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Aquifer Geochemistry and Effects of Pumping on Ground-Water Quality at the Green Belt Parkway Well Field, Holbrook, Long Island, New York

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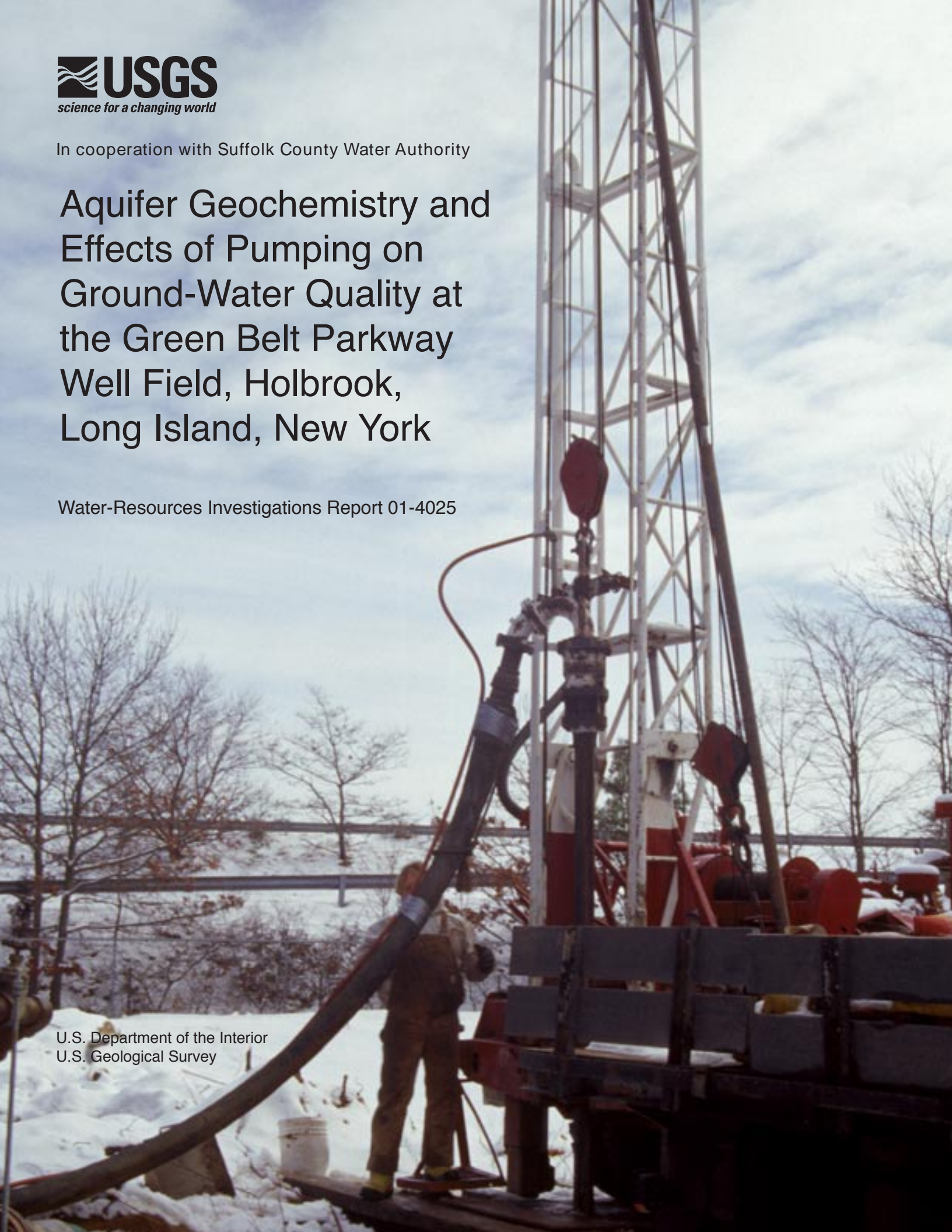
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U.S. DEPARTMENT OF THE INTERIOR

GAIL NORTON, Secretary

U.S. GEOLOGICAL SURVEY

Charles G. Groat, Director

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CONVERSION FACTORS, ABBREVIATIONS AND VERTICAL DATUM

Multiply	By	To Obtain

Length

inch	2.54	centimeter (cm)
foot	0.3048	meter (m)
mile	0.6214	kilometer (km)
acre	43,560	square feet (ft^2)

Hydraulic conductivity

feet per day (ft/d)	0.3048	meters per day (m/d)
	0.0003527	centimeters per second (cm/s)

Transmissivity

feet squared per day (ft2/d)	0.0929	meters squared per day (m^2/d)
	1.075×10^{-10}	centimeters squared per second (cm^2/s)

Pumpage

gal/min		gallons per minute
Mgal/d		millions of gallons per day

Temperature

degrees Fahrenheit (^{o}F)	0.0929	degrees Celsius (^{o}C)

Chemical Concentration

mg/L		milligram per liter
M		moles per liter
mmol/L		millimoles per liter
μmol/L		micromoles per liter
μmol/g		micromoles per gram
μCi		microcuries
‰		per mil

Other abbreviations used

<		less than
>		greater than
δ		delta
min		minutes
h		hours
psi		pounds per square inch

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

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Craig J. Brown[1], Steven Colabufo[2], and John D. Coates[3]

ABSTRACT

Geochemistry, microbiology, and water quality of the Magothy aquifer at a new supply well in Holbrook were studied to help identify factors that contribute to iron-related biofouling of public-supply wells. The organic carbon content of borehole sediments from the screen zone, and the dominant terminal electron-accepting processes (TEAPs), varied by depth. TEAP assays of core sediments indicated that iron reduction, sulfate reduction, and undetermined (possibly oxic) reactions and microbial activity are correlated with organic carbon (lignite) content. The quality of water from this well, therefore, reflects the wide range of aquifer microenvironments at this site.

