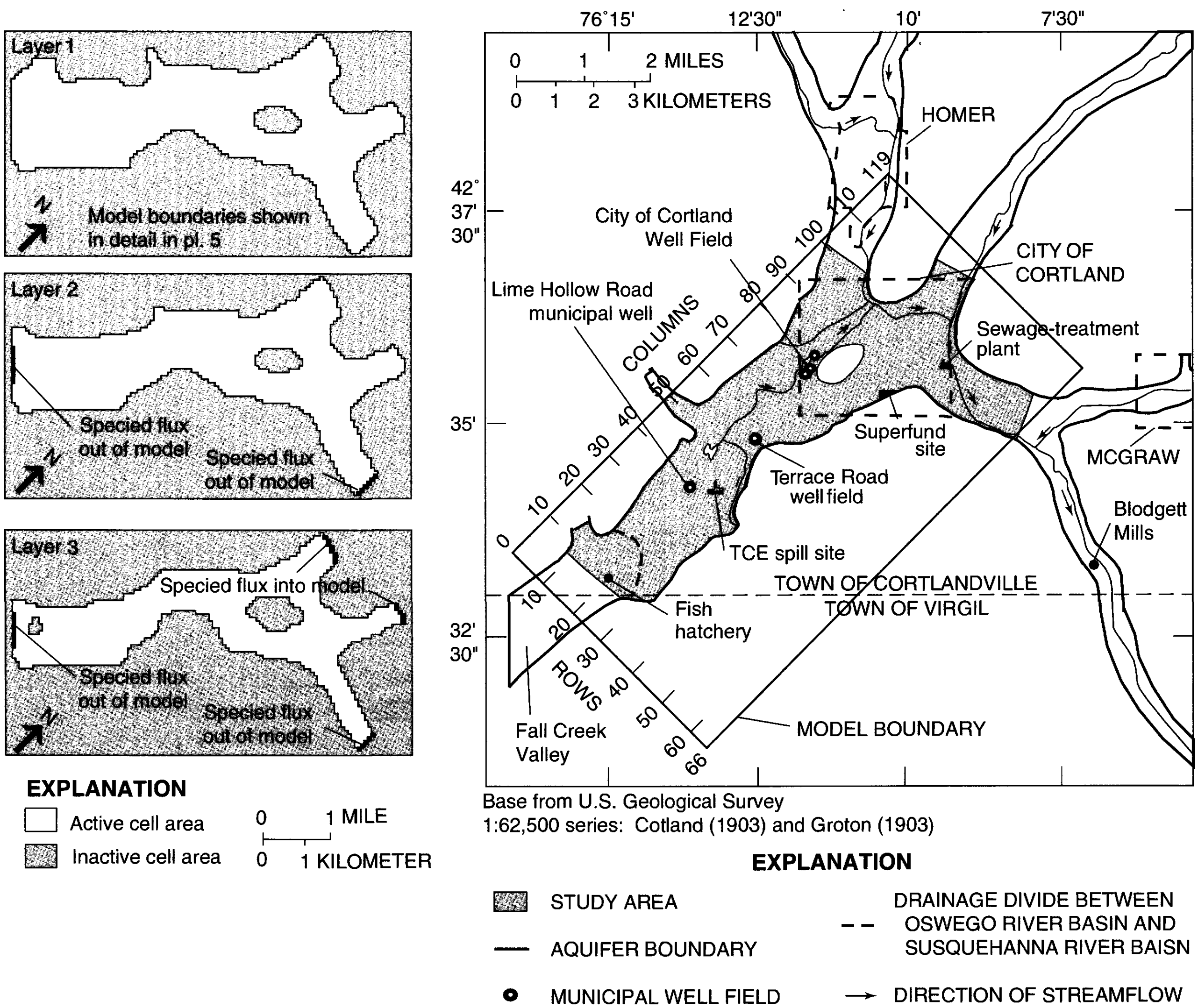


Figure 24. Locations of active and inactive grid boundaries in layers 1, 2, and 3 of the three-dimensional ground-water flow model of Cortland, N.Y. study area.

except along the valley walls, where till or bedrock surface forms the bottom of layer 1. The bottom of layer 2 is either the top surface of the lacustrine confining unit (fig. 12) in the central parts of the valley or the top of layer 3 along some reaches of the valley walls (fig. 23). The top of layer 3 is the bottom of the confining unit or, where the confining unit is absent, the bottom of layer 2. The bottom of layer 3 is the till or bedrock surface in the valley (fig. 23).

Hydraulic Conductivity

Horizontal hydraulic conductivity of the aquifers was estimated to be 10 times the vertical hydraulic conductivity throughout the modeled area (anisotropy 10:1). Vertical hydraulic conductivity of stratified drift tends to be less than horizontal hydraulic conductivity because, at a small scale, the stratified drift consists of many layers of sediment particles, some of which are plate shaped and tend to settle horizontally, thereby impeding the vertical flow of ground water.

Unconfined Aquifer

Horizontal hydraulic conductivity values ranging from 1 to 1,200 ft/d were assigned to layers 1 and 2, on the basis of (1) eight aquifer tests that used large pumping wells, such as municipal and industrial wells (table 2), and (2) several additional hydraulic conductivity measurements made by Blasland, Bouck and Lee Engineers (1992) during slug tests of test wells at the Rosen Superfund site in the southeastern part of the aquifer (pl. 1).

Hydraulic conductivity values of less than 10 ft/d were assigned to the unconfined aquifer on the back (west) side of the Valley Heads moraine in the western part of the study area to represent the poorly sorted, silty sand and gravel and the fine-grained deposits of till and lacustrine fine sand, silt, and clay. Hydraulic conductivity values of 10 to 100 ft/d were assigned to (1) the poorly to moderately sorted silty sand and gravel that form kame deposits at the crest of the Valley Heads moraine, and (2) silty gravel outwash along parts of the valley walls. Blasland, Bouck and Lee Engineers (1992) calculated an average hydraulic conductivity of about 10 ft/d for kame deposits and 30 ft/d for outwash, and a range of 3.4 to 136 ft/d in 20 slug tests of test wells at the Rosen"Superfund" site.

Hydraulic conductivity values ranging from 100 to 300 ft/d were assigned to areas along the edges of the valley, where alluvial inwash and colluvium that consist of silty sand and gravel deposited by upland tributaries and by runoff are mixed with well-sorted outwash sand and gravel along the sides of the valley. This zone is well developed where large tributaries flow onto the aquifer and is weakly developed where small tributaries flow onto the aquifer and where slope erosion has occurred along the valley walls.

Values ranging from 300 to 1,200 ft/d were assigned to areas containing well-sorted outwash sand and gravel in the central parts of the valleys. In general, hydraulic conductivity values northeast of the moraine progressively decrease from more than 1,000 ft/d to less than 400 ft/d to reflect the decreasing grain size of the outwash deposits with increasing distance from the moraine.

Confined Aquifer

Little information is available on hydraulic properties of the confined aquifer (layer 3); therefore, model values were estimated from (1) two aquifer tests in the western part of the study area, (2) six slug tests at the Rosen "Superfund" site, (3) several qualitative estimates of the water-producing capacity of wells installed in the confined aquifer, and (4) distribution of grain size of sediments collected from the confined aquifer during test drilling. The estimated values range from 10 to 150 ft/d and average 60 ft/d.

Stream-Aquifer Interaction

The Streamflow-Routing Package developed by Prudic (1989) was used to simulate the interaction between the water table and the streams and springs in the study area. Streams are divided into reaches and segments; each reach corresponds to an individual cell in the model grid, and a segment consists of a group of connected reaches in downstream order. Streams in the study area are represented by 425 reaches (cells) grouped into 52 segments.

Leakage between the stream and aquifer is subtracted from or added to the amount of streamflow in each reach, depending on the head difference between the stream surface and water table, and is adjusted according to a streambed-conductance term. The amount of leakage is computed by Darcy's Law as follows:

$$Q = C_{str}(H_s - H_a) \qquad (4)$$

where Q = leakage to or from the aquifer through the streambed (L^3/T);

H_s = head in stream (L);

H_a = head in aquifer side of streambed (L); and

C_{str} = streambed conductance (L^2/T), defined as the vertical hydraulic conductivity of the streambed, times width of the stream reach times stream length of the stream, divided by the streambed thickness.

Recharge to the aquifer from streams ceases when all streamflow leaks into the aquifer, leaving the stream dry. The stream can flow again in downstream reaches, however, wherever the head in the aquifer is above the streambed elevation.

All streams are in layer 1 of the model, and each stream cell is assigned values for the following: (1) the layer, row, and column number of the cell representing that reach, (2) the average water-surface elevation in the cell, (3) streambed conductance, (4) elevations of bottom and top of the streambed, and (5) stream discharge, in cubic feet per day, for the first reach of each segment. Water-surface and streambed elevations were determined by (1) continuous runs of levels made in the channels of Dry Creek, West Branch Tioughnioga and Tioughnioga Rivers, (2) spot measurements made with levels in the channels of Otter Creek and several other small tributaries, and (3) estimates from 1:24,000-scale USGS topographic maps with 20-ft contour intervals. Water levels and streambed elevations are accurate to several tenths of a foot where levels were run and are accurate to several feet where they were estimated from topographic contours. A streambed thickness of 1.5 ft, which was used in a model of the Cortland aquifer built by Cosner and Harsh (1978), was also used in this model.

Conductance of streambeds within the study area differs from reach to reach. Tributaries that erode fine-grained matrix of till in the uplands transport this material to streams that eventually flow over the aquifer, where they deposit some of it; thus, the streambed in the study area consists of both coarse and fine-grained sediments and has a lower hydraulic conductivity than the aquifer. Estimating the conductance of the streambed entailed adjusting the hydraulic conductivity value in the model until seepage to and from the stream approximated the gains and losses measured at 33 streamflow-measurement sites during each of the low-, average- and high-flow periods. Estimated hydraulic conductivity values ranged from 0.5 to 7.5 ft/d and typically averaged about 3.5 ft/d for streambeds in highly permeable outwash deposits and from 0.1 to 0.5 ft/d for streambeds over less permeable deposits, such as kames. Stream width was measured at the 33 streamflow-measuring sites and was estimated in many other places; the range was from less than 2 ft in small tributaries to 120 ft in the Tioughnioga River.

Boundary Conditions

Several types of boundaries were specified in the model to represent the aquifer system. The types used in layer 1 are indicated on plate 5. Natural boundaries were used where possible, but arbitrary boundaries were used to limit the modeled area because the aquifer system extends many miles beyond the study area. The arbitrary boundaries were placed far enough from municipal well fields and sources of chemical contamination that their effect on model results in these areas of concern would be negligible.

Specified-Flux boundaries refer to those boundaries where a volume of water per unit of time crosses a unit cross-sectional area (such as recharge from precipitation over the aquifer). A specified-flux boundary, represented by recharge wells, was used along the valley walls (pl. 5) to simulate the seepage of surface runoff and ground water from bordering unchanneled uplands into the unconfined aquifer (layer 1). The amount of inflow was determined by the size of the drainage area of the upland bordering the modeled area. Drainage areas of unchanneled uplands were delineated on maps, and their size measured by a digitizer. Then the drainage areas were divided by the number of bordering cells, and each of the resulting areas was multiplied by the recharge rate from uplands (See eq. 2).

A specified-flux boundary also was used to simulate ground-water flow into and out of the confined aquifer (layer 3) along all four major stream valleys (Fall Creek valley, West Branch and East Branch Tioughnioga Rivers, and Tioughnioga River). Ground water in layer 3 flows into the modeled area in the West and East Branches of the Tioughnioga River valleys and flows out of the modeled area in the Fall Creek and Tioughnioga River valleys.

No-flow boundaries represent geologic units or streamlines through which no flux occurs. A streamline is a curve that is tangent to the direction of ground-water flow; thus no flow crosses a streamline. A no-flow boundary was applied at the bottom of the confined aquifer (layer 3) to represent the contact between the aquifer and the underlying till or shale along the bottom of the valley because till and shale have extremely low hydraulic conductivity, and any flow across that boundary would be negligible compared to the amount of flow through the sand and gravel aquifer.

Arbitrary streamline (no-flow) boundaries were used where West Branch and East Branch Tioughnioga Rivers and the Tioughnioga River enter the modeled area and flow against the side of a valley; this results in ground-water flow from across the valley to the stream. These streamline boundaries were placed far from pumping wells and chemical plumes to avoid affecting model results.

A *free-surface recharge boundary* was used to represent the water table (top of the unconfined aquifer, layer 1), where recharge from precipitation is applied uniformly. The water table can rise or fall, depending on the balance of stresses in the aquifer system, such as pumping, recharge, and gain or loss of water from streams that flow over the aquifer.

A *specified-vertical leakance boundary* was used to simulate ground-water movement through the lacustrine confining unit between layer 2 and layer 3 (quasi-three-dimensional approach). Resistance to flow through the confining unit is included in the vertical leakance calculations and is defined as the vertical hydraulic conductivity of the confining unit, divided by its thickness. The volume of water that passes through a model cell (vertical conductance) between layers 2 and 3 is equal to the product of vertical leakance and model cell area.

Ground-Water Withdrawals and Recharge Basins

Large amounts of water are pumped from several municipal, industrial, and institutional wells completed in the unconfined aquifer (layers 1 and 2), but no large pumping wells tap the confined aquifer. Ground-water withdrawals by large pumping wells for the three simulated conditions are given in table 5. Withdrawals from pumping wells with a fully penetrating screen (extending from the top of layer 1 to the bottom of layer 2, such as the municipal wells for the City of Cortland) were distributed equally in layers 1 and 2. Withdrawals from wells with short screens (10 to 20 ft long) were assigned to the layer that contained the screen.

Water pumped from the recovery well at the typewriter plant is passed through an air stripper to remove VOCs, then routed through a pipe to the recharge basins in the northern part of the property, where it seeps back into the aquifer. Infiltration of water from the basins to layer 1 was represented by recharge wells in the model.

Model Calibration

The three steady-state models were calibrated to represent high-, average-, and low-recharge conditions. Calibration entailed matching measured and simulated hydraulic heads in the unconfined and confined aquifers, and simulated and measured gains and losses of streamflow along individual reaches of the modeled area. Steady-state conditions were assumed for the three recharge conditions. The water-level measurements used for calibration were made on March 28-29, 1990, during average high-recharge conditions, on May 28-June 4, 1991 during average-recharge conditions, and on October 7-9, 1991, during average low-recharge conditions. The long-term water-level monitoring well (well 102, pl. 1) at the City of Cortland well field and the USGS stream gage on the Tioughnioga River at Cortland (station number 01509000, pl. 2) were used as guides to determine when the three conditions occurred and the time when synoptic ground-water and streamflow measurements were to be made.

The model was calibrated by a trial-and error procedure, whereby the model is first run with the initial input values; if significant differences between measured and simulated water levels and streamflow are noted, the input values are adjusted, and the model is run again. The process is repeated until simulated values are close to measured values. The calibration process resulted in changes of horizontal hydraulic conductivity, vertical conductance of the streambed, and rate of areal recharge.

Calibration was considered satisfactory when: (1) simulated water levels were within 3 ft of the measured water levels, and (2) simulated streamflow displayed the gain-and-loss patterns indicated by measured and estimated values. Differences between simulated and measured ground-water levels are shown in table 11, and differences between simulated and measured streamflow gains and losses are shown in table 12. The resulting water budgets for each simulated condition are given in table 13.

In all three simulations, the largest source of recharge to the aquifer system (55 to 58 percent of total recharge) is from the uplands–seepage losses from upland streams that flow onto the aquifer plus unchanneled runoff and ground-water inflow from the uplands (table 13A). The second-largest source of recharge is precipitation (33 to 39 percent of total recharge) that directly falls over the aquifer. The largest discharge from the aquifer system (57 to 71 percent of total discharge) is leakage of ground water to streams (table 13B); the second largest (26 to 40 percent of total discharge) is to pumping wells.

Simulated heads in layers 1, 2, and 3 for high-, average-, and low-recharge conditions are shown in figures 25A, B, and C, respectively. Simulated heads in layer 2 are similar to those in layer 1 because both layers represent the same hydrogeologic unit.

Parts of the aquifer that have low hydraulic conductivity, such as the morainal deposits in the western part of the aquifer and kame deposits along the valley edges, have relatively steep hydraulic gradients, and parts that have high hydraulic conductivity, such as outwash deposits, have relatively low hydraulic gradients. Simulated ground-water levels in areas of low hydraulic conductivity differed from measured values more than in other areas, but the differences were less than 3 ft. Simulated water levels in areas with high hydraulic conductivity (outwash deposits) and near perennial streams in the northern and eastern parts of the aquifer were typically within 1 ft of measured ground-water levels.

Simulation of large pumping wells in the study area resulted in losses of streamflow in model stream

Table 11.-- Difference between measured and simulated heads at 49 selected wells in Cortland, N.Y., study area for high-, average-, and low-recharge conditions

[Values are observed head minus simulated head, in feet. Dashes indicate no water-level measurement made during calibration period because well was dry or not yet installed. Well and cell locations shown in pl. 1].

Location			Recharge conditions			Location			Recharge conditions		
Model row	Model column	Well number	High	Average	Low	Model row	Model column	Well number	High	Average	Low
5	91	13	1.7	-0.2	2.7	27	53	203	2.5	1.1	-0.5
5	95	114	0.4	0.3	1.1	28	40	22	-0.6	-0.1	1.9
12	77	404	-0.7	-1.3	0.1	30	11	327	2.5	2.4	0.4
13	67	369	1.3	-0.9	-0.1	30	25	348	1.8	2.0	--
14	53	106	-1.7	0.2	0.0	30	70	11	1.9	1.0	0.4
14	67	330	0.8	1.0	-0.1	31	45	401	--	2.2	2.2
14	96	446	0.1	-0.4	-0.9	31	112	420	1.4	0.8	1.0
16	91	373	0.8	--	0.1	32	45	402	--	2.4	--
18	51	5	0.3	0.4	1.0	32	112	419	1.2	0.5	0.9
20	60	204	1.8	2.0	1.1	36	18	33	3.6	0.2	-5.3
20	70	337	--	-0.1	-0.9	36	77	303	-0.5	-0.9	-1.0
20	74	47	-1.8	-2.0	-2.7	36	103	280	0.3	-0.8	-0.5
21	30	110	-3.1	-3.0	0.5	37	96	365	2.8	0.9	0.0
21	64	358	1.2.	0.9	0.1	37	101	335	--	-0.3	-0.3
21	69	357	0.8	0.4	-0.4	37	105	279	2.3	1.0	1.1
22	49	340	--	-2.0	0.2	38	36	307	1.3	-1.6	-7.5
23	39	306	1.4	-1.3	2.8	38	81	359	4.1	1.8	--
23	43	121	-0.6	-0.5	2.3	38	83	360	-1.0	-1.7	--
23	73	102	0.2	-0.6	-1.8	41	7	108	-4.1	-0.8	-1.0
24	33	320	-1.2	-0.8	4.3	41	95	332	--	-0.6	-0.1
24	47	105	0.4	0.4	1.2	42	87	321	-5.1	-1.4	1.0
24	68	356	-0.5	1.4	-0.6	47	101	281	1.5	0.3	0.5
25	54	368	0.4	0.3	1.8	48	102	282	1.6	0.5	0.6
26	53	4	2.9	2.4	-0.1	50	98	346	-0.8	-1.9	-2.2
27	33	349	-0.2	-0.8	--						
						ROOT MEAN SQUARED			1.92	1.73	1.96

Table 12.-- Measured and simulated streamflow gains and losses, for selected stream reaches during high-, average-, and low-recharge conditions in Cortland, N.Y. study area.

[Values are in cubic feet per second (ft^3/s). Positive numbers indicate gains; negative numbers indicate losses. Dashes indicate no measurement was made in that reach. Reach locations shown in figure 14.]

		Recharge conditions					
		High		Average		Low	
Stream	Reach	Measured March 29, 1990	Simulated	Measured May 30-June 4, 1991	Simulated	Measured October 9, 1991	Simulated
West Branch Tioughnioga River	A	--	9.3	9.2	8.4	5.9	5.4
Tioughnioga River	A	--	3.5	1.9	3.2	3.8	2.5
	B	--	4.1	5.7	4.0	-1.3	2.5
Otter Creek	A	-1.2	-1.7	-0.4	-0.4	Dry	
	B	--	0.0	-0.2	-0.6	Dry	
	C	0.9	0.8	0.1	-0.1	Dry	
	D	-0.8	-0.9	0.0	-0.7	Dry	
	E	1.3	-0.2	0.1	-0.1	Dry	
	F	-1.6	-0.6	-0.3	-0.4	Dry	
	G	0.4	-0.6	-1.2	-0.7	Dry	
Tributary to Otter Creek	A	-1.8	-0.7	-0.2	-0.4	Dry	
Dry Creek	A	-1.0	-0.6	-0.4	-0.4	-0.2	-0.2
	B	-0.6	-0.4	0.0	-0.1	-0.2	-0.1
	C	-0.6	-0.3	-0.4	-0.3	Dry	
	D	-0.6	-0.3	0.0	0.0	Dry	
	E	2.0	0.1	1.0	-0.1	Dry	
Perplexity Creek	A	-0.6	-0.6	-0.2	-0.1	Dry	
Tributary to Perplexity Creek	A	-0.4	-0.3	-0.1	-0.2	-0.05	-0.1
	B	-0.8	-0.1	Dry	-0.1	Dry	

Table 13. Steady-state water budgets for the glacial aquifer system at Cortland, N.Y., for high-, average-, and low-recharge conditions.

[Rates are in cubic feet per second, (ft^3/s)]

	Recharge conditions					
	High March 28-29, 1990		Average May 28-June 4, 1991		Low October 7-9, 1991	
Budget component	Amount	Percent of total	Amount	Percent of total	Amount	Percent of total
A. Recharge to the aquifer system						
Precipitation on the aquifer	16.2	39	14.4	38	9.3	33
Upland sources						
Seepage losses from tributary streams	15.2	36	12.2	32	10.4	38
Unchanneled runoff and ground-water inflow from uplands	9.2	22	8.8	23	5.4	19
Ground-water inflow from valleys to model area	1.0	3	.9	3	.5	2
Infiltration at recharge basins	0.0	0	1.7	4	2.2	8
TOTAL	41.6	100	38.0	100	27.8	100
B. Discharge from aquifer system						
Pumping wells	10.7	26	10.7	28	11.0	40
Discharge from aquifer to streams	29.5	71	26.1	69	15.9	57
Ground-water outflow from model area	1.4	3	1.2	3	.9	3
TOTAL	41.6	100	38.0	100	27.8	100

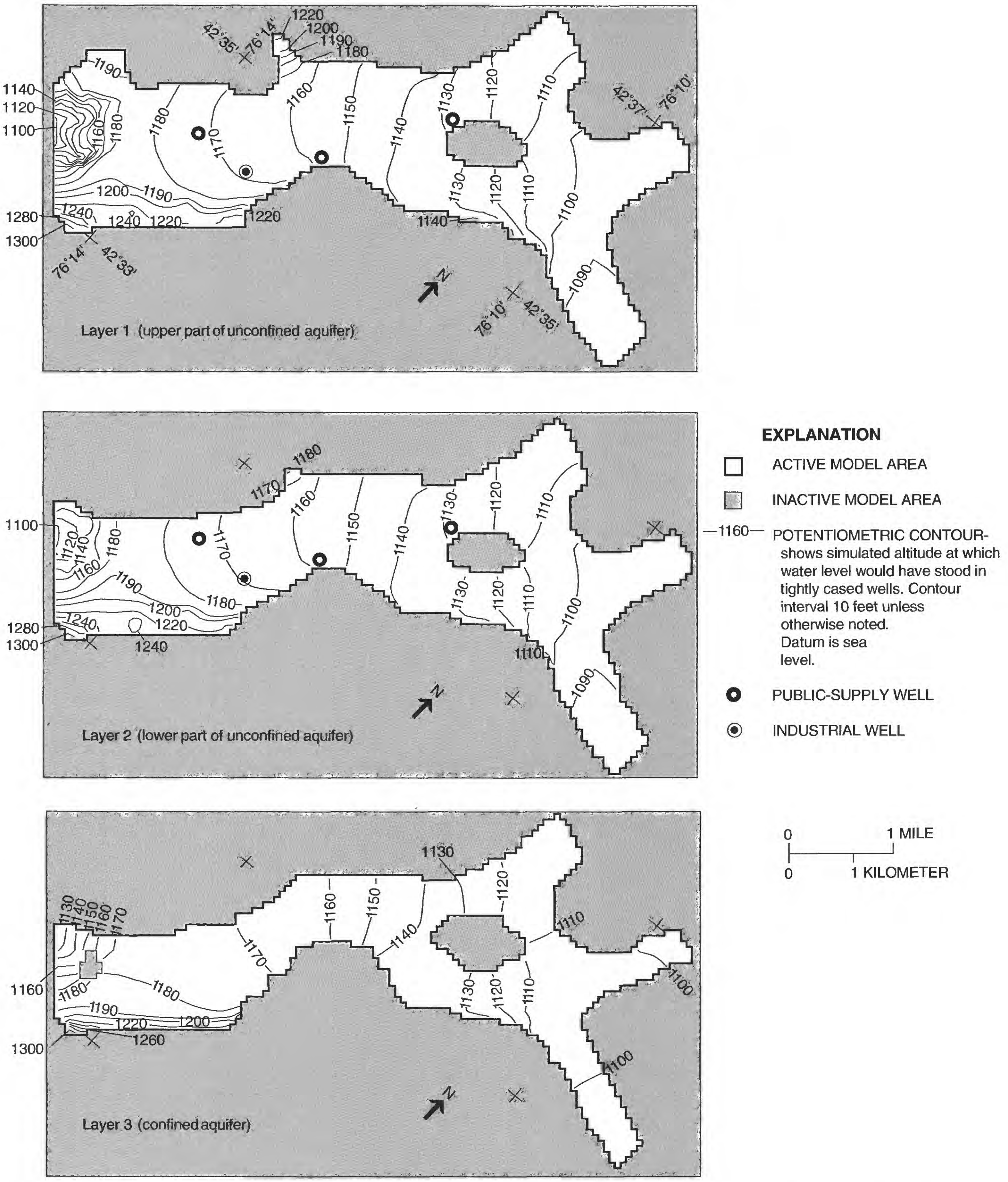


Figure 25A. Simulated head in model layers 1, 2, and 3 during steady-state high-recharge conditions in Cortland, N.Y. study area. (Locations and vertical positions of layers are shown in fig. 23.)

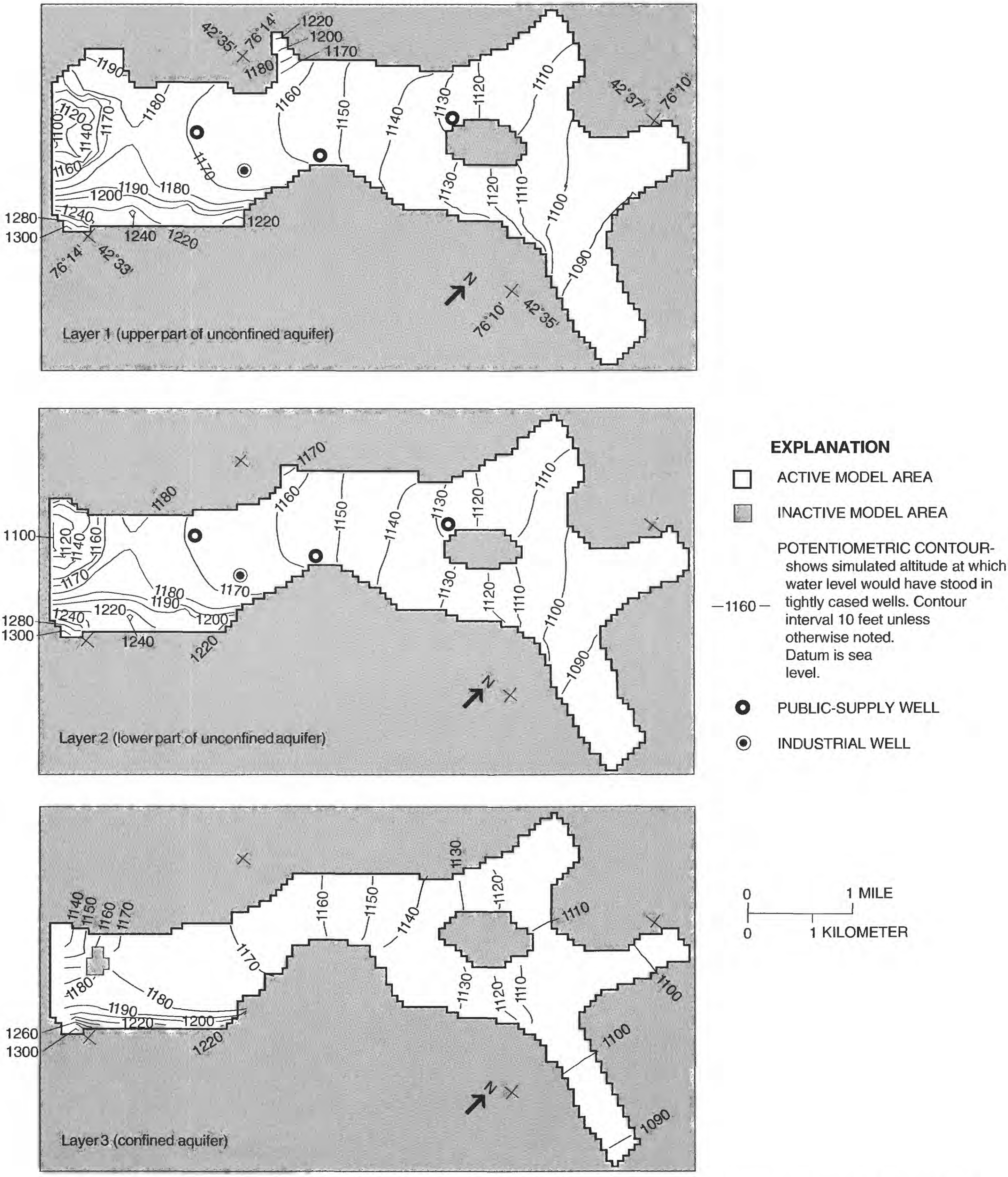


Figure 25B. Simulated head in model layers 1, 2, and 3 during steady-state average-recharge conditions in Cortland, N.Y. study area. (Locations and vertical positions of layers are shown in fig. 23.)

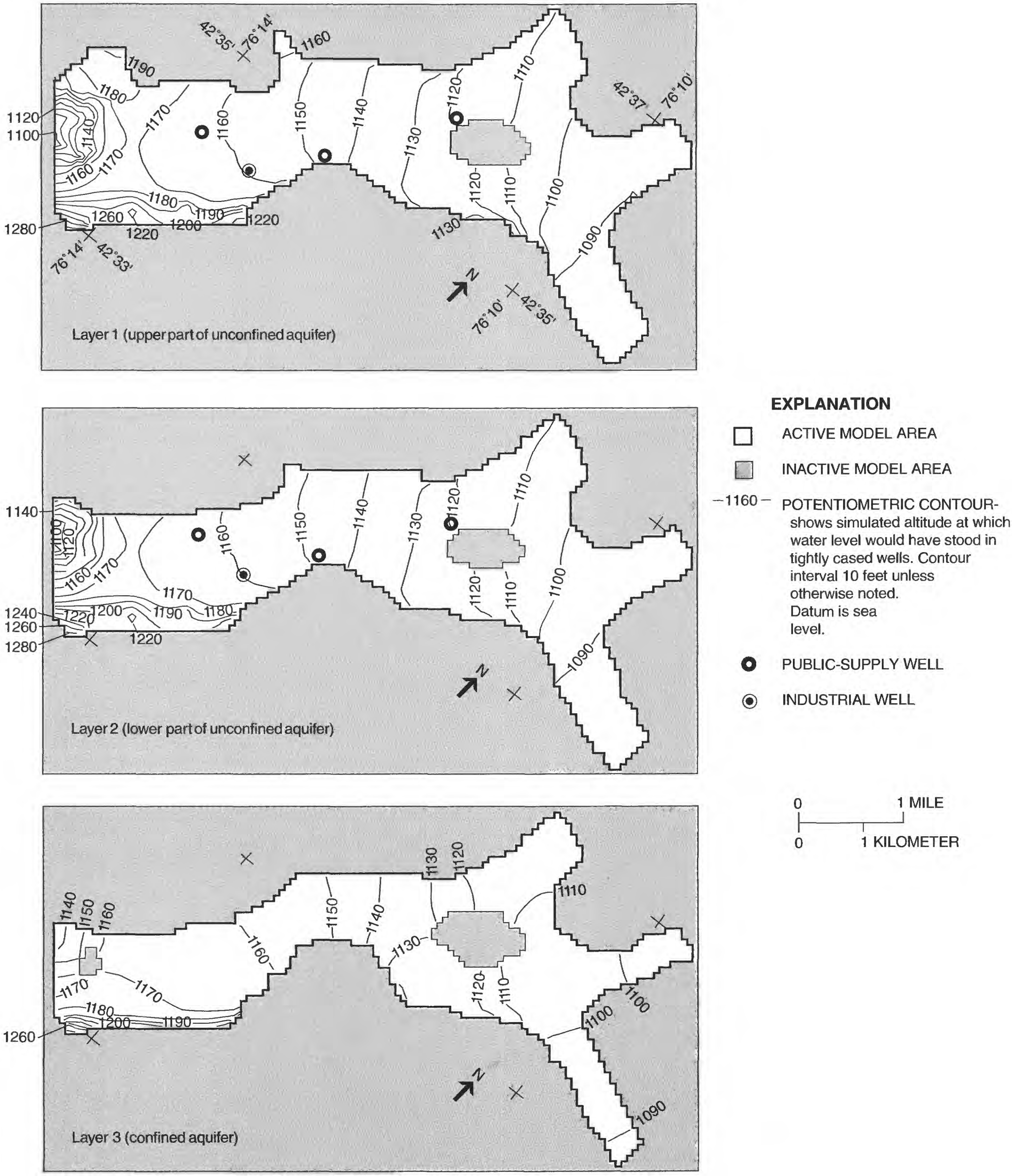


Figure 25C. Simulated head in model layers 1, 2, and 3 during steady-state low-recharge conditions in Cortland, N.Y. study area. (Locations and vertical positions of layers are shown in fig. 23.)

reaches that are near the major pumping wells, such as where Otter Creek flows by the City of Cortland well field.

Model Sensitivity

Sensitivity analyses of the model simulating average-recharge conditions were conducted to assess which model parameters resulted in large changes, and which ones resulted in small changes, in the simulated water levels (heads) and in the streamflow gains or losses. Future data-collection efforts can be directed to those aquifer properties to which the model is most sensitive.

Recharge, horizontal hydraulic conductivity of the unconfined aquifer, vertical hydraulic conductivity of the streambed, and conductance between the unconfined aquifer (layer 2) and the confined aquifer (layer 3) were varied one at a time, and the effect on calculated heads (fig. 26) and on gains or losses in streamflow in reaches of the West Branch Tioughnioga River and Tioughnioga River (fig. 27) were noted. The vertical axis in figure 26 shows the root mean square of the difference between the computed and observed heads at 48 observation wells. The root mean square of the difference between calculated and measured head was 1.29 for the final calculated model (multiplication factor equal to 1 in the graph); all sensitivity analyses for multiplication factors other than 1 had root mean squares greater than 1.29.

Results of these analyses indicate that the model is relatively sensitive to recharge and horizontal hydraulic conductivity of the unconfined aquifer, moderately sensitive to vertical hydraulic conductivity of the streambed, and insensitive to vertical conductance between the unconfined and confined aquifers

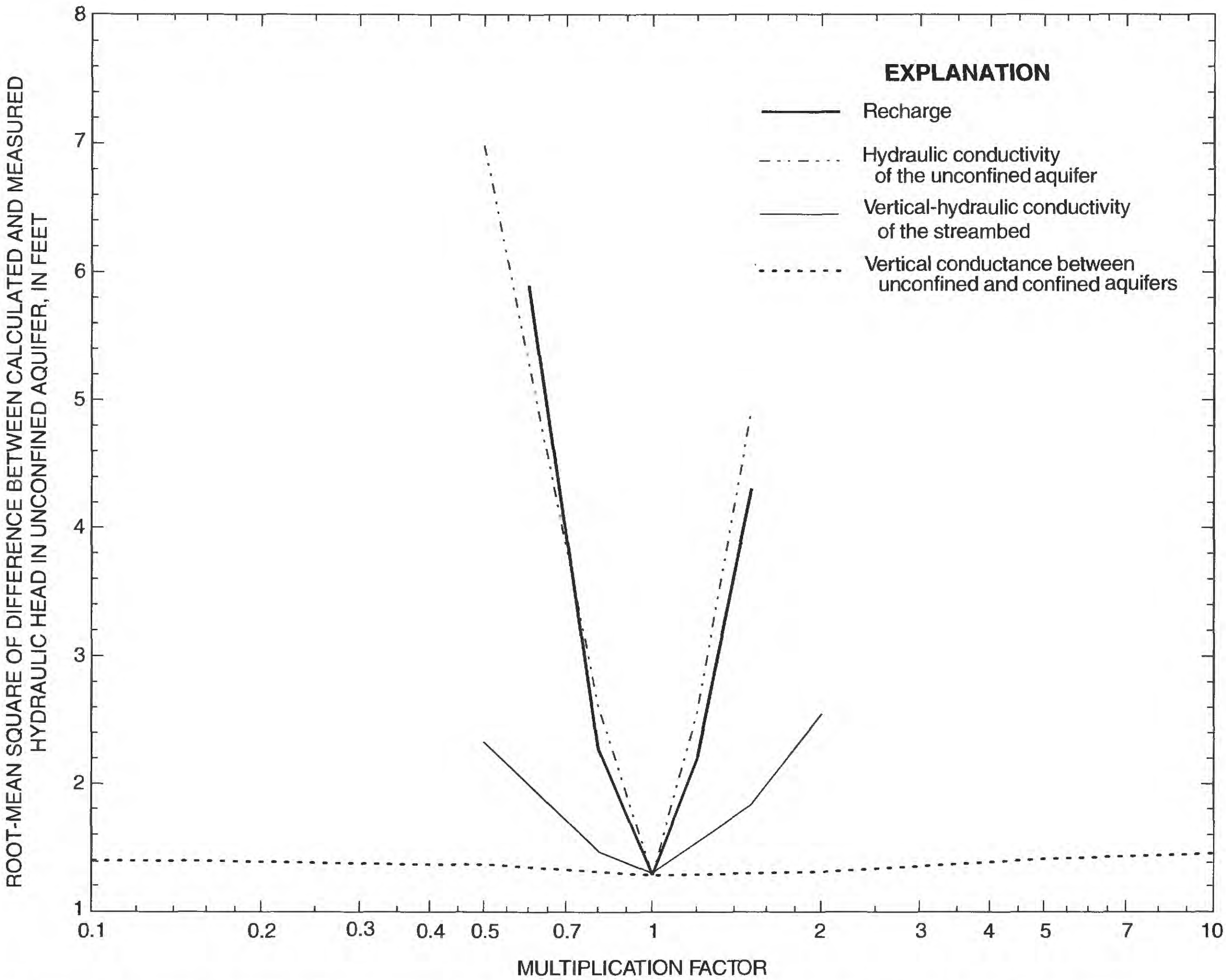


Figure 26. Results of sensitivity analyses for hydraulic head in unconfined aquifer in Cortland, N.Y. study area. (Root-mean squared calculated at 48 model cells containing observation wells.)