High concentrations of dissolved iron (3.6 to 6.4 micromoles per liter) in water samples from this well indicate that some water is derived from Fe(III)-reducing sediments within the aquifer, but traces of dissolved oxygen indicate inflow of shallow, oxygenated water from shallow units that overlie the local confining units. Water-quality monitoring before and during a 2-day pumping test indicates that continuous pumping from the Magothy aquifer at this site can induce downward flow of shallow, oxygenated water despite the locally confined conditions. Average concentrations of dissolved oxygen are high (5.2 milligrams per liter, or mg/L) in the overlying upper glacial aquifer and at the top of the Magothy aquifer (4.3 mg/L), and low (<0.1 mg/L) in the deeper, anaerobic part of the Magothy; average concentrations of phosphate are high (0.4 mg/L) in the upper glacial aquifer and lower (0.008 mg/L) at the top of the Magothy aquifer and in the deeper part of the Magothy (0.013 mg/L). Concentrations of both constituents increased during the 2 days of pumping. The $\delta^{34}S$ of sulfate in shallow ground water from observation wells (3.8 to 6.4 per mil, or ‰) was much heavier than that in the supply-well water (-0.1 ‰) and was used to help identify sources of water entering the supply well. The $\delta^{34}S$ of sulfate in a deep observation well adjacent to the supply well increased from 2.4 ‰ before pumping to 3.3 ‰ after pumping; this confirms that the pumping induced downward migration of water. The lighter $\delta^{34}S$ value in the pumped water than in the adjacent observation well probably indicates FeS_2 oxidation (which releases light $\delta^{34}S$ in adjacent sediments) by the downward flow of oxygenated water.

INTRODUCTION

High concentrations of dissolved iron in ground water can lead to screen encrustation and iron-related biofouling of wells and requires costly well-reconditioning and replacement programs for water suppliers. This condition arises from the redox gradient created in the aquifer material surrounding

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the well screen when a well is drilled and operated. The gradient typically forms between shallow, oxic ground water, and deeper, iron-rich ground water that is anoxic.

Declines in the specific capacity of Suffolk County Water Authority (SCWA) supply wells on Long Island were correlated with elevated concentrations of iron in ground water (Walter, 1997a) and are attributed to iron encrustation and biofouling of the well screens and surrounding aquifer sediments. The oxidation of ferrous iron and subsequent encrustation of iron on the well screen is catalyzed by highly resilient and nearly ubiquitous bacteria, which form a biofilm that also clogs the screen (Walter, 1997b). Methods to eliminate the bacteria problem are limited; therefore, emphasis is placed on preventive treatment. Factors related to supply-well pumping (such as pumping rates and frequency) also can affect the biofouling process—cyclic pumping or long periods of idleness can promote biofilm growth and associated encrustation (Smith, 1992); a biofouling study in Suffolk County by Walter (1997b) showed that most of the well-encrusting material is deposited when the wells are shut down. Recent work (Brown and others, 1999; 2000) has shown that the concentrations of iron and other redox-active constituents in ground water are affected by (1) the organic carbon content of the aquifer material, which varies spatially, (2) microbially mediated redox processes within the aquifer, and (3) the distance of the screen from the source of recharge. Thus, the location of the well and the depth of the screened interval can affect the degree of biofouling.

Routine monitoring of water quality and supply-well performance is necessary to (1) detect deleterious water-quality changes and assess the potential for biofouling and encrustation, and (2) assess the need for maintenance and treatment to prolong optimal performance (Cullimore, 1986). For example, pumping from an anoxic aquifer can induce the downward movement of shallow ground water that may contain dissolved oxygen, phosphate, and other constituents that can promote well encrustation and bacterial growth. Dissolved oxygen promotes iron encrustation through the oxidation of ferrous iron, and phosphate can be a

limiting nutrient for iron-bacteria biofilms (Cullimore, 1986; Walter, 1997b). Thus, study of the effects of pumping practices and well placement on the chemical reactions and water-quality characteristics that are related to biofouling is necessary for understanding of the biofouling process.

In 1998, the U.S. Geological Survey (USGS), in cooperation with the SCWA, began a study of iron-related biofouling at the Green Belt Parkway well field in Holbrook, N.Y (fig. 1) to examine the effects of well-screen placement and pumping on factors and chemical constituents that affect iron-related biofouling. The study focused on a new supply well screened in the Magothy aquifer, and on several nearby observation wells screened in the upper glacial and Magothy aquifers. The spatial extent of aquifer redox zones and their associated microbial communities in core sediments from the borehole at the proposed screen zone were examined to document
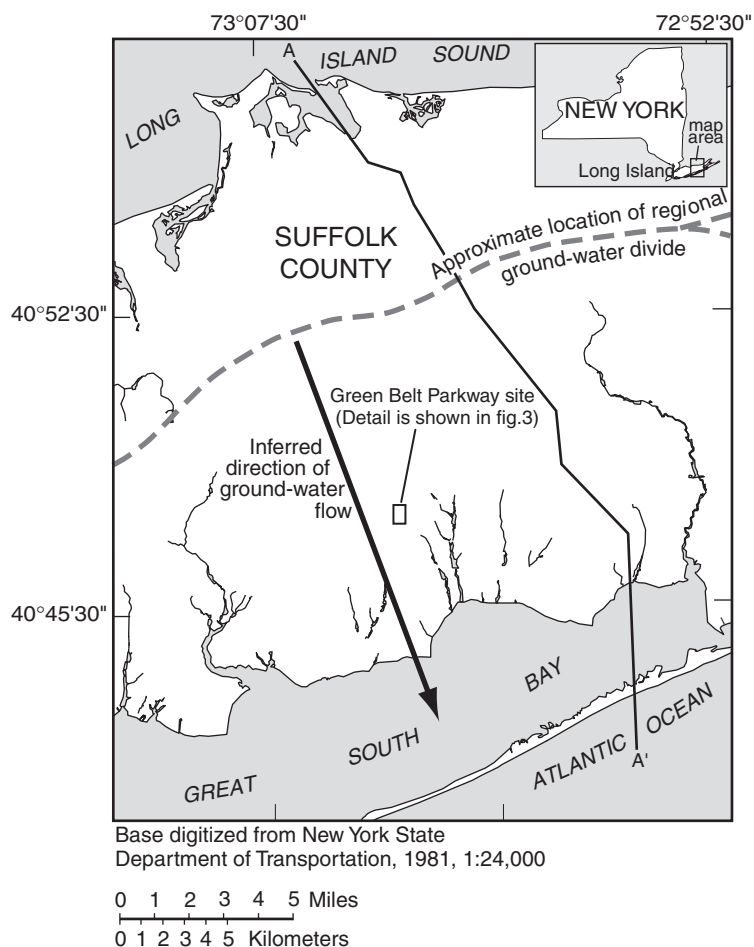
Figure 1. Location of study area at the Green Belt Parkway wellfield at Holbrook, Suffolk County, N.Y. (Section A-A´ is depicted in fig. 2)

their effects on the quality of water that enters the well. The new supply well and the three adjacent observation wells were monitored before and during a 2-day pumping test to detect changes in concentrations of selected constituents (including dissolved oxygen, iron, organic and inorganic carbon, and phosphorus) that are related to iron biofouling.