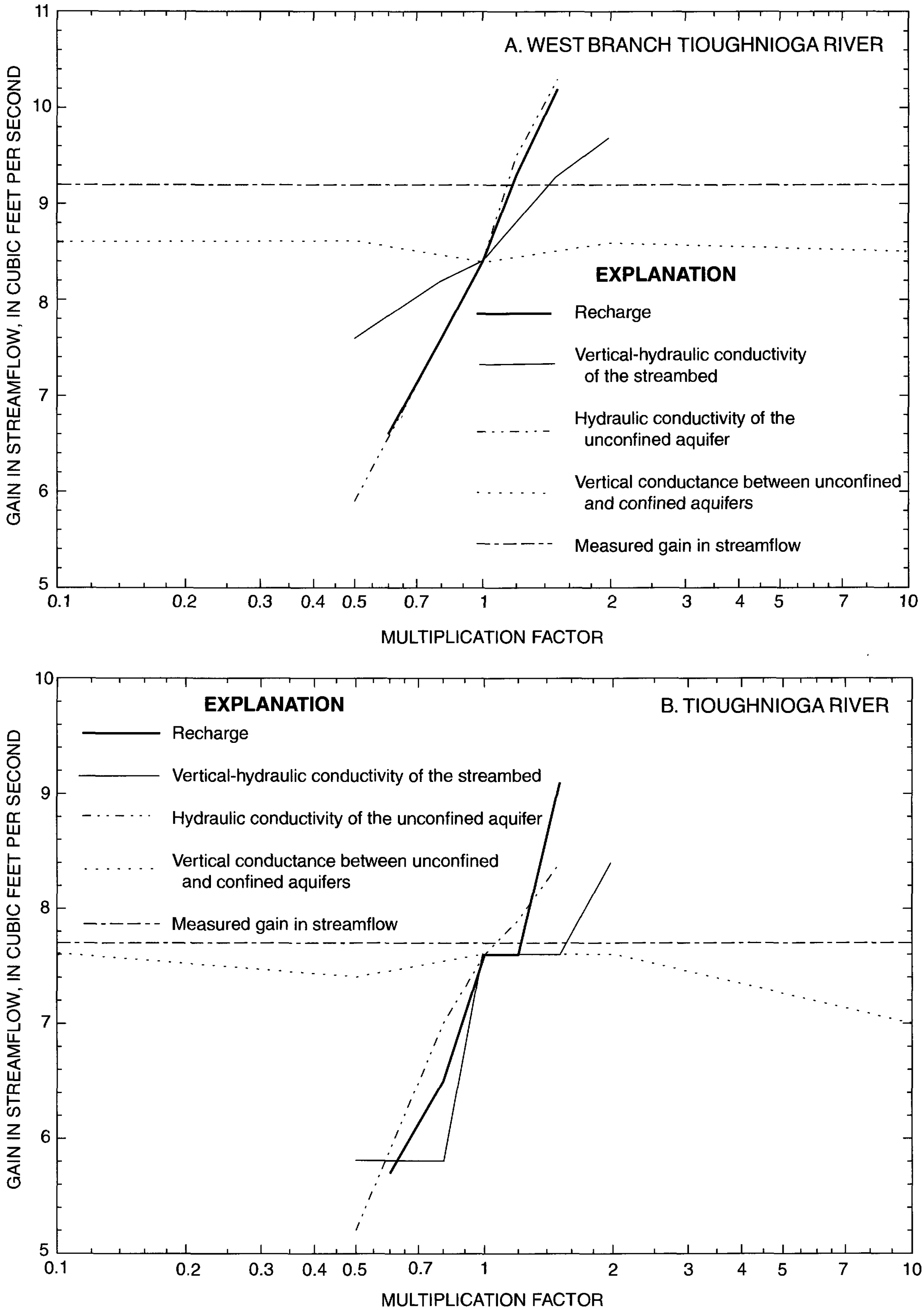


Figure 27. Results of sensitivity analyses for ground-water discharge to major streams during average-recharge conditions in the glacial-drift aquifer in the Cortland, N.Y. study area: A. Reach A of West Branch Tioughnioga River. B. Reaches A and B of Tioughnioga River. (Reach locations are shown in fig. 14.)

(fig. 26). The most sensitive areas in the model are those with low hydraulic conductivity (kame deposits). Neither the vertical hydraulic conductivity of the streambed, nor the vertical leakance between the unconfined and confined aquifers could be measured directly, and both can vary over a wide range of values; therefore, the values of these parameters were tested over a greater range than the others.

Results of the sensitivity analyses for streams (fig. 27) indicated that the ground-water discharge to West Branch Tioughnioga River and to Tioughnioga River was relatively sensitive to changes in recharge, vertical-hydraulic conductivity of the streambed, and horizontal hydraulic conductivity of the unconfined aquifer. The simulated heads and streamflow were relatively insensitive to vertical conductance between the unconfined and confined aquifer.

Model Applications

Delineation of contributing areas to wells by use of numerical flow models has a high potential for accuracy because models can incorporate many of the hydrogeologic factors that affect ground-water flow, such as aquifer geometry, hydraulic conductivity, recharge rate, and pumping rate. Particle tracking provides a simple means of evaluating the advective-transport characteristics of ground-water systems, including computation of the flowpath and traveltimes of the advective phase of contaminants.

Areas Contributing Recharge to Municipal Wells

Pumping large quantities of ground water from an aquifer system causes a drawdown within the aquifer, and the drawdown decreases with increasing distance from the pumping well. The lowering of head that results from pumping causes ground water to flow to the well, and the flowpaths to the well depend on the hydrogeologic characteristics of the flow system, the well location and pumping rate, the system boundaries, and the rate and distribution of recharge to the aquifer system. Factors that affect the areas contributing recharge to wells are described in detail in Reilly and Pollock (1993).

Areas contributing recharge to major pumping wells in the glacial-aquifer system in the study area were delineated for the periods of high, average, and low recharge described previously. The ground-water flowpaths for the three conditions were calculated by the MODPATH program (Pollock, 1989) from the output from MODFLOW (McDonald and Harbaugh, 1988). The simulated areas contributing water to municipal wells and to the recovery well at the typewriter plant are delineated in plates 2, 3, and 4. A porosity of 0.3 for the aquifers and confining unit was used for MODPATH calculations.

The contributing-area analyses indicate that the contributing areas to pumping wells are U-shaped (open end facing upgradient of the well) and extend over most of the unconfined aquifer upgradient from the wells. In general, the contributing areas resulting from the low-recharge simulation were the largest, and those resulting from the high-recharge simulation were the smallest (pl. 2, and 4). The City of Cortland municipal well had the largest contributing area in all three simulations. Recharge from tributaries such as Otter Creek and the unnamed tributary north of Otter Creek were important sources of water to the city well; thus, evaluations of the quality of water pumped by the well need to consider water quality in these two streams. At present, land use in the proximal parts of the contributing area to the city well field is mostly residential and forest, and land use in the distal parts is mostly residential and commercial, with some industry and agriculture. The typewriter plant in the western part of the aquifer was not part of the contributing area to the city well field in any simulations when the purge well at the plant was pumping (pls. 2, 3, and 4), but when the purge well was turned off, the industrial site was part of the contributing area in the high- and average-recharge simulations.

The contributing area to the Town of Cortlandville well field at Terrace Road is relatively small. This well field also receives recharge from a reach of Otter Creek (pls. 2, 3, and 4). Land use within the contributing area is mostly commercial. Chemical spills near the contributing area have come close to contaminating this well field, and, as a result, the Town has installed another municipal well at Lime Hollow Road, which is upgradient of most of the commercial and industrial areas.

The municipal well for the Town of Cortlandville at Lime Hollow Road began pumping in 1991; therefore, the contributing area for this well during high-recharge condition of 1990 was not simulated. The contributing areas for this well under average- and low-recharge conditions extend to the ground-water divide in the southwestern part of the study area and contain several ponds (pls. 3 and 4). Land use within the contributing area is mostly agricultural and forest, with some residential areas and one industry. This well's contributing area is in the least developed part of the study area and, therefore, should be the least threatened by urban sources of contamination.

Flowpaths to Wells and Streams from Sources of Contamination

The flowpaths and traveltimes of the advective phase of contaminants in the study area were determined through the MODPATH program, which computes paths (tracks) of imaginary "particles" of water moving through a simulated ground-water system and keeps track of their traveltime. Particle tracking provides a simple means of evaluating the advective-transport characteristics of ground-water systems. Advective-flow models cannot be used to compute solute concentrations in ground water because they do not account for the effects of dispersion, adsorption, chemical reactions, or other transport phenomena, but they are useful intermediate step between ground-water flow models and solute-transport models. Chemical dispersion typically cause contaminant plumes to be larger than indicated by advective-flow models. Particles were tracked from the contaminated sites at the typewriter plant in the western part of the study area and at the Superfund site in the southeastern part; and flow velocities were calculated from an average porosity of 0.3.

Typewriter Plant

Movement of particles from the typewriter plant to discharge points was tracked in simulations in which the purge well was pumping to represent conditions during remediation work; the resulting flowpath analyses indicated that the TCE spill is within the contributing area of the purge well. Particles were then tracked in simulations in which the purge well was not pumping, to represent the flowpath of the advective movement of TCE during the several years before the remedial pumping began. Particles were applied to the water table (top face of cell in layer 1) at the cell representing the TCE spill; the resulting flowpaths in the unconfined aquifer during high-, average-, and low-recharge conditions are shown in figures 28A, B, and C. Ground water flows northeastward from the spill area to the center of the aquifer. Flowpaths shifted progressively southward from a northeastward route during high-recharge conditions to more eastward paths during average- and low-recharge conditions, respectively, as a result of differences in the distribution of recharge during those conditions.

The discharge areas of ground water that flows from the TCE spill vary according to recharge conditions. During high- and average-recharge conditions, ground water flows 2.25 mi northeastward, then discharges to the City of Cortland municipal well (fig. 28A, B) and to a small pond near the municipal well. The flowpaths shift slightly to the south during average-recharge conditions, and the traveltime of ground water flowing from the typewriter plant to the municipal well is about 4 years.

Simulated ground-water flowpaths from the TCE spill site shift even farther southward during low-recharge conditions and do not end at the City's municipal well or at the pond, but discharge into the Tioughnioga River (fig. 28C), 3.7 mi northeast of the spill site. Traveltime is about 7 years from the spill site to the Tioughnioga River.

Superfund Site

The movement of particles from the Rosen Superfund site also were tracked from the water table to delineate the flowpath and traveltime of ground water migrating from the site to the discharge area (fig. 28A, B, C). Ground water flows about 1 mi northeastward from the site to the central part of the valley, where it bends to the southeast and discharges into the Tioughnioga River about 1 mi east of the site. Traveltime of ground water from the site to the Tioughnioga River ranges from 3 years during high-recharge conditions to just under 4 years during low-recharge conditions. The flowpaths shift progressively from northeastward paths during high-recharge conditions to more southward traces during average- and low-recharge conditions (figs. 28A, B, C). The particle-tracking analyses indicate that some ground water may also discharge to an industrial well owned by ETL, Inc. on the east side of the river (fig. 28A, B, C). Trichloroethane (TCA) is one of the contaminants found in ground water at, and migrating from, the Superfund site (Blasland, Bouck and Lee, Engineers, 1992); it also was found at the ETL well. A detailed study would be needed to determine whether the TCA at the ETL well comes from the "Superfund" site, the ETL property, or some other source.

Flowpaths that originated in the unconfined aquifer at the Superfund site under the three simulated conditions extended through the model cell that contains USGS test well 332 (local well number 90-

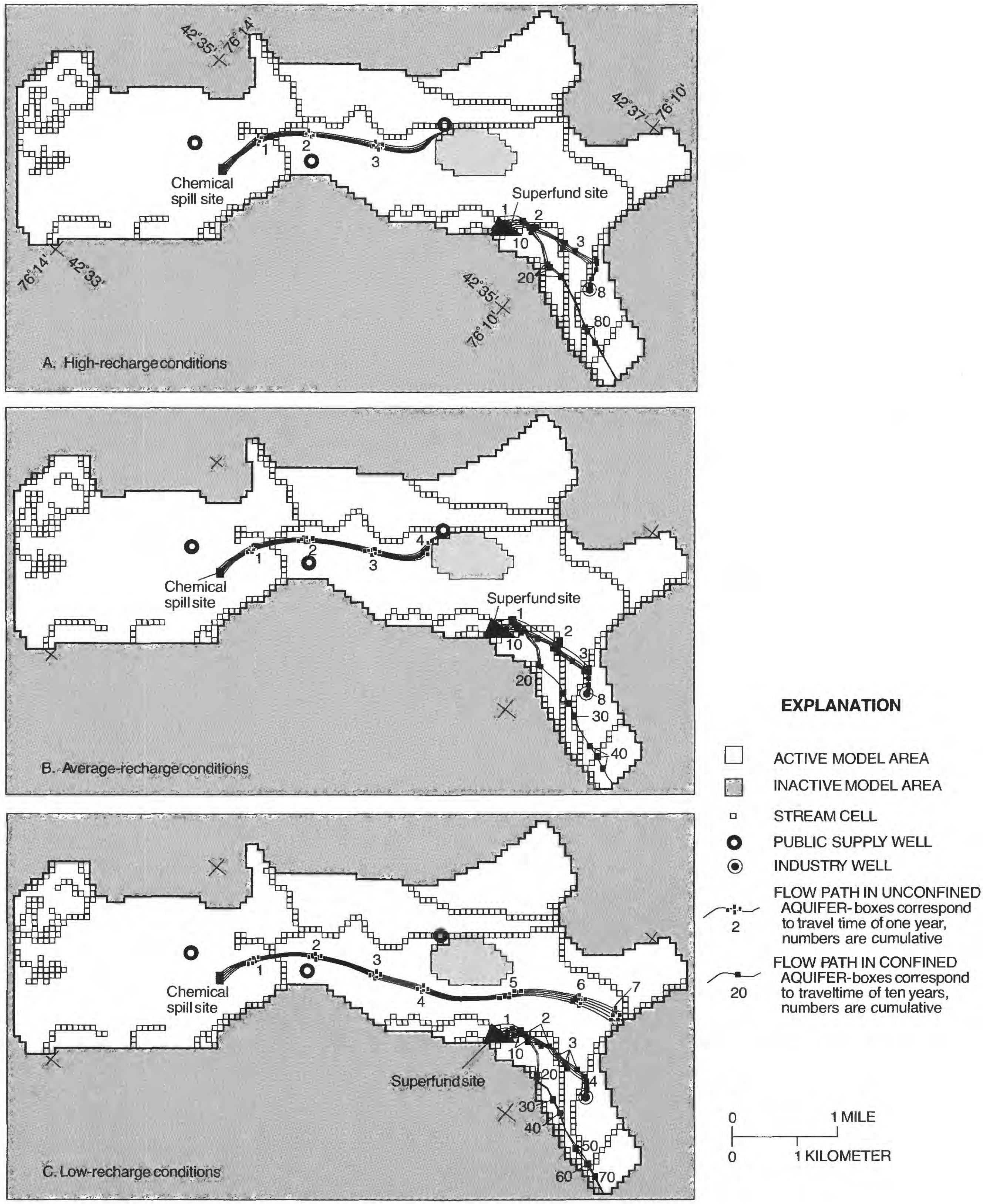


Figure 28. Flowpaths and traveltime of ground water moving from two contaminant sources in Cortland, N.Y. study area: A. Under high-recharge conditions. B. Under average-recharge conditions. C. Under low-recharge conditions. (Location is shown in fig.24.)

1S, pl. 1), in which TCA, TCE, and *trans*-DCE were detected in concentrations of 107, 15.2, and 28.9 μg/L, respectively (appendix 3). Although the particle-tracking analyses indicate that those contaminants have migrated to well 332 and beyond, their origin at the Superfund site is uncertain because the area between well 332 and the Superfund site contains other potential sources of these contaminants.

Particles were then tracked from the bottom of layer 3 at the Superfund site to simulate conditions where the confining layer is absent along the valley wall (layer 3 is in hydraulic connection to layers 1 and 2) and where a DNAPL could readily sink from land surface to the bottom of the layer 3, releasing a dissolved-phase contaminant to ground water. Whether the Superfund site contains a DNAPL is uncertain; therefore this scenario is hypothetical. Particles were not placed in cells of layer 3 where it is confined because contaminants would not move readily through the confining layer. Flowpaths in the confined aquifer initially trend northeastward from the "Superfund" site, then bend to the southeast, where they exit the modeled area as underflow through the Tioughnioga River valley (fig. 28A, B, C). Traveltime from the Superfund site to the eastern edge of the modeled area ranged from 30 years under high-recharge conditions and to more than 70 years under low-recharge conditions.

SUMMARY

Glacial aquifers in the Otter Creek-Dry Creek Valley and in parts of the adjacent West Branch, East Branch, and Tioughnioga River Valleys are the sole source of water for the City of Cortland and surrounding communities. Several parts of the aquifer system have been contaminated by: (1) solvents and degreasers, including trichloroethylene (TCE), trichloroethane (TCA), and dichloroethene (DCE), (2) gasoline from leaking storage tanks at least at two service stations, (3) bacteria from failing septic systems, and (4) leachate from a "Superfund" site. The USGS, in cooperation with the Cortland County Departments of Planning and Health, studied the hydrogeology and water quality of a glacial-aquifer system in Cortland County during 1989-93 and simulated ground-water flow to delineate areas contributing recharge to municipal wells and to the ground-water flowpaths from two chemical-spill sites.

The unconsolidated deposits in the study area were deposited between 10,000 and 23,000 years ago during Late Wisconsinan glaciation. The central parts of the valley contain kames deposits that form a confined aquifer where they are overlain by fine-grained lacustrine sediments. The kame deposits are typically 60 to 170 ft thick in the western and eastern parts of the valley. Kames are overlain by outwash where the confining layer is absent in some places along the edges of the valley.

A large moraine system (Valley Heads Moraine) formed in central and western New York valleys during a major standstill of the ice front 14,000 and 14,900 years ago. The western part of the study area contains a Valley Heads moraine in the Otter Creek-Dry Creek valley; the moraine is a heterogeneous deposit consisting of coarse sand and gravel in the upper part, and till and lacustrine deposits in the lower part.