This report presents and interprets data on sediment microbiology and geochemistry of the Magothy aquifer at the new well site, and discusses the effects of pumping this well on water quality to determine the potential for iron-related biofouling.

Gratitude is extended to Richard Bova and Paul Kuzman of SCWA for assistance with drilling and coring, and coordination of water sampling.

HYDROGEOLOGIC SETTING

Long Island is underlain by a sequence of upper Cretaceous and Pleistocene sediments that were deposited on a southeastward dipping bedrock surface (figs. 1 and 2). The deposits reach a maximum thickness of more than 2,000 ft in southeastern Long Island. The principal aquifer on Long Island is the Magothy aquifer, which consists of the Matawan Group and Magothy Formation, undifferentiated, of Cretaceous age. Along the southern shore, the Magothy aquifer is unconformably overlain by the Monmouth Group (Monmouth greensand) of Cretaceous age; elsewhere in the southern part of the island, it is unconformably overlain by the Gardiners Clay (an upper Pleistocene interglacial unit) and by glacial deposits of Pleistocene age (upper glacial aquifer). Cretaceous deposits north of the Gardiners Clay are unconformably overlain by the upper glacial aquifer (Smolensky and others, 1989). The lateral extents of the Monmouth greensand and the Gardiners Clay appear to be south of the 6-acre study area.

The Magothy aquifer consists of alternating beds and lenses of clay, silt, sand, and some gravel, as well as some mixtures of these materials (Perlmutter and Geraghty, 1963); these sediments were deposited in a transitional fluviodeltaic environment (Lonnie, 1982). The sand consists mostly of quartz but contains some lignite, muscovite, and iron concretions and contains about 2 to 3 percent heavy minerals by
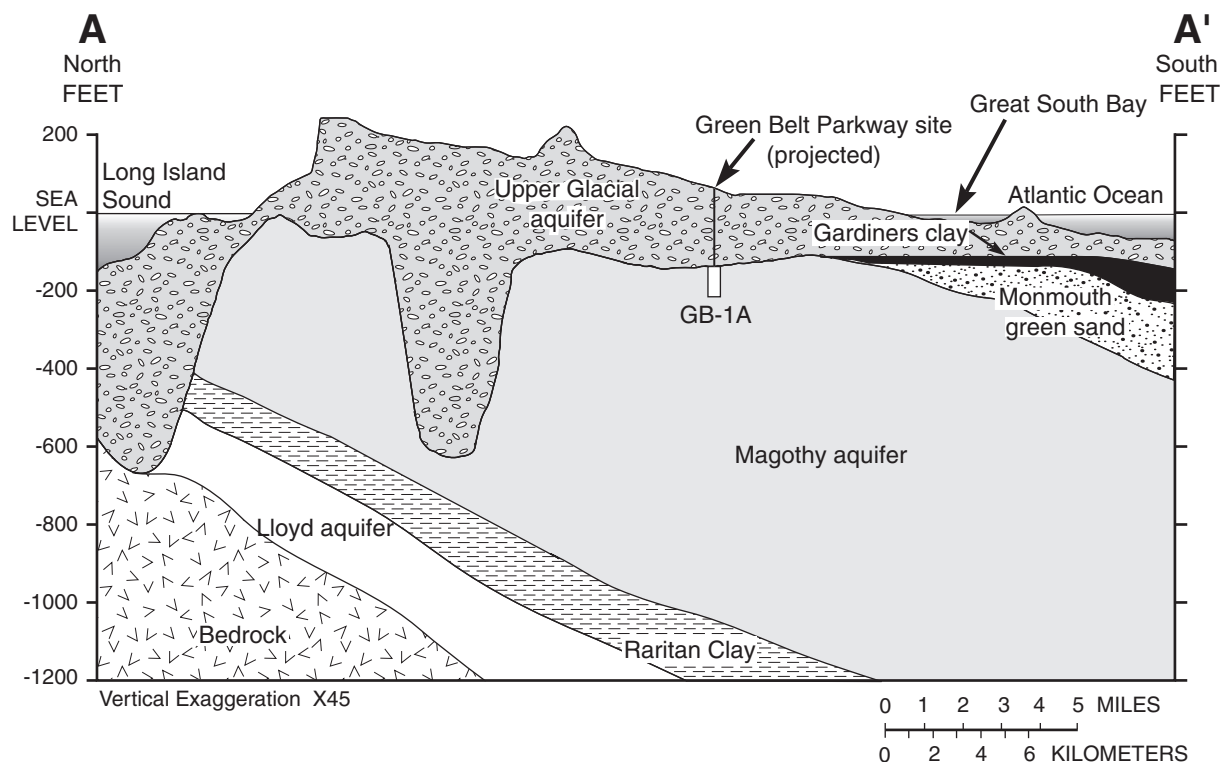
Figure 2. Vertical section A-A´ through central Suffolk County, N.Y., showing hydrogeologic units and location of study area. (Modified from Smolensky and others, 1989, sheet 1.)

weight; it generally has no carbonate minerals and few other reactive minerals, although organic carbon in the form of lignite is a reactive electron donor in redox reactions (Pearson and Friedman, 1970). Lignite is typically present in silt and clay but may also be dispersed through the sand (Smolensky and others, 1989). Much of the iron in the Magothy aquifer on Long Island is in the form of Fe(III) oxyhydroxides, iron-sulfide minerals (FeS_2), iron-rich clay minerals, and other less soluble minerals, including hematite, leucoxene, ilmenite, and magnetite (Brown, Rakovan, and Schoonen, 2000).

The upper glacial aquifer, which contains the water table, is characterized mainly by coarse sand but also contains gravel, silt, and clay. The glacial deposits can contain the same minerals as the Cretaceous sediments but have a greater variety and abundance of heavy minerals such as amphibole, pyroxene, fresh muscovite, biotite, and chlorite, as well as rock fragments and unweathered feldspar (Suter and others, 1949). In general, upper glacial aquifer sands are coarser grained and contain a smaller silt and clay fraction than Magothy sands.

The Long Island ground-water system is recharged solely by precipitation. Most of the recharge that enters the water table moves laterally through the upper glacial aquifer and discharges to streams or to coastal waters. Precipitation near the mid-island ground-water divide (fig. 1) flows downward through the upper glacial aquifer, recharges the Magothy and Lloyd aquifers, then flows to either the north or the south shore.

Water in the upper glacial aquifer generally is oxic and contains low concentrations of dissolved iron and other cations, except in areas of discharge near the south shore, where it has become anoxic through microbially mediated redox reactions along its flowpaths. Water in the Magothy aquifer generally contains higher concentrations of dissolved iron than water in the upper glacial aquifer and, therefore, can cause more pronounced iron-related biofouling of wells. Dissolved-oxygen concentrations in the Magothy aquifer in Suffolk County can be high (up to 0.34 mmol/L) near the ground-water divide but decrease with distance southward along the deep flow path; dissolved iron concentrations, in contrast, are low near the divide and increase with distance southward (Brown and others, 1999).

The Magothy aquifer at the Green Belt Parkway well field (fig. 3) is locally confined by fine-grained

0   25   50   100 FEET

0   10   25 METERS

EXPLANATION

B———B'	Vertical Section - shown in figs. 5 and 9 (wells are projected)
GB-1 ◉	Supply Well
GB-1A ●	New Supply Well
OW-1 ○	Observation Well Cluster

Figure 3. Principal features of Green Belt Parkway well field (site GB), Holbrook, N.Y. (Location is shown in fig. 1. Section B-B´ is depicted in fig. 5.)

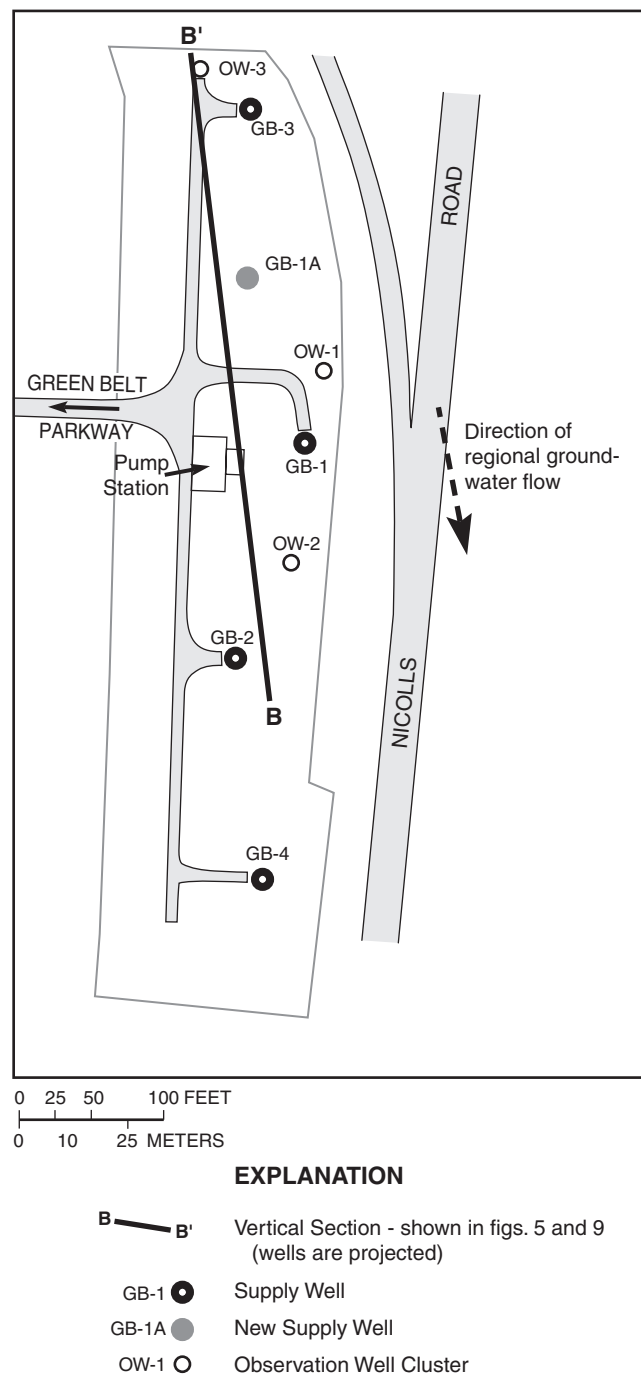units (varying mixtures of fine sand, silt, and clay) at the contact between the Pleistocene and Cretaceous deposits. An aquifer-test study conducted at the site (ERM-Northeast, 1991) reported that the pumping of supply wells screened in the Magothy aquifer had little effect on water levels in the upper glacial aquifer. Magothy transmissivity ranges from 6,000 to 14,000 ft^2/d (64 to 140 cm^2/s), storativity from 10^{-4} to 10^{-3}, and vertical hydraulic conductivity from 0.93 to 1.4 ft/d (3.3 to 5.1 x 10^{-4} cm/s) (ERM-Northeast, 1991).

STUDY METHODS

The borehole was drilled to a depth of 310 ft, and core sediments were obtained for geochemical and microbial analysis. The borehole was subsequently converted to a public-supply well (GB-1A, fig. 3). Water samples were collected from GB-1A and three adjacent observation wells (OW-1, 2, and 3), and water levels in these wells were monitored.

Drilling and Sediment Sampling

Split-spoon cores were obtained from Magothy sediments at borehole GB-1A with a reverse-rotary drill rig. Natural gamma-radiation and electrical-resistance logs were collected from the borehole before the installation of casing material. Eleven cores from the borehole were selected for analysis and were designated C1 through C11. Sediment subsamples were collected from the center of a split-spoon core sample lined with a plastic sleeve, with a modified syringe under a stream of N_2, as described by Chapelle and others (1987).

The sediment samples for microbial analyses were placed in 20-mL serum vials and sealed with butyl stoppers and crimp caps. The headspace and interstitial space were purged by injecting N_2 and venting purged gas through an exit needle. Part of each core sample was placed in septa vials and used for the extraction and analysis of pore water and iron coatings. Sediment (0.1 to 0.2 g) was later transferred from septa vials to 20-mL plastic scintillation vials within an anaerobic glovebox for iron-coating extractions. About 3 g of sediment subsample was also collected for organic carbon and total sulfur analyses. Pore-water samples were later inspected for drilling-fluid contamination through a comparison of anion concentrations—chloride and sulfate concentrations in

core samples were much higher than in the drilling fluid, and the ion ratios differed considerably. Some cores with a high sand content were contaminated with drilling fluid (that is, anion ratios were similar to those in drilling fluid); their chemical data (table 1) are flagged.