A proglacial lake formed in valleys of the Tioughnioga River basin during deglaciation. Fine-grained sediments that were deposited within this lake range from 90 ft thick in the eastern part of the study area to 150 ft in the northern and central parts, and to 170 ft in the southwest part. This unit extends throughout the study area except where it pinches out along the edges of the valley.

After the proglacial lake drained from the study area, glacial meltwaters from the Valley Heads ice deposited large amounts of outwash atop the lacustrine unit. The outwash grades from coarse boulder gravel near the ice-front location in the southwestern part of the study area to coarse cobble-and-pebbly sand and gravel in distal reaches in the central and eastern parts.

The glacial-aquifer system consists of 40 to 80 ft of unconfined sand and gravel (mostly outwash) that overlies a confining layer (lacustrine deposits and till), that ranges from 1 to 155 ft thick. This unit, in turn, overlies confined sand and gravel (kame deposit) that ranges from 0 to 170 ft thick. The confining unit impedes ground-water movement between the unconfined and confined aquifers in the middle of the valley, but the two aquifers are hydraulically connected wherever the confining layer is absent along the valley walls.

Hydraulic conductivity of the unconfined aquifer, as determined from aquifer tests at large pumping wells, ranges from 85 to 1,150 ft/d, and hydraulic conductivity of the confined aquifer, as determined from aquifer tests where range from 60 to 65 ft/d at a fish hatchery in the western part of the

study area and from 3 to 140 ft/d at the Superfund site in the eastern part.

Water levels were measured in about 100 wells during three periods–early spring (March 28-29, 1990), late spring and early summer (May 28 through June 4, 1991), and fall (October 7-9, 1991)—to document ground-water levels during high-, average-, and low- recharge periods, respectively. Data from these three periods were used to calibrate the ground-water-flow model. The unconfined aquifer supplies four major pumping centers– (1) the City of Cortland well field in the central part of the study area, (2) the Town of Cortlandville well field at Terrace Road, (3) the Town of Cortlandville municipal well at Lime Hollow Road, and (4) a purge well at a typewriter production plant in the western part. Water in the unconfined aquifer generally moves from the edges of the valley toward the center, then northeastward along the axis of the Otter Creek-Dry Creek valley, where it discharges to pumping wells, West Branch Tioughnioga, and Tioughnioga Rivers. Water in the confined aquifer generally follows the direction of flow in the unconfined aquifer.

The aquifer system receives recharge from three sources under natural (nonpumping) conditions: (1) direct infiltration of precipitation on the aquifer, (2) runoff from unchanneled hillsides that border the aquifer, and (3) seepage from tributary streams that flow over the aquifer. The unconfined aquifer receives additional recharge from two sources under pumping conditions– (1) treated pumped water from the typewriter plant that infiltrates to the aquifer at recharge basins, and (2) induced infiltration from streams and ponds near the major pumping wells. Average annual recharge to the aquifer system from precipitation is 23.0 in.

Most tributary streams in the study area lose water to the aquifer where they flow into the main valley, except for some reaches in Otter Creek. Only part of the streamflow in upland tributaries seeps into the aquifer during high-flow conditions during the spring and during large storms throughout the year, however; the rest flows over the aquifer and discharges into the West Branch Tioughnioga and Tioughnioga Rivers. Most tributary streams lose all their water to the aquifer during low-flow conditions in the summer, fall, and winter, except for Dry Creek, which goes dry only during exceptionally dry periods. Losing streams typically dry up in the upstream direction, whereas gaining streams typically dry up starting at the headwaters.

Ground water discharges from the unconfined aquifer system by (1) seeping into major streams and seasonally into some reaches of Otter Creek; (2) flowing to pumping wells; (3) moving as underflow along the Tioughnioga River valley; and (4) seeping to springs that form the headwaters to the Fall Creek Valley in the western part of the study area. Most water in the unconfined aquifer either discharges into streams or is pumped from municipal wells, and most of the water pumped from municipal wells is eventually treated at the sewage-treatment plant, then discharged into the Tioughnioga River. Ground-water withdrawals from the unconfined aquifer through municipal and industrial wells range from 6.76 to 7.20 Mgal/d. The largest ground-water user is the City of Cortland which, during 1984-92, pumped from 3.9 to 4.3 Mgal/d. The direction of ground-water flow in the confined aquifer generally is similar to that in the unconfined aquifer.

The extent of a TCE plume in the unconfined aquifer was determined for three sampling periods (April 4-5, 1990, September 17-20, 1990, and April 27, 1993); results indicate that TCE has migrated 1.25 mi northeastward from its source at the typewriter plant in the western part of the study area. The extent of the plume was similar during all three sampling periods, indicating that steady-state conditions have been reached. Little or no TCE was detected in the confined aquifer.

TCE concentrations were highest during 1987-88; then decreased slightly from 1989 through mid-1992, and dropped significantly at the end of the 1992, probably in response to removal of contaminated soil and pumping of a recovery well at the source.

The "pump and treat" remedial program at the typewriter plant was expected to significantly lower the TCE concentrations throughout the aquifer by April 1993, but the results of the April 1993 sampling showed the concentrations at most wells in the middle and distal parts of the plume had increased significantly since the preceding fall and were nearly as high as the maximum values in 1987-89. The increase in April 1993 is attributed to desorption of TCE from sediments that had been unsaturated for 10 years, when the water table rose to its highest levels in 10 years in response to above-normal recharge in March and April, 1993.

TCE concentrations at wells within 1,500 ft of the source fluctuated seasonally; they were highest during the spring and lowest during the summer and fall. TCE concentrations at wells more than 1,500 ft from the source showed little or no seasonal trend.

Detection of a TCE degradation product (*cis*-1,2-DCE) in most wells in the plume indicates biologically mediated reductive dehalogenation. The fate of TCE after biodegradation to *cis*-1,2-DCE is uncertain; other degradation compounds either were not detected (vinyl chloride) or were detected only on rare occasion in trace amounts (1,2-DCA). The end degradation products of TCE are carbon dioxide, water, and chloride.

Ground-water samples were collected from both aquifers during April and September 1990 and analyzed for inorganic and organic chemical constituents; results indicate that the quality of water generally meets New York State drinking-water standards, except for part of the unconfined aquifer that is contaminated by TCE. Elevated concentrations of chloride are generally found in ground water near major roads that are heavily salted. Median concentrations of chloride during the April and September 1990 samplings, were 37 and 39 mg/L, respectively. The trend of increasing chloride concentrations since the early 1940's at the City of Cortland well field, noted by Buller (1978), has continued.

Nitrate concentrations in ground water ranged from 0.1 mg/L to 12.0 mg/L, with a median concentration of 4.3 mg/L. The concentrations were higher in the agricultural areas than elsewhere.

A quasi-three-dimensional, digital ground-water flow model was constructed to simulate hydraulic head, estimate the contributing areas for municipal wells, and delineate the flowpaths of ground water migrating from two sources of contamination. The aquifer system was represented as three layers–the upper two represent the unconfined aquifer, and the third represents the confined aquifer. The resulting areas contributing recharge to wells are U-shaped and extend over most the aquifer upgradient from the pumping wells. The largest contributing areas resulted from low-recharge simulations, and the smallest resulted from high-recharge simulations. The City of Cortland municipal well had the largest contributing area in all three simulations. Otter Creek and an unnamed tributary north of Otter Creek are within the contributing area to the city's wells; thus, their water can affect the municipal ground-water supply.

The contributing area for the Town of Cortlandville well field at Terrace Road is relatively small. The well receives recharge from a reach of Otter Creek. The contributing area for the Town of Cortlandville municipal well on Lime Hollow Road extends to the ground-water divide in the southwestern part of the study area. The contributing area for the well on Lime Hollow Road is in the least developed part of the study area and, therefore, is expected to be only minimally affected by contamination from urban sources.

The flowpaths and traveltimes of ground water moving from two major chemical-spill sites (the typewriter plant in the western part of the study area and the Superfund Site in the southeastern part) were determined through MODPATH, a particle-tracking program. Results indicate that, during high- and average-recharge conditions, ground water from the typewriter plant discharges to the City of Cortland municipal well, 2.25 mi to the northeast. No significant concentrations of TCE (above 5 μg/L) were detected at the municipal well because degradation and volatilization had reduced them below this level within 1.25 mi of their source. Traveltime from the source to the municipal well is about 4 years. During low-recharge conditions, flowpaths shift southward, bypass the municipal well, and end at the Tioughnioga River. Traveltime from the source to the river is about 7 years.

Ground water from the Superfund site flows to the central part of the unconfined aquifer and discharges into the Tioughnioga River about 1 mi to the east. Traveltime from the source to the Tioughnioga River ranged from 3 to 4 years.

REFERENCES CITED

Apfel, E. T., 1967, Monarch-Edlund water wells as of December 1, 1967, South Cortland, Cortland County, New York: Apfel and Associates, Inc., Syracuse, N.Y., 20 p.

Asselstine, E.S., 1946, Progress report on the ground-water conditions in the Cortland quadrangle, New York: New York State Water Power and Control Commission Bulletin GW-16, 49 p.

Barbee, G.C., 1994, Fate of chlorinated aliphatic hydrocarbons in the vadose zone and ground water: Ground Water Monitoring Review, v.14, no. 1, p. 129-140.

Barrio-Lage, G., Parsons, F.Z., Nasser, R.S., and Lorenzo, P.A., 1986, Sequential dehalogenation of chlorinated ethenes: Environmental Science and Technology, v. 20, no. 1, p. 96-99.

Behnke, J.J., 1974, A summary of nitrogen compounds in ground water: Jour. of Hydrology, v. 27, p. 155-167.

Blasland, Bouck and Lee, Engineers, 1992, Remedial inves-tigation report, Rosen Site, Cortland, New York: Syracuse, N.Y., Blasland, Bouck and Lee Engineers, 210 p.

______1995, Natural attenuation at the Rosen Brothers Superfund Site, Cortland, New York: Syracuse, N.Y., Blasland, Bouck and Lee Engineers, 19 p.

Buchanan, T.J., and Somers, W.P., 1969, Discharge measurements at gaging stations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A8, 65 p.

Buller, William, Nichols, W.J., and Harsh, J.F., 1978, Quality and movement of ground water in the Otter Creek-Dry Creek basin, Cortland County, New York: U.S. Geological Survey Water-Resources Investigations, Open-File Report 78-3, 63 p.

Campbell, J.B., Szabo, C.O., Sherwood, D.A., and Deloff, D.D., 1992, Water Resources Data, New York, Water Year 1991, v. 3, Western New York: U.S. Geological Survey Water Data Report NY-91-3, 200 p.

Cho, H.J., Jaffe, P.R., and Smith, J.A., 1991, Design of a field experiment to study the dynamics of trichloroethylene vapors in the unsaturated zone during an infiltration event, *in* Mallard, G.E. and Aronson, D.A., (eds.), 1991, U.S. Geological Survey toxic Substances Hydrology Program--Proceedings of the Technical Meeting, Monterey, California, March 11-15, 1991: U.S. Geological Survey Water-Resources Investigations Report 91-4034, p. 721-725.

Conover, W.J., and Iman, R.L., 1981, Rank transformations as a bridge between parametric and nonparametric statistics: American Statistician, v. 35, p. 124-129.

Cosner, O.J. and Harsh, J.F., 1978, Digital-model simulation of the glacial-outwash aquifer, Otter Creek-Dry Creek basin, Cortland County, New York: U.S. Geological Survey Water-Resources Investigations-Open-File Report 78-71, 34 p.

Cressey, G.B., 1966, Land Forms, *in* Thompson, J.H., (ed.), Geography of New York State: Syracuse University Press, fig. 9, p. 26.

Davis, Andy, and Olsen, R.L, 1990, Predicting the fate and transport of organic compounds in ground water (Part 1): Hazardous Material Control, v. 3, no. 3, p. 39-64.

Dethier, B. E., 1966, Precipitation in New York State: New York State College of Agriculture at Cornell University, Ithaca, N.Y., Bulletin 1009, 78 p.

Ehlke, T.A., Imbrigiotta, T.E., Wilson, B.H., and Wilson, J.T., 1991, Biotransformation of *cis*-1,2-dichloroethylene in aquifer material from Picattiny Arsenal, New Jersey, *in* Mallard, G.E. and Aronson, D.A. (eds.), 1991, U.S. Geological Survey Toxic Substances Hydrology Program–Proceedings of the Technical Meeting, Monterey, California, March 11-15, 1991: U.S. Geological Survey Water-Resources Investigations Report 91-4034, p. 689-697.

Farrell, James, and Reinhard, Martin, 1994, Desorption of halogenated organics from solids, sediments, and soil under unsaturated conditions: Environment Science and Technology, v. 28, no. 1, p. 53-62.

Fullerton, D.S., 1980, Preliminary correlation of post-Erie interstadial events (16,000-10,000 radiocarbon years before present), Central and Eastern Great Lakes Region, and Hudson, Champlain, and St. Lawerence Lowlands, United States and Canada: U. S. Geological Survey Professional Paper 1089, 52 p.

Galson Technical Services, Inc., 1988, Subsurface investigation for Monarch Cortland facility, South Cortland, New York: East Syracuse, N.Y., Galson Technical Services, Inc., 15 p.

Haeni, F.P., 1988, Application of seismic-refraction techniques to hydrologic studies: U.S. Geological Survey Techniques of Water-Resources Investigations, book 2, chap. D2, 86 p.

Heath, R.C., 1983, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, p. 13.

Imbrigiotta, T.E., Ehlke, T.A., and Martin, Mary, 1991, Chemical evidence affecting the fate and transport of chlorinated solvents in ground water at Picatinny Arsenal, New Jersey *in* Mallard, G.E. and Aronson, D.A. (eds.), 1991, U.S. Geological Survey toxic Substances Hydrology Program--Proceedings of the Technical Meeting, Monterey, California, March 11-15, 1991: U.S. Geological Survey Water-Resources Investigations Report 91-4034, p. 681-688.

Isachsen,Y.W., Landing Ed, Lauber, J.M., Rickard, L.V., and Rogers, W.B., 1991, Geology of New York—a simplified account: New York State Museum-Geological Survey Educational Leaflet no. 28, 284 p.

Jeffers, P.M., Ward, L.M., Woytowitch, L.M., and Wolfe, N.L., 1989, Homogeneous hydrolysis rate constants for selected chlorinated methanes, ethanes, ethenes, and propanes: Environmental Science and Technology v. 23, no. 8, p. 965-969.

Kennedy, E.J., 1990, Levels at streamflow gaging stations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chapter A19, 27 p.

MacKay, D.M., Roberts, P.V., and Cherry, J.A., 1985, Transport of organic contaminants in ground water: Environmental Science and Technology, v. 19, no. 5, p. 384-392.

McCarty, 1991, Engineering concepts for in-situ bioremediation, *in* Bioremediation, Fundamentals and effective applications–Third annual symposium of the Gulf Coast Hazardous Substance Research Center, Lamar University, Beaumont, Texas: February 21-22, 1991 p. 3-13.

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

Miller, T.S., Brooks, T.D., and Stelz, W.G., 1981, Geohydrology of the valley-fill aquifer in the Cortland-Homer-Preble area, Cortland and Onondaga Counties, New York; U.S. Geological Survey Open-File Report 81-1022, 7 sheets, scale 1:24,000.

Morrissey, D.J., Randall, A.D., and Williams, J.H., 1987, Upland runoff as a major source of recharge to stratified drift in the glaciated northeast, *in* Regional aquifer systems of the United States–The northeast glacial aquifers: American Water Resources Association, AWRA monograph series no. 11, p. 17-36.

Muller, E.H., 1970, Glacial geology and geomorphology between Cortland and Syracuse, *in* New York State Geological Association, 42nd annual meeting, Syracuse, N.Y., p. 1-15.

Muller, E.H., Braun, D.D., Young, R.A., and Wilson, M.P., 1988, Morphogenesis of the Genesee Valley, *in* Northeastern Geology, v. 10, no. 2, p. 112-133.

Muller, E.H., and Calkin, P.E., 1993, Timing of Pleistocene glacial events in New York State, *in* Canadian Journal of Earth Science, v. 30, p. 1829-1845.

National Academy of Sciences, 1977, Drinking Water and Health: National Research Council, Washington D.C., 939 p.

National Oceanic and Atmospheric Administration, 1990, Climatological Data-Annual Summary, New York, 1990: Asheville, N.C., National Climate Data Center, v. 102, no. 13, 36 p.

______, 1991, Climatological Data-Annual Summary, New York, 1991: Asheville, N.C., National Climate Data Center, v. 103, no. 13, 36 p.

______ 1992, Climatological Data-Annual Summary, New York, 1992: Asheville, N.C., National Climate Data Center, v. 104, no. 13, 36 p.

______ 1993, Climatological Data-Annual Summary, New York, 1993: Asheville, N.C., National Climate Data Center, v. 105, no. 13, 36 p.

Neuman, S.P., 1974, Effect of partial penetration on flow in unconfined aquifers considering delayed gravity response: Water Resources Research, v. 10, no. 2, p. 303-312.

O'Brien and Gere Engineers, Inc., 1987, Site investigation and interim remedial action plan: Syracuse, N.Y., O'Brien and Gere, Engineers, Inc., 28 p.

______ 1990, Supplemental site investigation, Smith Corona Corporation: O'Brien and Gere, Engineers, Inc., Syracuse, New York, 27 p.

Olsen, R.L. and Davis, Andy, 1990, Predicting the fate and transport of organic compounds in ground water (pt. 2): Hazardous Material Control, v. 3, no. 4, p. 18-37.

Plumb, R.H., 1991, The occurrence of Appendix IX organic constituents in disposal site ground water *in* Ground Water Monitoring Review, v. 11, no. 2, p. 157-164.

Pollock, D.W., 1989, Documentation of computer programs to compute and display pathlines using results from the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 89-622, 49 p.

———, 1994, Users guide for MODPATH/ MODPLOT, Version 3– A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94-464, 246 p.

Prudic, D.E., 1989, Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model: U.S. Geological Survey Open-File Report 88-729, 113 p.

Randall, A.D., 1972, Records of wells and test borings in the Susquehanna River basin, New York: New York State Department of Environmental Conservation Bulletin 69, 92 p.

Lyford, F.P. and Cohen, A.J., 1987, Estimation of water available for recharge to sand and gravel aquifers in the glaciated northeastern United States, *in* Randall, A.D., and Johnson, A.I., (eds.) Regional aquifer systems of the United States- The northeast glacial aquifers: American Water Resources Association, AWRA monograph series no. 11, p. 37-42.

Randall, A.D., Snavely, D.S., Holecek, T.J., and Waller, R.M., 1988, Alternative sources of large seasonal ground-water supplies in the headwaters of the Susquehanna River basin, New York: U.S. Geological Survey Water-Resources Investigations Report 85-4127, 121 p.

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

Resource Engineering, 1987, Site Investigation Report of J. M. Murray Center for the handicapped, Inc: Cortland, N.Y., Resource Engineering, 16 p.

Reynolds, R.J., 1985, Hydrogeology of the surficial outwash aquifer at Cortland, Cortland County, New York: U.S. Geological Survey Water-Resources Investigations Report 85-4090, 43 p.

———., 1987, Diffusivity of a glacial-outwash aquifer by the floodwave-response technique: Ground Water, v. 25, no. 3, p. 290-299.

Roffner, J.A., 1985, Climate of the States: Gale Research Company, Detroit, Michigan, 1572 p.