Ground-Water Sampling

Water-chemistry data were collected during sampling by standard procedures (Wilde and Radtke, 1998). Colorimetric procedures (Hach Company, 1993) were used onsite to measure concentrations of total dissolved sulfide (H_2S and HS^-), Fe(II) and Fe(III), and dissolved oxygen (< 0.025 mmol/L); a dissolved oxygen meter and the revised Winkler method were used to measure dissolved-oxygen concentrations exceeding 0.025 mmol/L. Dissolved SO_4^{2-} in ground water was collected on an anion-exchange resin column for sulfur-isotope analysis and was analyzed for $BaSO_4$ precipitates by procedures described in Carmody and others (1998). Water samples for $\delta^{13}C$ analysis of dissolved inorganic carbon (DIC) were collected in 1-L glass bottles, which were filled from the bottom up and sealed with a Teflon/silicon septa cap after 3 to 5 L had overflowed to eliminate oxygen.

Laboratory Analyses

Ground water, pore water, sediment bacteria, and sediment coatings were analyzed by the techniques described in the following paragraphs.

Ground Water

All ground-water samples were measured for alkalinity by incremental titration within a few hours after sample collection, and for major elements by Inductively Coupled Plasma-Atomic Emission Spectrometry and Ion Chromatography at the USGS National Water Quality Laboratory in Arvada, Colo. Sulfur-isotope analyses of water and iron disulfide samples were conducted at the USGS Geochemistry Laboratory in Reston, Va.; results are reported (in ‰) relative to the Vienna Canyon Diablo Troilite (VCDT) standard. Carbon-isotope analyses of water samples and lignite samples were conducted at the University of Waterloo, Ontario, Canada, and are reported (in ‰) relative to the Vienna Peedee Belemnite (VPDB)

standard. The uncertainty associated with $\delta^{34}S$ and $\delta^{13}C$ values for water is ± 0.2 ‰; the uncertainty associated with $\delta^{34}S$ of iron disulfide is ± 0.4 ‰.

Pore Water

The inner, sampled part of core samples generally yielded insufficient pore water for analysis; therefore, 5 g of subsampled core material was mixed with 2 to 40 mL of deionized water for 1 to 3 min, followed by filter pressing with N_2 (Lusczynski, 1961) as described in Brown and others (1999). The diluted pore water was measured for pH, then placed in plastic scintillation vials and refrigerated until further analysis. Pore water analyzed for dissolved iron was acidified immediately after extraction. Some ferrous iron in pore water may have been oxidized during pore-water extraction, however, because anaerobic conditions are difficult to maintain during extraction; further discussion is given in Brown, Schoonen, and Candela (2000). Moisture content of the sediments was measured by oven drying (to $110°$ C) a separate subsample of the same material; the resulting values were used to calculate the extent of pore-water dilution by deionized water. Concentrations of pore-water constituents were then multiplied by the dilution factor for correction.

Sediment Bacteria

Subsamples of sediment cores from several depths were examined to identify the predominant anaerobic microbial populations through terminal-electron-accepting process (TEAP)-identification assays. Sulfate-reducing bacteria (SRB), Fe(III)-reducing bacteria (IRB), and methanogenic bacteria in sediment samples were qualitatively identified through [^{14}C]-labeled acetate procedures as described by Lovley (1995) and Coates and others (1996a). In brief, soil samples (2 g) were transferred in duplicate into 10-mL serum vials under a headspace of 95 percent N_2 and 5 percent CO_2 by volume. The vials were sealed with thick butyl rubber stoppers, and the samples were amended with 1 μCi of [2-^{14}C]-acetate. The production of $^{14}CO_2$ and $^{14}CH_4$ in each vial in the presence and absence of 10-mmol/L molybdate, which specifically inhibits the sulfate-reducing organisms, was monitored by gas chromatography with gas-proportional counting of 1.0-mL-headspace samples. The profile of biogas production was used to identify the predominant microbial TEAP (Coates and others,

1996b). Assays were described as "undetermined" if the ^{14}C-amended sediment samples did not generate a measurable amount of $^{14}CO_2$ and $^{14}CH_4$ within an 8-h period.

Iron Coatings, Carbon, and Sulfur Within Sediments

Iron coatings on sediments were measured by 0.5-M HCl and 6-M hydroxylamine extraction (Lovley and Phillips 1987), which indicates (1) the amount of poorly crystalline Fe(III), and (2) the iron fraction that is readily available to microbes in the sample (Heron and others, 1994). The detection limit of this method is about 0.1 μmol Fe(III) per gram of sediment. Percentages of carbon forms and total sulfur in sediments were measured by combustion (Arbogast, 1996).

AQUIFER GEOCHEMISTRY

The following sections describe (1) the lithology at supply well GB-1A and observation wells OW1, OW-2, and OW-3, (2) the concentrations of iron coatings, organic carbon, total sulfur, and constituents of pore water in borehole sediments, and results of the TEAP assays, and (3) water quality and water levels near GB-1A before and during the 2-day pumping test. Gamma-radiation and electrical-resistance logs, and lithologic descriptions are shown in figure 4, with depth profiles of organic carbon, total sulfur, and iron-coatings concentrations in sediments, and of dissolved iron, sulfate, and dissolved organic carbon (DOC) concentrations in pore water. Where more than one subsample of the same core interval was analyzed for a particular constituent, average values were plotted with the measured values (figs. 4C, D, and E), so that connecting lines could be added.