Scott, J.H., Tibbetts, B.L., and Burdick, R.G., 1972, Computer analysis of seismic refraction data: U.S. Bureau of Mines Report of Investigation 7595, 95 p.

Tepper, D.H., Morrissey, D.J., Johnson, C.D., and Maloney, T.J., 1990, Hydrogeology, water quality, and effects of increased pumpage of the Saco River Valley Glacial aquifer- Bartlett, New Hampshire to Fryeburg, Maine: U.S. Geological Survey Water-Resources Investigations Report 88-4179, 113 p.

Thomas, M.P., 1966, Effect of glacial geology upon the time distribution of streamflow in eastern and southern Connecticut: U.S. Geological Survey Professional Paper 550-B, p. B209-B212.

U.S. Environmental Protection Agency, 1991a, Final rule, National primary drinking-water regulations--Synthetic organic chemicals and inorganic chemicals (sections 141.11, 141.12, 141.32, 141.50, 141.51, 141.61, and 141.62 of part 141 143.3 of part 143): U.S. Federal Register, v. 56, no. 20, January 30, 1991, p. 3526-3597.

———, 1979, Methods of chemical analysis of water and wastes: Environmental Monitoring and Support Laboratory, Cincinnati, Ohio, EPA-600/4-79-020, 430 p.

U.S. National Oceanic and Atmospheric Administration, 1990, Climatological data - annual summary, New York, 1991: U.S. Department of Commerce, National Climatic Center, 28 p.

______ 1991, Climatological data - annual summary, New York, 1991: U.S. Department of Commerce, National Climatic Center, 28 p.

______ 1992, Climatological data - annual summary, New York, 1991: U.S. Department of Commerce, National Climatic Center, 28 p.

______ 1993, Climatological data - annual summary, New York, 1990: U.S. Department of Commerce, National Climatic Center, 28 p.

Wilson, B.H., Ehkle, T.A., Imbrigiotta, T.E., and Wilson, J.T., 1991, Reductive dechlorination in anoxic aquifer material from Picatinny Arsenal, New Jersey, *in* Mallard, G.E. and Aronson, D.A., 1991, U.S. Geological Survey Toxic Substances Hydrology Program--Proceedings of the Technical Meeting, Monterey, California, March 11-15, 1991: U.S. Geological Survey Water-Resources Investigations Report 91-4034, p. 704-707.

Woodrow, D.L., and Sevon,W.D., 1985, The Catskill Delta: Geological Society of America Special Paper 201, 246 p.

Appendix 1. *Records of wells and test borings in the Cortland, N.Y., study area.*

[Well locations shown on pl. 1.]

USGS well no.	Local identifier	Latitude ° ′ ″	Longitude ° ′ ″	Owner	Date drilled (mo d yr)	Elevation land-surface (feet)	Well depth (feet)	Depth to bedrock (feet)	Elevation of top of casing (feet)	Water level below land surface: Feet	Water level below land surface: Date	Reported yield (gal/min)	Remarks (Numbers refer to depths below land surface.)
3	TH 3	423548	0761155	City of Cortland	08-16-79	1,136	55	--	1,137.67	11.95	08-16-79	75	Test well. 0-25 fine sand, 25-45 gravel, 45-58 sand and gravel, 58-67 ft silty sand and clay.
4	CP 4	423454	0761242	Town of Cortlandville	12-29-75	1,173	63	--	1,173.45	19.50	12-29-75	--	Test well.
5	CP 5	423507	0761309	Town of Cortlandville	03-04-76	1,172	40	--	1,172.64	6.55	03-04-76	--	Well abandoned.
6	TH 6	423545	0761152	City of Cortland	08-29-79	1,136	55	--	1,137.24	11.60	08-29-79	75	Test well.
8	CP 8	423526	0761131	Leonard Barker	1974	1,146	20	--	1,146.2	12.97	02-27-76	--	Test well.
9	CP 9	423527	0761132	Leonard Barker	1976	1,146	20	--	1,146.2	12.13	02-27-76	--	Test well.
10	CP 10	423535	0761140	Curtis	1974	1,149	20	106	1,148.6	14.06	02-27-76	--	--
11	CT 11	423518	0761141	Cortland County	12-04-75	1,154	60	--	1,156.5	20.90	12-15-75	--	0-15 clay and sand, 15-50 pebbly sand, 50-55 sand and gravel, 55-60 gravelly sand, 60-65 clayey sand, 65-75 silty gravel, 75-85 sand and gravel, 85-100 pebbly fine to coarse sand, 100-104 ft gray clay.
13	CP 13	423650	0761140	Cortland County	11-01-73	1,116	25	--	1,116.6	7.80	11-01-73	--	Test well.
15	CP 15	423704	0761108	Cortland County	02-27-76	1,114	--	--	1,114.3	5.57	02-27-76	--	Test well.
20	CT 20	423414	0761428	Cortland County	09-10-76	1,247	160	124	1,247.11	68.20	09-10-76	--	0-11 sand and gravel, 11-16 clay with some gravel, 16-48 sand and gravel, 48-64 clay with some embedded gravel (till?), 64-65 silt and fine sand, 65-72 sand and gravel, 72-85 clay with some gravel, 85-87 sand and gravel, 87-89 clay, 89-94 sand and gravel, 94-97 silty clay with some gravel, 97-118 clay, 118-124 clay with some shale pebbles (till), 124-160 ft shale.
22	CT 22	423429	0761317	Cortland County	09-15-76	1,186	45	--	1,186.38	22.91	09-15-76	--	0-45 ft sand and gravel.
23	CT 23	423346	0761332	Cortland County	09-20-76	1,228	85	--	--	58.30	09-20-76	--	Well destroyed. 0-13 sand and gravel, 13-28 silt with some gravel, 28-85 ft silty sand and gravel.
24	CT 24	423314	0761415	Cortland County	09-28-76	1,270	105	--	--	--	--	--	Well destroyed. 0-100 dirty gravel, 100-105 ft clay. No water encountered during drilling.
33	CP 1	423323	0761403	Monarch Tool Corp.	11-10-75	1,259	209	207	--	58.27	11-10-75	25	0-83 sand and gravel, 83-130 clay and gravel, 130-178 sand and gravel, 178-183 fine sand, 183-187 fine sand and gravel, 187-207 sand and gravel, 207-209 ft shale.
39	CT 1D	423558	0761215	Cortland County	09-29-75	1,155	143	--	1,154.96	17.57	11-24-75	--	--
40	CT 1S	423558	0761215	Cortland County	09-29-75	1,155	44	--	1,155.39	15.06	11-24-75	--	--
47	CT 2D	423548	0761153	Cortland County	10-01-75	1,138	49	--	1,137.38	7.55	10-07-75	--	0-58 sand and gravel, 58-70 ft fine sand and clay.
48	CT 2S	423548	0761153	Cortland County	10-01-75	1,138	25	--	1,137.03	7.15	11-24-75	--	0-25 ft sand and gravel.
102	C-102	423541	0761147	City of Cortland	--	1,137	45	--	1,138.59	7.68	08-30-76	--	USGS water-level observation well.
105	CT 5D	423447	0761306	Gutchess Lumber	10-09-75	1,170	59	--	1,170.89	10.62	12-01-75	--	0-15 sand and gravel, 15-20 clay and gravel (till?), 20-35 sand and gravel, 35-50 sand, 50-65 sand and gravel, 65-75 sandy clay and gravel, 75-80 sand and gravel, 80-82 fine sand, 82 ft clay.
106	CP 6	423522	0761315	Cortland County Airport	1970	1,198	75	--	1,198.43	34.50	02-26-76	--	--

Appendix 1. Records of wells and test borings in the Cortland, N.Y., study area (continued)

USGS well no.	Local identi-fiier	Lati-tude ° ′ ″	Longi-tude ° ′ ″	Owner	Date drilled (mo d yr)	Elevation land-surface (feet)	Well depth (feet)	Depth to bedrock (feet)	Elevation of top of casing (feet)	Water level below land surface: Feet	Water level below land surface: Date	Reported yield (gal/min)	Remarks (Numbers refer to depths below land surface.)
107	CP 7	423528	0761138	Barker, Leonard	1974	1,147	20	--	1,147.0	11.82	02-27-76	--	Test well.
108	CT 8	423251	0761423	Cortland County	10-30-75	1,299	38	--	1,300.77	7.62	12-03-76	--	0-25 clay hardpan, 25-37 fine sandy clayey gravel (no water), 37-40 sand and gravel, 40-67 f sand and gravel, 67-92 silty clay, 92-95 ft sand and gravel.
110	CT 10D	423422	0761409	Cortland County	11-28-75	1,202	99	116	1,201.95	42.16	10-08-91	--	0-20 clayey sand and gravel, 20-25 sand and pebbles, 25-30 fine to medium sand, 30-65 clayey silty sand and gravel (till?), 65-70 fine to medium sand, 70-100 sand and gravel, 100-106 till, 106 ft shale.
112	CT 12D	423518	0761141	Cortland County	12-18-75	1,152	60	--	--	21.30	01-06-76	--	Well destroyed. 0-65 sand and gravel, 65-75 silty sand and gravel, 75-90 sand and gravel, 90-100 pebbly clayey sand, 100-105 sand and gravel, 105-110 silty sand and, 110-115 ft sand and gravel.
113	CT 13	423518	0761141	Cortland County	12-15-75	1,152	63	--	--	18.26	02-04-76	--	Well destroyed.
114	CP-14	423700	0761130	Cortland County	11-01-73	1,120	25	--	1,120.3	10.80	11-01-73	--	--
119	C 19	423539	0761148	City of Cortland	--	1,140	13	--	--	5.97	07-01-67	--	Well destroyed 5-7-76 and replaced by well C-102.
121	CT 21	423440	0761325	Cortland County	09-13-76	1,166	32	--	1,167.38	5.74	09-13-76	--	0-32 ft sand and gravel.
135	--	423305	0761438	Griswold, S.	10-01-65	1,277	254	254	--	96	10-01-65	8	--
138	Well I	423318	0761509	Tunison Fish Hatchery	10-18-62	1,120	52	--	--	6	10-18-62	154	0-43 clay, 43-52 sand and gravel, 52 ft clay.
139	Well R	423318	0761514	Tunison Fish Hatchery	--	1,130	60	--	--	26	09-17-92	--	--
140	Well S	423318	0761516	Tunison Fish Hatchery	10-21-80	1,130	69	--	--	23	11-06-80	100	0-41 clay and gravel, 41-51 sand and gravel, 51-69 sand and gravel, 69-70 ft clay and gravel.
142	Well A	423319	0761459	Tunison Fish Hatchery	05-22-62	1,120	56	--	--	--	--	7	0-6 gravel, 6-16 clay and gravel, 16-20 sandy clay, 20-21 sand and gravel, 21-28 clay, 28-35 fine sand, clay and gravel, 35-56 ft sand and gravel.
143	Well 1	423320	0761459	Tunison Fish Hatchery	05-11-59	1,120	185	--	--	+3.5	05-11-59	--	Well abandoned. 0-35 silt, 35-50 fine to medium sand and silt, 50-70 fine to coarse sand and some gravel, 70-100 fine sand and silt, 100-104 sand and gravel, 104-166 clay, 166-187 fine to coarse sand, 187-200 ft f sand and silt. Pumped 42 gal/min with 7-ft drawdown.
144	Well H	423320	0761509	Tunison Fish Hatchery	10-18-62	1,115	52	181	--	7.5	10-18-72	180	0-12 clay, 12-43 clay and sand, 43-52 sand and gravel, 52-78 clay, 78-108 clay with some gravel (till?), 108-110 clay and gravel, 110-139 clay, 139-142 sand and gravel, 142-181 clay, 181-185 ft shale.
149	Well F	423327	0761457	Tunison Fish Hatchery	1962	1,140	137	--	--	flowing	09-14-62	74	0-20 clay and gravel, 20-30 coarse sand, 30-41 clay and gravel, 41-44 gravel, 44-55 clay and gravel, 55-60 sand and gravel, 60-67 sand, 67-76 gravel, 76-137 ft clay and gravel.
150	Well C	423320	0761517	Tunison Fish Hatchery	1963	1,110	124	--	--	flowing	07-31-62	--	0-5 clay and gravel, 5-30 clay, 30-45 sand, 45-56 sand and gravel, 56-76 gravel with clay, 76-97 sand and gravel, 97-102 clayey gravel, 102-124 ft gravel.
151	Well E	423327	0761458	Tunison Fish Hatchery	1962	1,140	134	--	--	flowing	09-06-62	500	0-30 clay and gravel, 30-32 gravel, 32-52 clay and gravel, 52-62 sand and gravel, 62-66 sand, 66-71 clay and gravel, 71-84 sand and gravel, 84-109 clay and gravel, 109-113 sand and gravel, 113-133 clay and gravel, 133-134 gravel, 134-140 ft clay and gravel. Screen silted up and well was abandoned.
152	--	423329	0761355	Monarch Tool	1966	1,255	79	--	--	--	--	45	--
155	--	423333	0761343	Moser H. F.	1965	1,240	60	--	--	31.8	08-02-67	37	--

Appendix 1. Records of wells and test borings in the Cortland, N.Y., study area (continued)

USGS well no.	Local identi-fiier	Lati-tude ° ′ ″	Longi-tude ° ′ ″	Owner	Date drilled (mo d yr)	Elevation land-surface (feet)	Well depth (feet)	Depth to bedrock (feet)	Elevation of top of casing (feet)	Water level below land surface: Feet	Water level below land surface: Date	Reported yield (gal/min)	Remarks (Numbers refer to depths below land surface.)
163	--	423428	0761452	Armstrong, Roger	1976	1,290	155	30	--	50	1976	4	0-15 gravel, 15-30 till, 30-155 ft bedrock.
167	--	423516	0761152	Abdallah Creamery	1945	1,155	69	--	--	--	--	40	--
168	--	423520	0761115	Lehigh Railroad	1932	1,136	28	--	--	3	--	75	--
170	--	423528	0761130	Mobil Oil	1974	1,147	24	--	--	16.70	07-25-75	--	--
171	--	423533	0760824	Polkville Agway	--	1,096	34	--	--	8	--	35	0-37 ft sand and gravel.
172	PW-4	423542	0761154	City of Cortland	03-01-57	1,138	68	--	--	5	03-01-57	4,500	Public water-supply well. 0-68 sand and gravel, 68-77 ft sand and clay.
173	--	423548	0761015	Brewer Tichener	1944	1,115	155	--	--	8	--	75	--
174	--	423549	0761143	City of Cortland	1917	1,138	16	--	--	9	08-01-65	4,000	Dug well. Former public water-supply well. Currently used for water-level observation well by city of Cortland.
176	--	423602	0761019	Rubbermaid	1923	1,110	185	--	--	3	--	22	Formerly owned by Brockway Motors. 0-35 sand and gravel, 35-130 clay, 130-185 ft sand and gravel.
177	Well 1	423604	0761039	Cortland County	07-09-79	1,117	101	--	1,111.88	15.50	08-16-79	70	0-55 sand and gravel, 55-85 clay, 85-102 ft sand and gravel.
178	--	423606	0761233	Ames, Bob	07-24-77	1,180	158	75	--	34	07-24-77	10	0-5 gravel, 5-15 till, 15-158 ft bedrock.
179	--	423610	0761209	Murray Center	1943	1,150	65	--	--	20.0	04-23-87	150	--
180	--	423610	0761209	Murray Center	1943	1,150	125	75	--	--	--	60	0-75 sand and gravel, 75-125 ft shale.
181	--	423619	0760946	Brewer Tichener	1962	1,105	47	--	--	15.6	02-18-72	310	--
183	--	423631	0761115	Cortland Hospital	05-01-60	1,121	44	--	1,120.84	11	05-01-60	250	--
184	--	423638	0761006	Cortland Ready Mix	08-01-63	1,100	49	--	--	16	08-01-63	100	--
186	--	423657	0761107	Gates, Al	05-01-66	1,115	45	--	--	14	05-01-66	35	--
187	--	423709	0761119	Briggs, Lynn	02-22-66	1,120	195	188	--	--	--	30	0-20 sand and gravel, 20-75 sand and clay, 75-177 clay, 177-188 sand and gravel, 188-195 ft shale.
188	--	423710	0761127	Shultz, Al	1966	1,125	156	148	--	10	--	40	--
203	CP 3	423451	0761244	Town of Cortlandville	02-27-76	1,183	70	--	1,183.44	19.08	02-27-76	--	Test well.
204	CT 4D	423522	0761239	Cortland County	10-07-75	1,149	46.5	--	1,152.15	5.21	10-10-75	--	0-60 sand and gravel, 60-70 pebbly sand, 70-75 ft clay.
205	CT 5S	423447	0761306	Cortland County	10-09-75	1,170	26	--	1,173.14	10.56	12-01-75	--	0-15 sand and gravel, 15-20 clay and gravel (till?), 20-35 ft sand and gravel.
207	CT 7D	423353	0761303	Cortland County	10-24-75	1,232	46	--	1,233.09	26.60	10-08-91	--	0-5 gravel, 5-15 clayey gravel (till?), 15-32 sand and gravel, 32-37 fine sand, 37-41 medium sand, 41-50 fine sand and gravel, 50-54 till.
210	CT 10S	423422	0761407	Cortland County	11-28-75	1,202	42	116	1,201.75	40.5	10-08-91	--	0-20 clayey sand and gravel, 20-25 sand and pebbles, 25-30 fine to medium sand, 30-65 clayey silty sand and gravel (till?), 65-70 fine to medium sand, 70-100 sand and gravel, 100-106 till, 106 ft shale.
214	CT 14	423632	0761051	Cortland County	01-27-76	1,112	24	--	1,114.5	9.23	02-04-76	--	Well removed. 0-7 fill, 7-14 silt, 14-23 sand and gravel, 23-24 ft fine sand.
279	ELM A	423609	0760936	Cortland County	11-09-79	1,100	29	44	1,102.63	10.4	10-08-91	--	0-5 fill, 5-30 sand and gravel, 30-37 medium to coarse sand, 37-44 till, 44-45 ft shale.
280	ELM B	423609	0760942	Cortland County	11-15-79	1,102	34	--	1,103.87	9.4	10-08-91	--	0-45 sand and gravel, 45-50 ft fine to medium sand with some gravel
281	ETL A	423542	0760922	ETL	05-05-80	1,100	45	--	1,102.16	12.3	05-28-91	--	0-5 sand and gravel, 5-47 gravelly medium to coarse sand, 47-60 ft silty clay.

Appendix 1. Records of wells and test borings in the Cortland, N.Y., study area (continued)

USGS well no.	Local identi-fiier	Lati-tude ° ′ ″	Longi-tude ° ′ ″	Owner	Date drilled (mo d yr)	Elevation land-surface (feet)	Well depth (feet)	Depth to bedrock (feet)	Elevation of top of casing (feet)	Water level below land surface: Feet	Water level below land surface: Date	Reported yield (gal/min)	Remarks (Numbers refer to depths below land surface.)
282	ETL B	423542	0760917	ETL	05-09-80	1,102	50	--	1,105.06	15.6	05-28-91	--	0-15 sand and gravel, 15-52 medium to coarse sand with some gravel, 52-57 silty clayey sand, 57-60 ft silty clay.
291	--	423327	0761458	Tunison Fish Hatchery	1962	1,140	137	--	--	--	--	74	--
303	CT 3S	423518	0761104	Cortland County	10-03-75	1,138	28	--	1,141.03	8.74	12-03-75	--	0-5 fill, 5-30 ft gravel.
304	CT 4S	423522	0761239	Cortland County	10-07-75	1,149	23	--	1,152.22	5.29	12-04-75	--	0-60 ft sand and gravel.
305	Well G	423325	0761456	Tunison Fish Hatchery	10-04-62	1,130	215	197	--	3	10-04-62	25	0-39 clay and gravel, 39-52 clayey gravel, 52-74 clay and gravel, 74-194 clay, 194-197 gravel, 197-215 ft shale.
306	CT 6D	423433	0761333	Cortland County	10-22-75	1,173	255	267	1,173.01	9.51	12-03-75	--	0-100 sandy gravel, 100-105 pebbly sand, 105-130 sand and gravel, 130-150 fine sand, 150-165 sand and gravel, 165-170 clayey sand with pebbles, 170-180 sand and gravel, 180-190 fine sand, 190-267 silty sand and gravel, 267 ft bedrock
307	CT 7S	423353	0761303	Cortland County	10-24-75	1,232	24	--	1,134.72	11.96	12-02-75	--	--
317	PW 3	423551	0761149	City of Cortland	03-21-49	1,137	68	--	--	2.5	03-25-49	3,200	Public water-supply well. 0-68 sand and gravel, 68-77 ft sandy clay.
320	89-1	423350	0761351	Cortland County	11-22-89	1,196	90	--	1,198.43	28.87	12-29-89	--	0-19 sand and gravel, 19-28 pebbly sand, 28-59 sand and gravel, 59-70 sand and gravel, 70-100 ft sand and gravel.
321	--	423527	0761019	Cortland High School	01-05-87	1,200	80	--	1,201.74	72	03-28-90	--	0-80.5 ft silty sand and gravel.
322	--	423438	0761357	Park, David	06-10-81	1,215	273	103	--	--	--	2	0-18 gravel, 18-38 clay, 38-48 dirty gravel, 48-60 hardpan and sand, 60-94 clay and gravel, 94-103 till, 103-273 ft bedrock.
323	--	423244	0761419	McKee, John	10-06-88	1,320	185	75	--	--	10-06-88	7	0-20 hardpan, 20-50 gravel hardpan and clay, 50-53 gravel, 53-75 till, 75-185 ft shale.
324	--	423246	0761420	McKee, John	--	1,315	198	60	--	--	--	--	0-40 hardpan, 40-60 till, 60-198 ft shale.
325	--	423256	0761430	Ostrander, George	11-16-87	1,295	245	191	--	--	--	--	0-10 hardpan gravel, 10-70 cemented hardpan gravel, 70-120 hardpan gravel, 120-155 gravel, 160-191 clay, 191-245 ft shale.
326	90-14B	423416	0761457	USGS	07-02-90	1,240	--	38	--	--	--	--	Test boring. 0-28 coarse cobble gravel with some sand, 28-38 till with silt and clay matrix, 38-40 ft weathered shale.
327	CT 9	423230	0761440	Cortland County	11-17-75	1,242	110	304	1,242.8	63.11	12-03-75	--	0-30 clayey sand and gravel, 30-45 till, 45-130 sand and gravel, 130-300 clay, 300-304 till, 304 ft shale.
328	--	423402	0761457	Kannus	--	1,215	74	--	--	--	--	--	0-40 gravel hardpan, 40-60 sand, 60-74 ft hardpan (probably a dirty gravel since the well was finished at 74 ft).
329	--	423415	0761423	Mueller	--	1,252	150	124	--	--	--	--	0-65 sand and gravel, 65-80 till, 80-100 sand and gravel, 100-124 gravel and hardpan (till? TSM), 124-150 ft shale.
330	89-2S	423548	0761230	Cortland County	11-27-89	1,147	15	--	1,148.10	7.81	12-29-89	--	0-15 ft sand and gravel.
331	89-2D	423548	0761230	Cortland County	11-27-89	1,147	96	114	1,149.72	7.62	12-29-89	--	0-23 sand and gravel, 23-30 pebbly sand, 30-43 sand and gravel, 43-55 silt, 55-75 very fine sand, 75-91 silt and clay, 91-114 sand and gravel, 114-116 ft gray shale.
332	90-1S	423542	0760957	Cortland County	06-12-90	1,114	34	--	1,117.25	17.3	09-27-90	--	0-34 ft sand and gravel.
333	90-11	423526	0761228	City of Cortland	06-29-90	1,148	55	--	1,150.09	12.78	09-27-90	--	0-83.5 sand and gravel, 83.5-84 ft silt and clay.
334	90-1D	423542	0760957	City of Cortland	06-12-90	1,114	98	--	1,117.00	17.2	09-27-90	--	0-64 sand and gravel, 64-107 ft varved silt and clay.
335	90-2	423603	0760946	City of Cortland	06-13-90	1,102	34	66	1,102.03	8.40	09-27-90	--	0-46 sand and gravel, 46-50 f. sand and silt, 50-56 varved silt and clay, 56-66.5 till, bedrock at 66.5 ft.
336	90-10	423524	0761219	City of Cortland	05-28-90	1,158	37	--	1,150.33	23	09-27-90	--	0-39 ft sand and gravel.

Appendix 1. Records of wells and test borings in the Cortland, N.Y., study area (continued)

USGS well no.	Local identi-fiier	Lati-tude ° ′ ″	Longi-tude ° ′ ″	Owner	Date drilled (mo d yr)	Elevation land-surface (feet)	Well depth (feet)	Depth to bedrock (feet)	Elevation of top of casing (feet)	Water level below land surface: Feet	Water level below land surface: Date	Reported yield (gal/min)	Remarks (Numbers refer to depths below land surface.)
337	90-9S	423531	0761207	City of Cortland	06-28-90	1,138	42	--	1,140.41	8.22	09-27-90	--	0-44 ft sand and gravel.
338	90-9D	423531	0761207	City of Cortland	07-17-90	1,138	217	220	1,141.29	9.7	09-27-90	--	0-52 sand and gravel, 52-203 silt and clay, 203-219 sand and gravel, 219-220 till, 220-222 ft shale.
339	90-3	423623	0761116	City of Cortland	06-14-90	1,118	35	--	1,118.15	9.46	09-27-90	--	0-67 sand and gravel, 67-100 ft varved silt and clay.
340	90-6S	423457	0761305	Cortland County SPCA	06-26-90	1,165	35	--	1,166.28	13.70	09-27-90	--	0-4 silty gravel, 4-12 till, 12-18 sand and gravel, 18-34 medium to very coarse sand, 34-35 ft sand and gravel
341	90-6D	423457	0761305	Cortland County SPCA	07-19-90	1,164	137	--	1,168.14	17.2	09-27-90	--	0-5 topsoil, 5-12 till, 12-37 sand and gravel, 37-60 medium to coarse sand, 60-83 very fine sand and gravel lenses, 83-108 silt and very fine sand, 108-137 ft sand and gravel.
342	90-5	423517	0761157	Cortland County	06-21-90	1,160	52	--	1162.56	28.8	09-27-90	--	0-50 sand and gravel, 50-75 very coarse sand and fine gravel, 75-82 ft sand and gravel.
343	90-7	423440	0761336	Stupke	06-27-90	1,169	24	--	1,171.35	12.3	09-19-90	--	0-25 sand and gravel, 25-30 ft till.
344	90-13	423446	0761239	Cortland County	07-02-90	1,185	31	31	1,187.57	26.6	09-27-90	--	0-7 topsoil and debris, 7-12 silt and gravel, 12-31 silt and gravel, 31 ft gray shale.
345	90-4B	423441	0761309	USGS	06-19-90	1,185	93	--	--	17.9	06-19-90	--	Test boring. 0-18 cobbles, 18-44 till, 44-86 sand and gravel, 86-93 ft fine sand and silt.
346	Kellogg	423528	0760921	Cortland County	07-09-80	1,096	24	--	1,095.94	5.52	09-27-90	--	0-10 clay soil, 10-15 silty gravel, 15-25 sand and gravel, sand with some clay, 35-43 medium to coarse sand with some clay, 43-99 ft varved silt and clay.
347	SPCA	423457	0761303	Cortland County SPCA	--	1,168	--	--	1,167.68	--	--	--	Dug well.
348	MW-1	423352	0761400	Gunzenhauser	07-24-87	1,235	73	--	1,237.37	70.25	09-27-90	--	0-45 sand and gravel, 45-50 fine to coarse sand with some silt, 50-76 ft sand and gravel.
349	MW-2	423413	0761340	Gunzenhauser	07-29-87	1,223	65	--	1,225.64	61.56	09-27-90	--	0-66 ft sand and gravel.
350	--	423430	0761319	Danglier	--	1,185	57	--	--	--	--	30	--
351	--	423429	0761319	Pace	05-12-62	1,185	55	--	--	--	--	30	--
352	--	423430	0761315	Fitts	--	1,185	--	--	--	--	--	--	--
353	--	423450	0761251	Pauldine	--	1,155	--	--	--	--	--	--	--
354	T-103	423452	0761240	Town of Cortlandville	01-13-59	1,184	72	--	--	27	01-13-59	440	0-20 clayey sand and gravel, 20-36 clayey sand, 36-37 gravel, 37-45 coarse sand, 45-55 gravel and clay, 55-72 sand and gravel, 72-76 ft gravel and clay.
355	T-103	423454	0761240	Town of Cortlandville	08-21-75	1,177	63	--	--	29.7	09-11-75	660	0-30 sand and boulders, 30-63 coarse sand and gravel, 63-65 sand and gravel with clay, 65-70 ft gravel hardpan.
356	MW-3D	423528	0761205	City of Cortland	12-11-86	1,143	58	--	1,145.03	4.52	03-28-90	--	0-60 silty sand and gravel, 60.5-61 ft silt.
357	MW-1	423538	0761204	City of Cortland	12-11-86	1,141	48	--	1,142.84	5.34	03-28-90	--	0-48 ft sand and gravel.
358	MW-2	423528	0761223	City of Cortland	12-16-86	1,143	36	--	1,144.99	1.96	03-28-90	--	0-47 ft sand and gravel.
359	Dowzer 1	423523	0761047	Dowzer Corp.	--	1,140	23	--	1,142.3	10.8	05-25-90	--	--
360	Dowzer 2	423524	0761042	Dowzer Corp.	--	1,136	23	--	1,138.9	7.3	05-25-90	--	0-3 fill, 3-7 silt and clay, 7-23 ft fine to coarse sand with some gravel.
361	MW-3S	423527	0761206	City of Cortland	12-18-86	1,142	25	--	1,143.81	5.3	03-28-90	--	0-45 ft sand and gravel.

Appendix 1. Records of wells and test borings in the Cortland, N.Y., study area (continued)

USGS well no.	Local identi-fiier	Lati-tude ° ' "	Longi-tude ° ' "	Owner	Date drilled (mo d yr)	Elevation land-surface (feet)	Well depth (feet)	Depth to bedrock (feet)	Elevation of top of casing (feet)	Water level below land surface: Feet	Water level below land surface: Date	Reported yield (gal/min)	Remarks (Numbers refer to depths below land surface.)
362	--	423507	0761251	Pall Trinity Corp.	12-20-86	1,167	67	--	1,169.00	--	--	--	0-67 sand and gravel, 67 ft fine sand. Screened intervals 60-67 ft.
363	Well 1	423502	0761249	Pall Trinity Corp.	12-15-83	1,165	63	--	1,167.69	12	12-15-83	170	0-20 gravel, 20-32 silty gravel, 32-63 ft gravel.
364	Substa	423501	0761253	Pall Trinity Corp.	--	1,168	35	--	1,169.68	12.7	03-13-91	--	--
365	Hess 1	423554	0761003	--	1982	1,130	13	--	1,107.47	9.5	03-28-90	--	--
366	--	423554	0761032	--	--	1,135	--	--	--	--	--	--	--
367	--	423432	0761327	Stupke	--	1,173	--	--	--	--	--	--	--
368	Ames	423458	0761245	--	1986	1,168	24	--	1,170.31	20.3	09-19-89	--	Test well for gasoline spill.
369	--	423551	0761235	Turner Veterinarian	--	1,163	55	--	1,167.67	22.17	03-28-90	--	0-55 ft sand and gravel.
370	MW-4	423613	0761207	Murray Center	02-25-87	1,154	42	42	1,156.64	25.5	02-25-87	--	0-42 sand and gravel, 42 ft shale.
371	--	423602	0761225	Wright	--	1,170	65	25	--	--	--	--	0-25 gravel hardpan, 25-65 ft shale.
372	--	423617	0761254	Hart	--	1,220	195	108	--	--	--	--	0-25 gravel hardpan, 25-38 coarse gravel, 38-68 gravel hardpan, 68-108 gray hardpan, till?, 108-195 ft gray shale.
373	--	423632	0761116	Cortland Hospital	09-07-78	1,121	42	--	1,120.84	10.27	03-28-90	556	0-42 ft sand and gravel.
375	--	423434	0761433	Petrella	--	1,260	115	15	--	--	--	--	0-15 sand and gravel, 15-115 ft shale.
376	--	423411	0761408	Space	--	1,230	52	--	--	--	--	--	0-30 sand and gravel, 30-49 clay and sand, 49-52 ft gravel.
377	--	423512	0761407	Miller	--	1,245	76	21	--	--	--	--	0-15 hardpan gravel, 15-21 gray hardpan gravel (till?), 21-76 ft shale.
378	NW-5D	423423	0761328	Smith Corona Corp.	12-11-86	1,176	69	--	1,179.07	13.8	12-11-86	--	0-78 sand and gravel, 78-80 ft fine sand with little silt.
379	MW-4D	423424	0761313	Smith Corona Corp.	11-21-86	1,208	102	--	1,211.01	47.3	12-03-86	--	0-102 ft sand and gravel.
380	92-1A	423426	0761319	Cortland County	09-26-92	1,192	54	--	1,194.93	27.37	10-06-92	100	0-54 ft sand and gravel.
381	92-1B	423426	0761319	Cortland County	09-26-92	1,192	212	245	1,193.40	27.6	10-06-92	--	0-106 sand and gravel, 106-110 till, 110-175 varved silt and clay, 175-216 sand and gravel, 216-220 silt and clay, 220-245 sand and gravel, 245 ft bedrock (siltstone).
382	--	423232	0761412	Jacobs	--	1,410	100	22	--	--	--	--	0-15 till, 15-22 till and weathered shale, 22-100 ft shale.
383	--	423302	0761436	Williams	09-03-87	1,290	74	--	--	--	--	10	0-16 gravel, 16-48 sand and gravel, 48-72 dry gravel, 72-75 ft gravel.
384	--	423507	0761207	Tutino	--	1,160	45	--	--	--	--	--	0-20 gravel, 20-30 gravel and sand, 30-45 ft gravel.
385	--	423343	0761453	Baker, J.	--	1,190	75	75	--	7	03-31-60	--	0-75 sand and gravel, 75 ft shale.
386	--	423537	0760912	ETL Corp.	07-29-80	1,102	40	--	--	--	--	--	0-20 sand and gravel, 20-25 fine to medium sand, 25-45 sand and gravel, 45-47 fine to coarse sand, 47-56 sand and gravel, 56-106 ft silt, tr clay, very fine sand.
387	--	423439	0761447	Shedd	--	1,360	205	21	--	--	--	--	0-21 till, 21-205 ft shale.
388	--	423441	0761409	Space	--	1,215	330	59	--	--	--	--	0-25 gravel, 25-30 hardpan-gravel, 30-49 clay and sand, 49-52 gravel, 52-59?, 59-330 ft shale.
389	91-2	423524	0761409	Cortland County	05-14-91	1,250	22	33	1,251.95	14.3	05-14-91	--	0-28 sand and gravel, 28-33 till, 33 ft shale.
390	--	423512	0761326	--	--	1,205	198	--	--	53	05-15-86	--	--
391	--	423510	0761323	--	--	1,205	67	--	--	47	06-01-86	--	--

Appendix 1. Records of wells and test borings in the Cortland, N.Y., study area (continued)

USGS well no.	Local identifier	Latitude ° ′ ″	Longitude ° ′ ″	Owner	Date drilled (mo d yr)	Elevation land-surface (feet)	Well depth (feet)	Depth to bedrock (feet)	Elevation of top of casing (feet)	Water level below land surface: Feet	Water level below land surface: Date	Reported yield (gal/min)	Remarks (Numbers refer to depths below land surface.)
392	Well 2	423417	0761321	Smith Corona Corp.	12-15-74	1,212	100	--	--	42.1	12-31-74	1,060	0-70 sand and gravel, 70-100 coarse sand, 100-102 ft clay and gravel.
393	B-1	423520	0761302	Town of Cortlandville	07-01-86	1,158	72	--	--	8.5	07-01-86	--	Test boring. 0-71.5 ft sand and gravel.
394	--	423530	0761253	Cummins	--	1,260	32	--	--	--	--	--	0-32 ft sand and gravel.
395	--	423338	0761302	Bliss	--	1,275	44	29	--	--	--	--	0-5 Topsoil, 5-14 till, 14-28 fine sand, 28-29 sand and gravel, water bearing, 29-44 ft shale.
396	MW-3	423404	0761327	Smith Corona Corp.	1986	1,226	83	--	1,228.06	56.2	12-09-86	--	--
397	--	423520	0760840	Cortland County	07-08-80	1,094	19	--	1,097.45	9	07-08-80	--	0-25 sand and gravel, 25-28 fine to medium sand, 28-47 medium to very coarse sand with gravel, 47-50 clay and gravel, 50-99 ft varved silt and clay.
398	MW-13	423421	0761320	Smith Corona Corp.	09-23-92	1,210	124	--	--	--	--	--	0-104 sand and gravel, 104-107 pebbly sand, 107-110 silty gravel or till, 110-112 silty gravel, 112-116?, 116-120 silt and sand, 120-124 pebbles, 125 ft till.
399	C-15	423611	0761030	Beaudry Wall Paper	--	1,110	82	--	--	--	--	275	--
400	--	423424	0761303	Walmart	--	1,201	75	--	1,202.98	35.23	05-29-91	--	Well destroyed. Former Exxon well.
401	MW-2	423427	0761256	Walmart	02-26-91	1,199	40	--	1,201.23	34.77	05-29-91	--	0-46 ft sand and gravel.
402	MW-1	423428	0761250	Walmart	02-25-91	1,199	37	--	1,201.86	28.5	02-26-91	--	0-40 ft sand and gravel.
403	CT-3D	423518	0761104	Cortland County	10-03-75	1,138	54	--	1,139.37	8.79	12-03-75	--	0-5 fill, 5-30 gravel, 30-35 silty gravel, 35-40 pebbly sand, 40-50 sand and gravel, 50-55 medium to coarse sand, 55-60 sand and gravel, 60-70 fine sand and clay.
404	MW-1	423612	0761208	Murray Center	03-09-87	1,155	34	--	1,156.18	24.9	03-09-87	--	0-34 sand and gravel, 34-37 ft silt and fine sand.
406	CT-6S	423433	0761333	Cortland County	10-22-75	1,173	26	--	1,172.82	10.54	12-03-75	--	--
407	--	423716	0760922	Yellow Lantern	04-06-72	1,105	30	--	--	5	04-26-72	--	0-10 topsoil, 10-22 sandy clay and gravel, 22-25 cemented gravel, 25-30 sand and gravel, 30 ft clay.
408	--	423726	0760925	Sun Pipe Line	04-21-69	1,140	39	--	--	20	04-21-69	--	0-10 gravel, 10-39 ft sand and gravel.
410	91-6S	423528	0761102	Cortland County	10-01-91	1,134	30	--	1,136.64	15.6	10-01-91	--	0-44 ft sand and gravel.
411	--	423709	0761142	--	--	1,150	61	--	--	--	--	--	Finished in sand and gravel.
412	--	423709	0761139	--	--	1,145	121	--	--	--	--	--	Finished in confined sand and gravel aquifer.
413	--	423711	0761137	Edlund	06-09-69	1,138	136	--	--	--	--	--	100-136 ft sand and gravel.
414	C-17	423536	0761024	Cobaco Baking Co.	--	1,122	103	--	--	--	--	--	0-35 sand and gravel, 35-96 silty sand, 96-103 ft hardpan or gravel.
415	--	423504	0761016	Wilcox	--	1,285	75	43	--	--	--	--	43-75 ft shale.
416	--	423635	0760959	--	--	1,102	112	--	--	--	--	--	Test boring. 0-54 sand and gravel, 54-93 silt, 93-108 fine sand and silt, 108-112 ft silt with some sand and gravel.
417	--	423634	0760958	--	--	1,102	112	--	--	--	--	--	Test boring. 0-53 sand and gravel, 53-83 silt, 83-97 sand, with some gravel, 97-102 sand and silt, 102-108 sand, 108-112 ft silt and sand.
418	--	423631	0760944	--	--	1,090	43	--	--	--	--	--	Test boring. 0-18 sand and gravel, 18-28 fine to coarse sand, 28-43 ft sand and gravel.
419	Yaman A	423635	0760926	Cortland County	07-10-80	1,100	24	33	1,101.22	9.84	06-28-90	--	0-10 gravel, 10-11 clay, 11-13 gravel, 13-18 coarse sand and fine gravel, 18-25 clayey sand and gravel, 25-27 medium sand, 27-33 till, 33 ft shale.
420	Yaman B	423636	0760929	Cortland County	07-11-80	1,105	28	--	1,106.64	8.2	05-28-91	--	0-28 ft sand and gravel.