Lithology

The contact between upper glacial aquifer sediments and Magothy aquifer sediments at the study site is characterized by interfingered layers of medium to coarse sand with lenses of fine sand, silt, and clay are present near the upper glacial-Magothy aquifer contact (figs. 4 and 5). The fine-grained units were informally named F1, F2, and F3 in a previous aquifer-test report (ERM-Northeast, 1991) and are so designated here (fig. 5). The contact between the upper
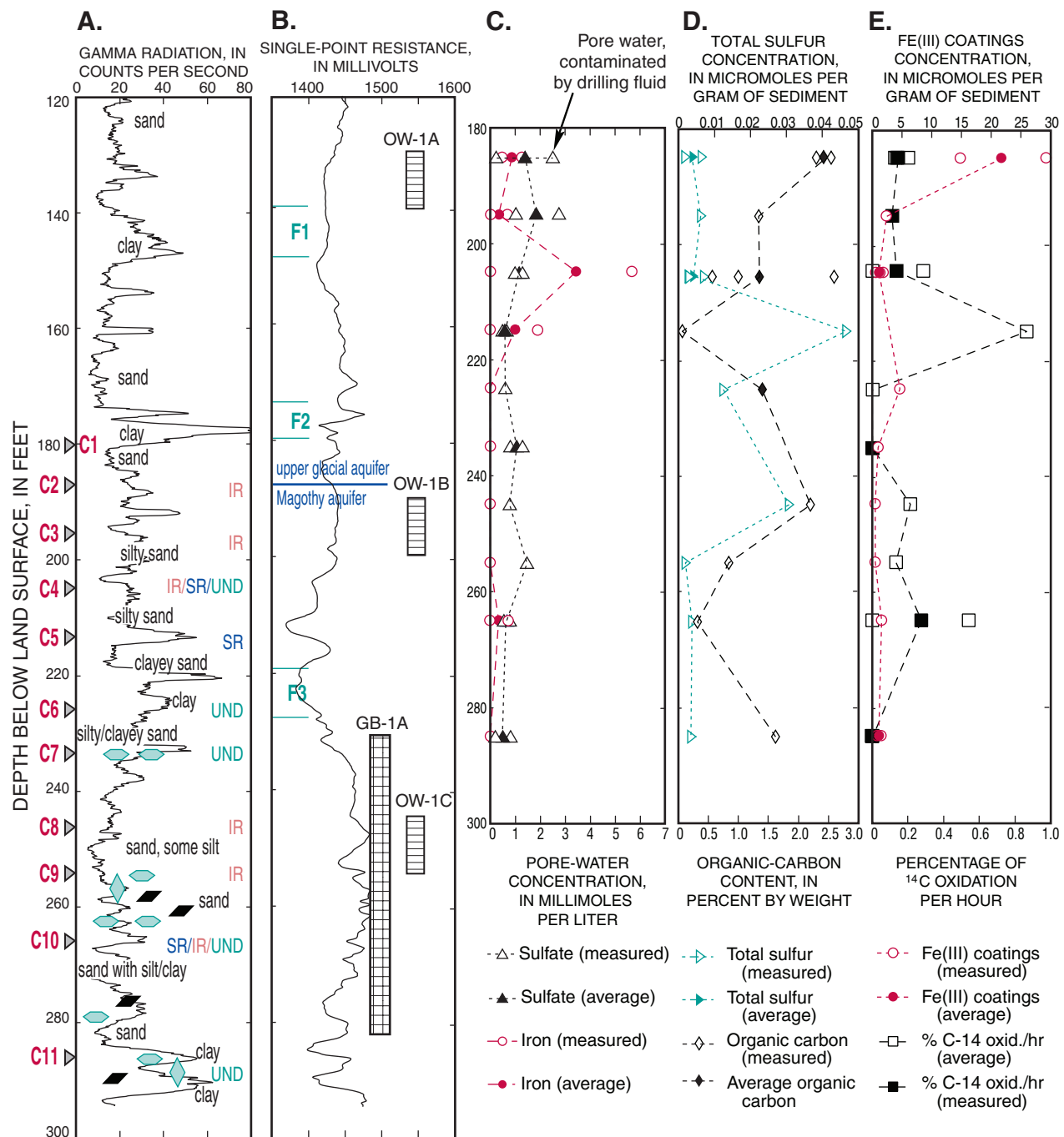
Figure 4. Vertical profiles of borehole GB-1A at Holbrook, N.Y.: A. Gamma-radiation log and predominant TEAPs. B. Single-point resistance log showing position of clay lenses (F1, F2, and F3) and well screen intervals for GB-1A and OW-1A, OW-1B, and OW-1C. C. Concentration of sulfate and iron in pore water. D. Organic carbon and total sulfur content of sediment. E. Concentration of Fe(III) coatings and rate of ^{14}C oxidation in sediments. (Locations of borehole and wells are shown in fig. 3.)

glacial aquifer and the Magothy aquifer at well GB-1A is 186 ft below land surface (108 ft below sea level), as indicated by the lithology of the GB-1A borehole (table 1; figs. 4, 5). Unit F1 is a lens of silt and fine sand that lies near the bottom of the Pleistocene deposits between depths of 140 to 148 ft below land surface. Unit F2 is a fine-grained unit of silt and clay near the bottom of the Pleistocene deposits (upper glacial aquifer) between 171 and 180 ft below land surface. Unit F3 is a fine-grained unit of silt and clay at the top of the Magothy aquifer between depths of 197 and 220 ft below land surface.

The lithology of borehole GB-1A is summarized in table 1. Public-supply well GB-1A is screened from 232 to 282 ft below land surface (table 2), directly below F3 (fig. 5). Well GB-1 has two separate screen zones_the upper part is screened in Magothy aquifer sand between units F2 and F3, from 187 to 210 ft below land surface, and the lower part is screened below, and partly in, unit F3, from 225 to 255 ft below land surface. Three observation-well clusters (OW-1, OW-2, and OW-3, figs. 3, 5) each consist of three 2-in-diameter polyvinyl chloride (PVC) wells. At each cluster, the shallow well (A) is screened above F1, the intermediate well (B) is screened between F1 and F2, and the deep well (C) is screened below F3 (fig. 5). Observation-well cluster OW-1 is 82 ft southeast of GB-1A and is the only well that was sampled for water quality. Well OW-1A is screened partly in upper glacial sand and partly in the silt and fine sand of F1, from 130 to 140 ft below land surface; OW-1B is screened in the Magothy between units F2 and F3, from 190 to 200 ft below land surface; and OW-1C is screened in the Magothy below F3; from 245 to 255 ft below land surface (table 2). Observation well clusters OW-2 and OW-3 were used only for water-level measurements; OW-3 is 150 ft north of GB-1A, and OW-2 is 205 ft south of GB-1A.

Figure 5. Vertical section through study area at Holbrook, N.Y., showing hydrogeologic units, contact between upper glacial-Magothy aquifers, silt and clay lenses F1, F2, and F3, and wells. (Well locations and trace of section are shown in fig. 3.)

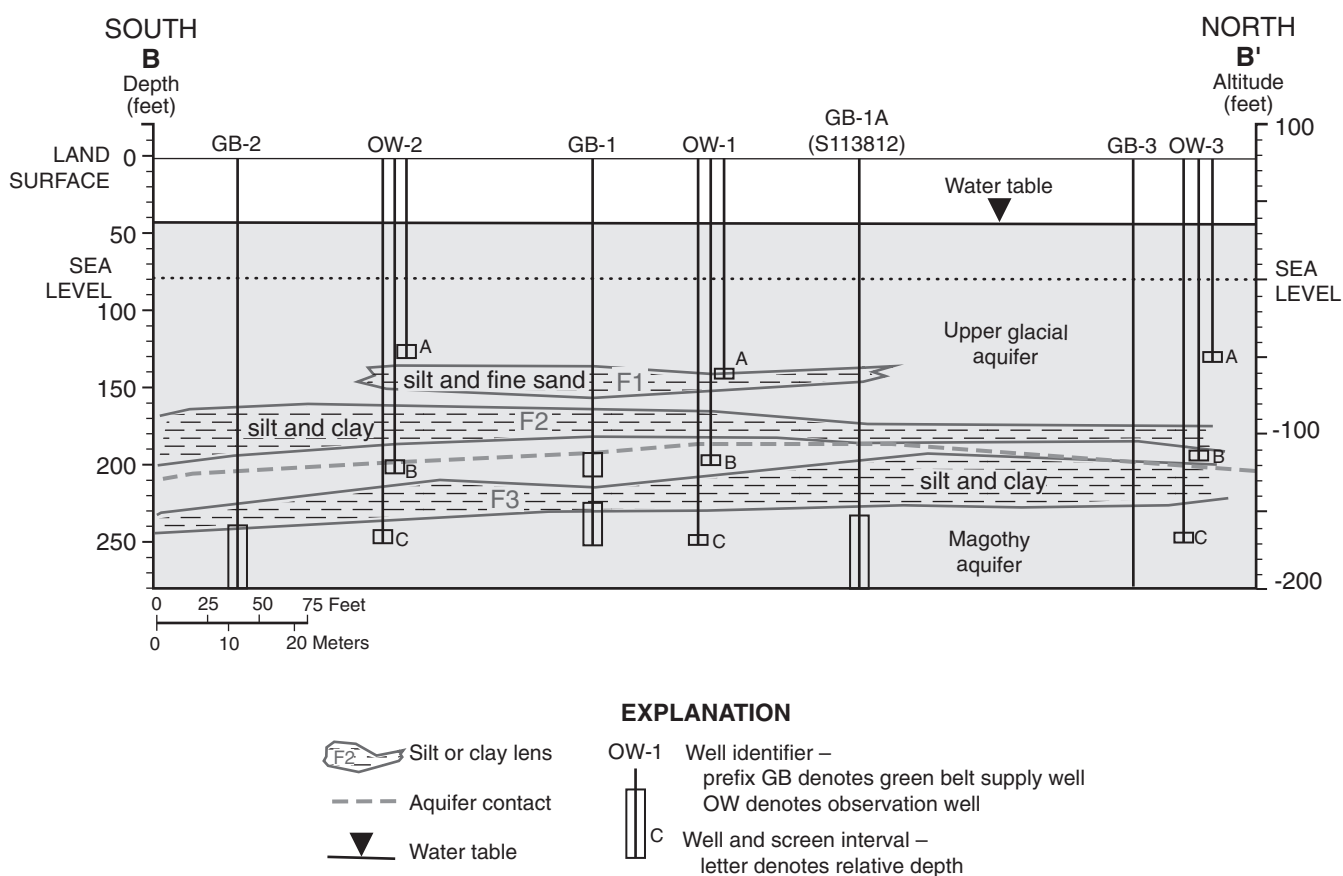**Table 1.** Color, lithology, hydrologic unit, dominant TEAP (terminal electron-accepting process), and sedimentary organic carbon, total sulfur, and Fe(III) content of core samples from borehole GB-1A (S113812T) at Green Belt Parkway well field in Holbrook, Suffolk County, N.Y.

[Depths and altitudes are in feet below land surface, numbers in parentheses are meters. µmol/g, micromoles per gram of sediment. UG, upper glacial aquifer; Mag, Magothy aquifer. F2 is a fine-grained unit near the bottom of the Upper glacial aquifer between depths of 171 and 180 ft; F3 is a fine-grained unit at the top of the Magothy aquifer between depths of 197 and 220 ft. NM, not measured; IRB, Fe(III)-reducing bacteria, SRB, sulfate-reducing bacteria, UND, no activity observed after 10 hours. Dashes indicate no data available. Borehole locations are shown in fig. 3]