Appendix 1. Records of wells and test borings in the Cortland, N.Y., study area (continued)

USGS well no.	Local identi-fiier	Lati-tude ° ′ ″	Longi-tude ° ′ ″	Owner	Date drilled (mo d yr)	Elevation land-surface (feet)	Well depth (feet)	Depth to bedrock (feet)	Elevation of top of casing (feet)	Water level below land surface		Reported yield (gal/min)	Remarks (Numbers refer to depths below land surface.)
										Feet	Date		
421	Well D	423320	0761512	Tunison Fish Hatchery	08-10-62	1,110	126	--	--	-3.0	08-10-62	--	0-20 clay and gravel, 20-27 coarse sand, 27-29 clay and gravel, 29-32 coarse sand, 32-44 fine sand, 44-60 clay, 60-70 clay and gravel, 70-73 gravel, 73-103 clay and gravel, 103-127 sand and gravel, 127-130 ft clay and gravel.
422	W-9	423534	0761021	Blasland & Bouck	02-20-91	1,122	73	--	1,123.57	12.0	05-10-91	--	0-3 fill, 3-17 medium to coarse sand with some gravel, 17-32 sand and gravel, 32-42 fine sand with some silt and gravel, 42-49 sand and gravel, 96-98 ft medium to coarse sand with some gravel.
423	W-15	423534	0761029	Blasland & Bouck	12-30-91	1,123	90	--	1,125.02	13.7	02-10-92	--	0-10 fill, 10-15 sand and gravel, 15-44 fine to coarse sand with little gravel, 44-58 sand and gravel, 58-77 fine sand and silt, 77-90 ft fine to coarse sand with some silt.
424	W-12	423533	0761035	Blasland & Bouck	02-06-91	1,126	50	--	1,127.63	13.3	05-10-91	--	0-35 medium to coarse sand with some gravel, 35-38 sand and gravel, 38-48 medium sand with some gravel, 48-60 ft fine sand.
425	W-11	423534	0761029	Blasland & Bouck	02-04-91	1,123	52	--	1,124.47	11.7	05-22-92	--	0-16 fine to coarse sand with some gravel, 16-30 sand and gravel, 30-50 fine to coarse sand with little gravel, 50-56 silt and sand, 56-58 ft fine sand.
426	W-14	423529	0761037	Blasland & Bouck	02-27-91	1,131	69	--	1,132.19	6.7	02-27-91	--	0-4 fill, 4-6 silt, 6-24 fine to coarse sand with some gravel, 24-29 gravelly silt, 29-39 sand and gravel, 39-70 medium to coarse sand with some gravel, 70-74 sand and gravel, 74-84 ft medium to coarse sand with some gravel.
427	B-5	423531	0761026	Blasland & Bouck	01-30-91	1,126	95	--	--	8.0	01-30-91	--	0-3 fill, 3-8 gravelly silt, 8-28 medium to coarse sand with some gravel, 28-42 sand and gravel, 42-80 medium sand with some gravel, 80-88 sand and gravel, 88-95 ft till.
428	TH-1	423551	0761149	City of Cortland	08-14-79	1,132	55	100	1,134.18	2.8	03-28-90	--	0-60 sand and gravel, 60-100 silt, 100 ft bedrock.
429	91-6D	423528	0761102	Cortland County	10-01-91	1,134	198	270	1,136.99	14.25	10-01-91	--	0-44 sand and gravel, 44-58 silty very fine sand, 58-65 silt and clay, 65-115 silt and very fine sand, 115-150 clay and silt, 150-182 very fine sand, 182-254 sand and gravel, 254-270 till, 270 ft shale.
430	91-1	423542	0760957	Cortland County	01-10-91	1,114	313	313	1,117.22	14.6	01-10-91	--	0-64 sand and gravel, 64-138 silt and clay, 138-149 sand and gravel, 149-180 sand, 180-227 sand and gravel, 227-234 silt and sand, 234-280 pebbly sand, 280-313 gravel, 313 ft bedrock.
431	B-2	423510	0761257	Town of Cortlandville	07-08-86	1,158	96	--	--	8.5	07-08-86	--	0-80 sand and gravel, 80-85 fine to medium sand, 85-90 silt and sand, 90-96 ft fine to medium sand.
432	C-104	423351	0761352	Town of Cortlandville	02-16-88	1,197	90	--	1,198.11	31	05-18-88	1,330	Public water-supply well. 0-90 ft sand and gravel.
434		423420	0761320	Smith Corona Corp.	10-20-89	1,208	92	--	--	--	--	975	Recovery well for TCE. 0-92 ft sand and gravel.
435		423424	0761404	Monarch Tool Corp.	--	1,259	87	--	--	46	08-02-67	150	Drawdown = 29 ft.
446	W2	423647	0761103	Cortland County Highway Department	05-12-86	1,114	14	--	1,115.84	6.7	05-30-91	--	Oil in well
447	28-29b	423738	0761039	N.Y. State Dept.. of Transportation.	--	1,116				--	--		0-40 sand and gravel, 40-52 silt, 52-61 till, 61-68 ft shale.
448	MW-7	423419	0761319	Smith Corona Corp.	12-09-86	1,212	57		1,213.51	47.04	06-11-87	--	0-57 ft sand and gravel
449		423432	0761332	Jebbet		1,172	--	--	--	--	--	--	

Appendix 2. Inorganic chemical analyses of ground water from selected wells in the glacial-aquifer system in Cortland, N. Y. study area

[--, no data available; <, less than. All values are in milligrams per liter unless otherwise noted; µS/cm, microsiemens per centimeter. Well locations shown on pl. 1].

A. APRIL 1990 (analyses by Chemistry Department at State University of New York at Cortland)

													Total recoverable (µg/L)				
Well no.	Well depth (feet)	Date (m/d)	Alkalinity	pH, field (units)	Specific conductance, field (µS/cm)	Phosphorus, total	Nitrate, total	Chloride, total	Sodium, total	Potassium, total	Magnesium, total	Calcium, total	Lead	Iron	Copper	Manganese	Zinc
5	36	04/04	185	7.78	513	0.06	6.0	21	12	1.0	13	78	<500	4400	<50	70	40
11	81	04/05	229	7.53	842	0.53	6.0	108	48	2.2	19	97	<500	6100	<50	70	30
22	45	04/03	173	7.45	610	0.03	4.5	69	34	1.9	12	76	<500	600	<50	<30	0
39	143	04/04	111	8.43	258	0.68	0.80	17	8	0.9	24	80	<500	28,500	<50	800	9,500
40	44	04/04	62	8.00	257	0.18	2.2	30	16	1.4	4.2	32	<500	900	<50	<30	80
47	49	04/05	190	7.76	470	1.29	6.3	27	13	0.9	14	80	<500	<200	<50	<30	60
48	25	04/05	194	7.50	514	0.82	6.6	37	19	0.9	13	82	<500	<200	<50	<30	40
105	59	04/05	168	--	--	0.84	4.6	43	17	1.4	14	77	<500	<200	<50	<30	60
106	75	04/03	139	--	--	0.06	5.7	30	8	1.6	9.4	63	<500	37,300	<50	600	800
108	38	04/03	174	7.50	330	0.02	3.0	29	12	1.2	16	72	<500	<200	<50	<30	1,300
110	100	04/03	239	7.56	623	0.02	2.6	35	12	0.8	25	87	<500	<200	<50	<30	2,000
114	--	04/05	216	7.68	539	0.01	2.4	36	16	1.3	16	87	<500	3400	<50	<30	40
121	32	04/04	219	7.61	673	0.82	5.7	56	27	1.8	17	92	<500	2400	<50	<30	40
170	--	04/03	131	--	--	0.13	4.1	50	26	2.6	24	89	<500	16,900	<50	1,000	50
172	69	04/05	196	--	--	0.43	4.8	28	17	1.0	15	79	<500	<200	<50	<30	50
177	92	04/06	190	7.74	1,440	0.65	4.8	274	204	1.8	16	89	<500	1400	70	<30	70
204	42	04/04	192	7.70	513	1.03	8.6	26	14	0.9	15	73	<500	<200	<50	<30	80
205	26	04/05	231	--	--	0.57	3.9	59	31	2.1	16	89	<500	<200	<50	<30	100
210	45	04/03	220	7.64	518	0.05	3.7	15	6	0.8	18	82	2,300	23,000	70	200	9,200
280	34	04/06	222	7.69	802	0.15	4.6	104	45	2.6	22	110	<500	21,400	<50	300	30
303	28	04/06	164	7.30	668	0.65	4.6	93	46	2.5	11	78	<500	16,500	<50	<30	1,300
304	23	04/04	196	7.68	550	0.55	12.0	31	15	1.1	15	79	<500	<200	<50	<30	20
306	255	04/04	168	8.10	412	0.30	1.4	28	6	1.0	25	80	<500	19,100	<50	300	9,800
307	32	04/03	73	7.44	323	0.04	1.8	43	23	2.0	5.8	38	<500	500	<50	<30	3,300
317	68	04/05	184	--	--	0.56	5.3	31	16	1.0	13	73	<500	<200	<50	<30	20
320	90	04/03	129	7.93	344	0.02	0.76	11	5	0.6	12	49	<500	600	<50	<30	20
330	15	04/05	247	7.25	787	1.14	5.9	80	39	2.7	14	105	<500	<200	<50	<30	30

Appendix 2. Inorganic chemical analyses of ground water from selected wells in the glacial-aquifer system in Cortland, N. Y. study area (continued)

A. April 1990 (continued)

Well no.	Well depth (feet)	Date (m/d)	Alkalinity	pH, field (units)	Specific conduct-ance, field (μS/cm)	Phos-phorus, total	Nitrate, total	Chlor-ide, total	Sodium, total	Potas-sium, total	Magne-sium, total	Calcium, total	Total recoverable (μg/L) Lead	Iron	Copper	Man-ganese	Zinc
343	--	04/05	195	--	--	0.65	5.6	37	16	1.1	14	76	<500	<200	<50	<30	0
346	24	04/06	253	7.60	814	1.26	2.2	61	46	3.1	41	241	1,400	46,500	150	3,400	200
347	--	04/05	157	--	--	0.71	0.	34	22	1.5	13	52	<500	1,100	<50	<30	200
348	73	04/03	176	--	--	0.15	8.1	19	28	8.3	124	780	<500	2,200	<50	5,700	100
349	65	04/04	210	--	--	0.64	7.4	24	15	2.9	138	572	<500	21,400	<00	4,,100	200
351	55	04/04	146	--	--	0.28	1.5	61	28	1.9	13	63	<500	2,100	70	90	400
352	55	04/03	154	--	--	0.33	2.5	107	37	1.7	12	70	<500	400	<50	<30	100
353	--	04/06	186	--	--	0.33	4.0	38	23	1.2	14	72	<500	8,200	<50	<30	500
354	--	04/06	160	--	--	0.56	3.4	48	26	1.4	11	68	<500	<200	<50	<30	20
355	63	04/03	163	--	--	0.01	2.8	45	27	1.4	10	69	<500	<200	<50	<30	0
356	57	04/05	196	7.63	589	0.48	4.5	44	29	1.3	15	72	<500	<200	<50	<30	20
357	48	04/05	196	7.57	533	0.12	5.1	26	13	0.90	15	79	<500	<200	<50	<30	0
358	35	04/05	203	--	--	0.40	4.5	31	17	1.1	14	79	<500	<200	<50	<30	50
359	23	04/03	122	--	--	0.05	3.2	66	39	1.9	7.8	53	<500	25,700	70	400	4,400
360	--	04/03	90	--	--	0.08	0.26	5	7	1.3	3.2	47	1,200	60,500	70	1,000	3,200
361	25	04/05	194	7.61	608	0.92	4.1	49	32	1.3	13	78	<500	<200	<50	<30	10
362	67	04/05	203	--	--	1.09	4.3	36	22	1.3	15	81	<500	2200	80	<30	400
363	63	04/03	198	--	--	0.85	5.3	56	24	1.6	15	75	<500	<200	<50	<30	40
364	35	04/04	152	--	--	0.44	0.24	42	20	1.5	14	74	<500	3600	<50	<30	10
365	14	04/03	248	--	--	0.12	0.44	90	46	2.7	26	122	<500	29,200	130	400	300
366	--	04/05	227	--	--	0.68	5.1	101	46	1.6	15	88	<500	<200	<50	<30	20
368	--	04/03	265	--	--	0.09	3.2	232	144	4.7	25	141	<500	19,400	80	500	200
375	--	04/05	187	--	--	0.47	7.2	23	11	0.90	12	79	<500	<200	<50	<30	20
376	--	04/03	137	--	--	0.50	0.	19	51	0.15	1.8	0.1	<500	<200	<50	<30	0
403	54	04/06	192	7.71	638	0.29	4.9	68	35	2.6	11	83	<500	<200	<50	<30	300
406	26	04/03	128	7.66	498	0.05	2.3	19	10	1.0	20	70	<500	6,800	100	1,000	7,800
420	--	04/06	238	7.55	616	0.18	5.5	33	16	1.3	16	91	<500	5,100	<50	<30	20
449	--	04/04	152	--	--	0.56	3.7	16	7	0.70	13	61	<500	<200	<50	<30	30
450	--	04/03	139	--	--	0.40	1.8	61	48	2.1	14	64	<500	19,500	<50	1,000	100

Appendix 2.--Inorganic chemical analyses of ground water from selected wells in the glacial-aquifer system in the Cortland, New York study area, September 1990.
[--, indicates no data available; <, less than; all values are in milligrams per liter unless otherwise noted; µS/cm, microsiemens per centimeter; µg/L, micrograms per liter; well locations shown on pl. 1].

B. SEPTEMBER 1990 (Analyses by the U.S. Geological Survey National Water Quality Laboratory)

					Dissolved, in milligrams per liter										
Well number	Well depth (feet)	Date m/d	Specific conductance (µS/cm)	pH (units)	Alkalinity	Nitrite plus nitrate as N	Phosphorus, ortho as P	Cyanide	Calcium	Magnesium	Sodium	Chloride	Sulfate	Fluoride	Silica
5	40	09/19	--	--	224	9.9	<0.01	--	--	--	--	40	19	0.1	--
11	81	09/19	--	--	223	5.0	<0.01	--	--	--	--	79	24	0.1	--
22	45	09/20	631	7.8	189	7.6	<0.01	--	79	13	34	--	--	--	6.3
48	25	09/17	568	7.5	220	6.4	<0.01	<0.01	87	14	16	--	--	--	7.4
105	59	09/17	554	7.8	175	4.9	<0.01	--	76	14	18	--	--	--	7.3
106	75	09/19	--	--	166	6.9	<0.01	--	--	--	--	21	17	0.1	--
108	38	09/17	--	--	300	6.0	<0.01	--	--	--	--	38	25	0.1	--
121	32	09/20	546	7.7	181	5.9	<0.01	--	75	14	20	--	--	--	7.2
172	69	09/18	559	7.6	206	5.3	<0.01	--	79	15	14	--	--	--	7.4
177	92	09/19	1,390	7.8	200	4.1	<0.01	--	74	14	170	--	--	--	7.5
204	46	09/17	--	--	197	4.6	<0.01	--	--	--	--	30	24	0.1	--
207	53	09/17	--	--	151	8.3	<0.01	--	--	--	--	29	23	0.1	--
210	45	09/17	413	7.7	--	--	--	--	61	14	4.8	--	--	--	7.5
280	34	09/19	807	7.7	204	4.7	<0.01	--	87	17	56	--	--	--	7.8
303	28	09/17	--	--	214	3.7	<0.01	--	--	--	--	72	25	0.1	--
304	23	09/17	--	--	226	4.0	<0.01	--	--	--	--	34	23	0.1	--
317	68	09/18	558	7.6	205	5.7	<0.01	--	78	15	14	--	--	--	7.6
320	90	09/20	363	8.0	140	1.7	<0.01	--	53	13	4.8	--	--	--	8.7
321	80	09/17	3,850	7.2	271	3.0	<0.01	--	230	39	530	--	--	--	10
330	15	09/17	651	7.4	218	6.5	<0.01	<0.01	89	12	31	--	--	--	6.8

Appendix 2. Inorganic chemical analyses of ground water from selected wells in the glacial-aquifer system in Cortland, N. Y. study area (continued)

B. SEPTEMBER 1990 continued.

Well number	Dissolved, in micrograms per liter: Arsenic	Barium	Beryl-ium	Cadm-ium	Chrom-ium	Cobalt	Copper	Iron	lead	Mang-anese	Molyb-denum	Nickel	Silver	Stron-tium	Vanad-ium	Zinc	Lithium
5	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
11	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
22	--	58	<0.5	<1	<5	<3	<10	33	<10	17	<10	<10	<1	110	<6	4	7
48	<1	29	<0.5	<1	<5	<3	<10	6	<10	1	<10	<10	<1	110	<6	24	7
105	--	49	<0.5	<1	<5	<3	<10	3	<10	2	<10	<10	<1	110	<6	62	8
106	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
108	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
121	--	66	<0.5	<1	<5	<3	<10	13	<10	12	<10	<10	<1	120	<6	15	13
172	--	61	0.8	<1	<5	<3	<10	23	<10	15	<10	<10	<1	110	<6	36	9
177	--	57	<0.5	<1	<5	<3	20	12	<10	6	<10	<10	<1	140	<6	35	14
204	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
207	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
210	--	73	<0.5	<1	<5	<3	<10	12	<10	42	<10	<10	<1	92	<6	430	7
280	--	87	<0.5	<1	<5	<3	<10	37	<10	2	<10	<10	<1	140	<6	7	10
303	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
304	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
317	--	63	<0.5	<1	<5	<3	50	14	<10	11	<10	<10	<1	100	<6	4	9
320	--	71	<0.5	<1	<5	<3	<10	4	<10	4	<10	<10	<1	91	<6	5	10
321	--	290	2.0	3	15	9	30	11	30	4	30	30	4	400	18	9	23
330	<1	35	<0.5	<1	<5	<3	<10	10	<10	2	<10	<10	<1	120	<6	28	6

Appendix 2. Inorganic chemical analyses of ground water from selected wells in the glacial-aquifer system in Cortland, N.Y. study area (continued).

B. SEPTEMBER 1990 continued.

					Dissolved, in milligrams per liter											
Well number	Well depth (feet)	Date mo/d	Specific conductance (µs/cm)	pH (units)	Alkalinity	Nitrite plus nitrate as N	Phorphous, ortho as P	Cyanide	Calcium	Magnesium.	Sodium	Chloride	Sulfate	Fluoride	Silica
332	34	09/18	815	7.7	230	0.7	<0.01	--	100	18	35	--	--	--	8.3
333	55	09/18	565	7.7	211	4.2	<0.01	--	77	16	16	--	--	--	7.8
335	34	09/18	854	7.7	255	5.1	<0.01	--	91	18	59	--	--	--	8.5
337	42	09/19	533	7.6	201	6.5	<0.01	<0.01	81	14	11	--	--	--	7.4
338	217	09/19	288	8.9	104	0.1	<0.01	--	13	6	42	--	--	--	0.55
339	35	09/18	584	7.7	200	5.4	<0.01	--	83	14	20	--	--	--	6.5
340	35	09/19	763	7.8	224	3.6	<0.01	--	98	17	34	--	--	--	8.7
341	137	09/19	716	8.0	111	0.1	<0.01	--	32	14	86	--	--	--	1.4
342	52	09/17	610	7.8	176	3.7	0.02	--	72	14	33	--	--	--	7.6
343	24	09/20	662	7.8	252	0.7	<0.01	<0.01	89	19	22	--	--	--	7.8
346	24	09/19	823	7.5	225	1.6	<0.01	--	92	16	52	--	--	--	8.5
347	--	09/20	--	--	193	2.8	<0.01	--	--	--	--	--	--	--	--
348	73	09/18	492	7.9	174	--	--	--	--	--	--	--	--	--	--
349	65	09/18	571	7.7	211	--	--	--	--	--	--	--	--	--	--
351	55	09/20	594	7.8	--	--	--	--	77	13	23	--	--	--	6.4
352	55	09/20	613	7.9	--	--	--	--	56	13	44	--	--	--	3.9
355	63	09/19	505	7.9	158	3.3	<0.01	--	61	10	24	--	--	--	5.7
356	58	09/18	--	--	199	4.0	<0.01	--	--	--	--	--	--	--	--
357	48	09/18	--	--	197	5.3	<0.01	--	--	--	--	--	--	--	--
358	35	09/18	--	--	231	4.4	<0.01	--	--	--	--	--	--	--	--
362	67	09/20	614	7.6	--	--	--	--	79	15	21	--	--	--	7.3
363	63	09/20	--	--	194	4.6	<0.01	--	--	--	--	57	23	0.1	--
364	35	09/20	633	7.7	199	4.7	<0.01	--	83	16	23	--	--	--	7.2
365	14	09/17	820	6.9	312	0.3	<0.01	--	110	17	45	--	--	--	14
366	----	09/20	--	--	209	3.5	<0.01	--	--	--	--	70	22	0.1	--
367	----	09/20	--	--	200	5.5	<0.01	--	--	--	--	--	--	--	--
368	----	09/17	1130	7.2	--	--	--	--	100	14	110	--	--	--	6.9

Appendix 2. Inorganic chemical analyses of ground water from selected wells in the glacial-aquifer system in Cortland, N.Y. study area (continued).

B. SEPTEMBER 1990, continued.

	Dissolved, in micrograms per liter																	
Well number	Arsenic	Barium	Beryl-ium	Cadm-ium	Chrom-ium	Cobalt	Copper	Iron	lead	Mang-anese	Molyb-denum	Nickel	Silver	Stron-tium	Vanad-ium	Zinc	Lithium
332	--	75	<0.5	<1	<5	<3	<10	10	<10	790	<10	<10	<1	200	<6	9	16
333	--	50	<0.5	<1	<5	<3	<10	32	<10	250	<10	<10	<1	110	<6	3	9
335	--	69	<0.5	<1	<5	<3	<10	95	<10	270	<10	<10	<1	170	<6	13	11
337	<1	53	<0.5	<1	<5	<3	<10	19	<10	26	<10	<10	<1	110	<6	3	7
338	--	120	<0.5	<1	<5	<3	<10	41	<10	33	<10	<10	<1	400	<6	5	29
339	--	38	<0.5	<1	<5	<3	<10	15	<10	12	<10	<10	<1	120	<6	6	5
340	--	72	<0.5	<1	<5	<3	<10	9	<10	64	<10	<10	<1	150	<6	7	10
341	--	210	<0.5	<1	<5	<3	<10	62	<10	65	<10	<10	<1	390	<6	9	240
342	--	42	<0.5	<1	<5	<3	<10	280	<10	200	<10	<10	<1	110	<6	15	9
343	<1	62	<0.5	<1	<5	<3	<10	5	<10	580	<10	<10	<1	150	<6	16	8
346	--	87	<0.5	<1	<5	<3	<10	17	<10	94	<10	<10	<1	130	<6	8	10
347	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
348	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
349	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
351	--	51	<0.5	<1	<5	<3	<10	6	<10	3	<10	<10	<1	110	<6	72	8
352	--	47	0.6	<1	<5	<3	<10	18	<10	27	<10	<10	<1	100	<6	91	8
355	--	43	<0.5	<1	<5	<3	<10	7	<10	1	<10	<10	<1	85	<6	11	7
356	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
357	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
358	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
362	--	59	<0.5	<1	<5	<3	<10	580	<10	14	<10	<10	<1	110	<6	120	11
363	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
364	--	61	<0.5	<1	<5	<3	<10	730	<10	20	<10	<10	<1	120	<6	4	9
365	--	150	<0.5	<1	<5	<5	40	7900	30	3600	<10	<10	<1	190	<6	210	12
366	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
367	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
368	--	71	0.5	2	<5	<3	<10	17	<10	4	<10	<10	<1	150	<6	8	9

Appendix 3.--Organic chemical analyses of ground water from selected wells in the glacial-aquifer system in the Cortland, N.Y. study area.

[Analyses by the U.S. Geological Survey National Water Quality Laboratory; --, no data available; <, less than; Well locations shown on pl 1]

				Concentration (total), in micrograms per liter										
Well number	Well depth (feet)	Sample date yr/mo/d	Sample depth (feet)	Tetra-chloro-ethylene	Tri-chloro-ethylene	1,1,1-Tri-chloro-ethane	1,1-Di-chloro-ethylene	Benzene	Toluene	Xylene	Dichlor-bromo-methane	Methyl-chloride	*trans*-1,2-dichloro-ethene	*cis*-1,2-dichloro-ethene
1	--	90/04/05	--	--	--	0.25	--	--	--	--	--	--	--	--
11	81.0	90/04/05	--	<0.20	0.40	2.0	<0.20	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	--
		90/09/19	--	--	0.04	1.4	--	--	--	--	--	--	--	--
22	45.0	90/04/03	--	<0.20	11.0	0.20	<0.20	<0.2	<0.2	<0.2	<0.2	<0.2	5.9	--
		90/09/20	--	--	14.6	0.05	--	--	--	--	--	--	--	3.50
		93/04/27	--	--	6.2	--	--	--	--	--	--	--	--	--
105	59.0	90/04/05	--	--	82.8	--	--	--	--	--	--	--	--	23.8
		90/09/17	--	--	53.9	--	--	--	--	--	--	--	--	16.8
		93/04/27	--	--	54.0	0.01	--	--	--	--	--	--	--	25.0
121	32.0	90/04/04	--	--	101	--	--	--	--	--	--	--	--	34.5
		90/09/20	--	--	66.8	0.20	--	--	--	--	--	--	--	21.0
		93/04/27	--	--	75.0	0.60	--	--	--	--	--	--	--	32.0
172	77.0	90/04/05	--	--	0.02	1.2	0.10	--	--	--	--	--	--	0.20
		90/10/02	--	--	--	0.60	--	--	--	--	--	--	--	--
		90/10/15	--	--	11.4	--	--	--	--	--	--	--	--	0.60
177	92.5	90/04/06	--	0.25	--	--	--	--	0.2	--	--	--	0.3	--
204	46.5	90/04/04	--	--	2.30	0.40	--	--	--	--	--	--	--	1.10
		90/09/17	--	--	1.90	0.30	--	--	--	--	--	--	--	0.80
		93/04/27	--	--	3.4	0.60	--	--	--	--	--	--	--	2.10
205	26.0	90/04/05	--	--	7.00	--	--	--	--	--	--	--	--	1.80
		90/09/17	--	--	24.2	--	--	--	--	--	--	--	--	10.0
		93/04/27	--	--	4.80	0.06	--	--	--	--	--	--	--	1.00
280	34.0	90/04/06	--	--	--	1.6	0.20	0.4	--	--	--	--	--	0.10
		90/09/19	--	--	--	1.5	--	--	--	--	--	--	--	--
304	23.0	90/04/04	--	--	2.70	0.20	--	--	--	--	--	--	--	0.40
		90/09/17	--	--	2.60	1.0	--	--	--	--	--	--	0.2	0.50
		93/04/27	--	--	2.3	0.40	--	--	--	--	--	--	--	0.50
317	68.0	93/04/27	--	--	0.40	0.30	--	--	--	--	--	--	--	0.95
320	90.0	90/09/20	--	--	0.10	--	--	--	--	--	--	--	--	1.20
330	15.0	90/04/05	--	--	--	0.10	2.4	--	0.8	--	--	--	1.0	--
		90/04/05	--	--	--	0.10	2.4	--	0.8	--	--	--	1.0	--
332	34.0	90/09/18	--	--	15.2	107	--	--	--	--	--	--	28.9	--

Appendix 3.--Organic chemical analyses of ground water from selected wells in the glacial-aquifer system in the Cortland, N.Y. study area, continued

Well number	Well depth (feet)	Sample date yr/m/d	Sample depth (feet)	Concentration (total), in micrograms per liter										
				Tetra-chloro-ethylene	Tri-chloro-ethylene	1,1,1-Tri-chloro-ethane	1,1-Di-chloro-ethylene	Benzene	Toluene	Xylene	Dichlor-bromo-methane	Methyl-chloride	*trans*-1,2-dichloro-ethene	*cis*-1,2-dichloro-ethene
333	55.0	90/09/18	--	--	1.10	2.4	--	--	--	--	--	--	--	2.10
335	34.0	90/09/18	--	--	0.10	2.7	--	--	--	--	--	--	--	--
336	37.0	90/09/18	--	--	0.06	0.4	--	--	--	--	--	--	0.3	0.04
340	35.0	90/09/19	--	--	40.2	0.35	--	--	--	--	--	--	--	10.1
		93/04/27	--	--	21.0	0.20	--	--	--	--	--	--	--	5.40
341	137.0	90/07/19	17	0.07	15.9	--	4.0	--	--	--	--	--	--	--
		90/07/19	27	--	35.0	--	10.30	--	--	--	--	--	--	--
		90/07/19	37	--	31.3	--	6.30	--	--	--	--	--	--	--
		90/07/19	47	--	19.6	--	3.30	--	--	--	--	--	--	--
		90/07/19	57	--	13.8	--	3.10	--	--	--	--	--	--	--
		90/07/19	67	--	0.50	--	0.20	--	--	--	--	--	--	--
		90/09/19	--	--	0.04	--	--	--	--	--	--	--	--	0.04
		93/04/27	--	--	0.10	--	--	--	--	--	--	--	--	--
342	52.0	90/09/17	--	--	0.06	1.40	--	--	--	--	--	--	0.3	--
343	24.0	90/09/20	--	--	0.40	--	--	--	--	--	--	--	--	--
346	24.0	90/04/03	--	--	--	6.20	0.50	--	--	--	--	--	--	--
		90/04/06	--	--	--	11.5	1.10	1.4	0.2	--	--	--	--	--
		90/09/19	--	--	--	13.8	--	--	--	--	--	--	0.6	--
347	--	90/04/05	--	--	65.1	--	0.15	--	--	--	--	--	--	12.6
		90/09/20	--	--	30.5	0.10	--	--	--	--	--	--	--	6.90
		90/10/15	--	--	62.8	0.04	--	--	--	--	--	--	--	16.0
		90/11/24	--	--	63.2	--	--	--	--	--	--	--	--	11.3
		90/12/12	--	--	44.2	0.20	--	--	--	--	--	--	--	12.0
		93/04/27	--	--	57.0	0.50	--	--	--	--	--	--	--	20.0
		93/04/29	--	--	59.0	0.40	--	--	--	--	--	--	--	24.0
348	73.0	90/09/18	--	--	--	0.04	--	--	--	--	--	--	0.2	--
351	55.0	90/04/05	--	--	101	--	0.20	--	--	--	--	--	0.2	62.2
		90/09/20	--	--	53.0	0.20	--	--	--	--	--	--	--	35.0
		90/10/15	--	--	59.0	0.15	--	--	--	--	--	--	--	36.0
		90/11/24	--	--	62.0	--	--	--	--	--	--	--	--	33.0
		90/12/12	--	--	61.5	--	--	--	--	--	--	--	--	39.0
		93/04/27	--	--	36	0.20	--	--	--	--	--	--	--	4.80

Appendix 3.--Organic chemical analyses of ground water from selected wells in the glacial-aquifer system in the Cortland, N.Y. study area, continued

Well number	Well depth (feet)	Sample date yr/m/d	Sample depth (feet)	Concentration (total), in micrograms per liter: Tetra-chloro-ethylene	Tri-chloro-ethylene	1,1,1-Tri-chloro-ethane	1,1-Di-chloro-ethylene	Benzene	Toluene	Xylene	Dichlor-bromo-methane	Methyl-chloride	*trans*-1,2-dichloro-ethene	*cis*-1,2-dichloro-ethene
352	55.0	90/04/04	--	--	15.6	--	--	--	--	--	--	--	--	0.54
		90/09/20	--	--	9.50	0.05	--	--	--	--	--	--	--	0.40
352	55.0	93/04/27	--	--	12	0.06	--	--	--	--	--	--	--	0.90
353	--	90/04/05	--	--	17.2	3.20	1.10	--	--	--	--	--	--	8.50
		90/10/17	--	--	6.90	1.20	--	--	--	--	--	--	--	5.10
355	63.0	90/04/03	--	--	--	0.15	--	--	--	--	--	--	--	--
		90/09/19	--	--	0.20	--	--	--	--	--	--	--	0.3	0.40
356	57.6	90/04/05	--	--	--	6.50	0.60	--	--	--	--	--	--	0.40
		90/09/18	--	--	0.60	3.20	--	--	--	--	--	--	--	0.30
357	48.0	90/04/05	--	--	0.03	0.40	0.20	--	--	--	--	--	--	0.20
		90/09/18	--	--	0.04	0.50	--	--	--	--	--	--	--	0.03
358	35.5	90/04/05	--	--	0.95	1.50	0.20	--	--	--	--	--	--	0.22
		90/09/18	--	--	0.90	0.80	--	--	--	--	--	--	--	0.30
362	67.0	90/04/05	--	2.50	49.1	3.10	--	--	--	--	--	--	--	14.9
		90/09/20	--	3.10	43.2	6.50	--	--	--	--	--	--	--	12.50
		90/10/15	--	--	37.4	6.30	--	--	--	--	--	--	--	10.9
		90/11/26	--	1.00	38.0	2.20	--	--	--	--	--	--	--	13.9
		90/12/12	--	2.90	39.8	4.20	--	--	--	--	--	--	--	11.0
		93/04/29	--	--	36.0	2.40	--	--	--	--	--	--	--	14.0
363	63.0	90/04/05	--	--	45.9	--	--	--	--	--	--	--	--	18.2
		90/09/20	--	--	25.3	0.20	--	--	--	--	--	--	--	10.4
		90/10/15	--	--	30.6	0.50	--	--	--	--	--	--	--	11.0
		90/11/26	--	--	31.5	--	--	--	--	--	--	--	--	9.90
		90/12/12	--	--	31.3	0.60	--	--	--	--	--	--	--	11.5
364	63.0	93/04/29	--	--	26.0	0.40	--	--	--	--	--	--	--	13.0
		90/04/05	--	0.30	53.8	--	--	--	--	--	--	--	--	17.3
		90/09/20	--	--	37.3	0.20	--	--	--	--	--	--	--	15.4
		90/10/15	--	--	49.6	0.40	--	--	--	--	--	--	--	15.4
		90/11/26	--	--	45.0	--	--	--	--	--	--	--	--	12.6
		90/12/12	--	--	44.6	0.30	--	--	--	--	--	--	--	15.4

Appendix 3.--Organic chemical analyses of ground water from selected wells in the glacial-aquifer system in the Cortland, N.Y. study area, continued

Well number	Well depth (feet)	Sample date yr/m/d	Sample depth (feet)	Concentration (total), in micrograms per liter										
				Tetra-chloro-ethylene	Tri-chloro-ethylene	1,1,1-Tri-chloro-ethane	1,1-Di-chloro-ethylene	Benzene	Toluene	Xylene	Dichlor-bromo-methane	Methyl-chloride	*trans*-1,2-dichloro-ethene	*cis*-1,2-dichloro-ethene
365	14.0	90/04/03	--	--	--	0.50	0.30	0.2	4.5	2.0	--	--	--	--
		90/09/17	--	--	0.10	0.30	--	--	--	--	--	--	0.4	0.06
		90/10/17	--	--	--	--	--	2.1	42.5	5.3	--	--	--	--
366	--	90/09/20	--	0.50	0.80	0.40	--	--	--	--	--	--	--	--
367	--	90/04/04	--	--	50.3	--	--	--	--	--	--	--	--	6.90
		90/09/20	--	--	19.5	--	--	--	--	--	--	--	--	2.30
367	--	90/10/15	--	--	25.3	--	--	--	--	--	--	--	--	3.10
		90/11/24	--	--	27.4	--	--	--	--	--	--	--	--	--
		90/12/12	--	--	31.7	--	--	--	--	--	--	--	--	4.70
		93/04/28	--	--	31.0	--	--	--	--	--	--	--	--	3.90
368	24.0	90/04/03	--	--	--	--	--	--	0.4	--	--	--	--	--
		90/09/17	--	--	0.06	0.02	--	--	--	--	--	--	0.2	0.20
380	54.0	93/04/27	--	--	17.0	0.08	--	--	--	--	--	--	--	1.90
406	26.0	90/04/03	--	--	0.10	--	--	--	--	--	--	--	--	--
		93/04/27	--	--	4.80	0.06	--	--	--	--	--	--	--	10.0