Sample	Sampling depth (feet)	Sampling altitude (datum is sea level)	Color (Geological Society of America rock-color chart)	Lithology	Hydro-geologic unit	TEAP	Sedimentary organic carbon (percent by weight)	Total S (µmol/g)	Fe (III), 0.5 mol/L HCl-extractable (µmol/g)
C1	180	-102 ft (-30.6 m)	Dark yellowish brown (10YR 4/2)	Very hard sand; some silt; trace clay, lignite, muscovite	UG (F2)	NM	--	--	--
C2-A*	185.0	-107 ft (-31.6 m)	Brownish gray (5YR4/1) to medium dark gray (N4)	Fine to medium sand, some silt and clay	UG	IRB	2.54	0.0066	15
C2-B	186.5	-108 ft (-32.8 m)	Brownish gray (5YR4/1) to olive gray (5Y4/1)	Same, some silt and clay pockets	UG	IRB	--	--	--
C2-C	185.7	-108 ft (-33.1 m)	Olive gray (5Y4/1) and gray black (N2)	Fine-medium silty sand, some clay; lignite laminae; ferric oxide grains	UG	IRB	2.3	.0019	29
C3-A*	195	-117 ft (- 35.7 m)	Dark yellowish brown (10YR4/2) to medium gray (N5)	Medium to coarse, silty sand to sand with silt, some lignite laminae.	Mag	IRB	--	--	--
C3-B	196	-118 ft (-36 m)	Grayish black (n2) to black (N1)	Fine silty sand	Mag	IRB	1.35	.0066	2.3
C4-A	205	-127 ft (-38.7 m)	Medium gray (N5)	Silty fine-to-medium sand, trace clay	Mag (F3)	IRB	1.00	.0031	1.2
C4-B	205.6	-128 ft (-38.9 m)	Dark gray (N3) to medium gray	Silty fine sand with clay	Mag (F3)	SRB	2.60	.0072	1.7
C4-C	206.2	-128 ft (-39.1 m)	Medium gray (N5)	Silty fine-to-medium sand, trace clay	Mag (F3)	UND	0.56	.0028	--
C5-A*	215	-137 ft (-41.8 m)	Dark gray (N3) to grayish black (N2)	Clayey sand, some silt	Mag	--	--	--	.41
C5-B	216	-138 ft (-42.1 m)	Medium gray (N5)	Fine-medium silty sand, trace clay	Mag	SRB	0.06	.047	--
C6	225	-147 ft (-44.8 m)	Medium-light gray (N6) to medium gray (N5) to dark gray (N3)	Silty fine-to-medium sand to clayey sand, some lignite laminae	Mag	UND	1.4	.013	4.4
C7*	235	-157 ft (-47.9 m)	Medium gray (N5)	Silty sand, trace clay, some pockets of silt or sand	Mag	UND	--	--	.85
C8	245	-167 ft (-50.9 m)	Medium dark gray (N4) to dark gray (N3)	Medium-coarse sand, some silt	Mag	IRB	2.2	.031	.36
C9	255	-177 ft (-54 m)	Grayish black (N2)	Silty very coarse to coarse sand, trace to some clay (layers), some silt	Mag	IRB	.84	.0022	.37
C10-A	265	-187 ft (-57 m)	Medium gray(N5) to medium dark gray (N5)	Medium-coarse to coarse sand with silt, with clay, some silt	Mag	IRB/ SRB	.32	.0041	--
C10-B	266	-188 ft (-57.3 m)	Medium-coarse sand with silt, some clay		Mag	UND	--	--	1.5
C11-A	285	-207 ft (-63.1 m)	Grayish black (N2) to medium dark gray (N5)	Silty clay to clay (lignitic) with laminae of very fine to fine sand and silt	Mag	UND	--	--	1.4
C11-B	286.5	-208 ft (-63.6 m)	Dark gray (N3) to grayish black (N2)	Very fine-to fine sand, some clay, some silt; laminae of lignitic silt	Mag	UND	1.62	.0037	.78

*Core sample had some contamination with drilling fluid

Table 2. Well-construction data for wells at Green Belt Parkway well field in Holbrook, Suffolk County, N.Y.

[Borehole locations are shown in fig. 3.]

Well identifier	Well number	Land-surface elevation, in feet above sea level	Well-construction and borehole details			
			Well depth, in feet below land surface	Depth of screen interval, in feet below land surface	Elevation of screen interval, in feet below (-) sea level	Elevation of screen interval, in meters below (-) sea level
OW-1A	S114872	78.3	140	130-140	-51.7 to -61.7	-15.8 to -18.8
OW-1B	S114874	78.3	200	190-200	-111.7 to -121.7	-34.1 to -37.1
OW-1C	S97070	78.3	255	245-255	-166.7 to -176.7	-50.8 to -53.9
OW-2A	S114870	78.3	130	120-130	-41.7 to -51.7	-12.7 to -15.8
OW-2B	S114875	78.3	205	195-205	-116.7 to -126.7	-35.6 to -38.6
OW-2C	S114876	78.3	250	240-250	-161.7 to -171.7	-49.3 to -52.4
OW-3A	S114873	78.8	137	127-137	-48.2 to -58.2	-14.7 to -17.7
OW-3B	S114869	78.8	197	187-197	-108.2 to -118.2	-33.0 to -36.0
OW-3C	S114871	78.8	250	240-250	-161.2 to -171.2	-49.1 to -52.2
GB-1A	S113812	77.9	282	232-282	-154 to -204	-47.0 to -62.2
GB-1	S54730	77.7	258	187-210	-109.3 to -132.3	-33.3 to -40.3
				225-255	-147.3 to -177.3	-44.9 to -54.0
GB-2	S59744	76.5	301	237.5-299	-161 to -222.5	-49.1 to -67.8
GB-3	S66183	78.1	543	425.5-454	-347.4 to -375.9	-105.9 to -114.6
				463-473	-384.9 to -394.9	-117.3 to -120.4
				507-532	-428.9 to -453.9	-130.8 to -138.4
GB-4	S66184	75.0	384	293-318.5	-218 to -243.4	-66.4 to -74.2
				345.5-381	-270.4 to -305.6	-82.4 to -93.2

Geochemistry and Microbiology

Geochemistry and microbiology of core samples from the borehole sediments were characterized through analyses of iron coatings, sedimentary organic matter (SOM), and total sulfur content, and through TEAP assays. Concentrations of 0.5-M HCl-extractable iron coatings in core sediments from the upper glacial aquifer were higher (as much as 29 µmol/g of sediment; table 1; fig. 4) than in Magothy sediments at depths greater than 195 ft (0.36 to 4.4 µmol/g) and than in deeper Magothy aquifer sediments elsewhere in Suffolk County (<0.1 to 4.3 µmol/g, Brown and others, 1999). The comparatively low Fe(III) concentrations in Magothy sediment coatings reflect the Fe(III)-reducing and sulfate-reducing TEAPs, both of which can lead to the reduction of Fe(III) (Lovley, 1987; Coleman and others, 1993).

Organic carbon (or) content of core-sample sediments ranged from 0.06 percent to 2.6 percent by weight (table 1), and total sulfur content ranged from 0.0019 to 0.047 µmol/g of sediment. The SOM content of Magothy aquifer sediments in Suffolk County generally is positively correlated with the silt and clay content and the total sulfur content (Brown, Rakovan, and Schoonen, 2000). The SOM in core samples from the upper glacial deposits was higher than in other parts of Long Island (Brown and others, 1999; Brown, Rakovan, and Schoonen, 2000) and may result from reworking of Magothy aquifer sediments during Pleistocene deposition of overlying glacial deposits. Sulfur content in Magothy sediments on Long Island generally is associated with iron-sulfide minerals (Brown, Rakovan, and Schoonen, 2000). The total sulfur content at the Green Belt Parkway site was positively correlated with the concentration of 0.5 M HCl-extractable iron coatings in Cretaceous (Magothy) deposits at GB-1A (fig. 6). The absence of a similar correlation in deep Magothy sediments in Suffolk County (Brown, Rakovan, and Schoonen, 2000) suggests that Fe(III) oxyhydroxide coatings in the shallow, slightly oxygenated part of the aquifer originate from the oxidative weathering of iron sulfide (FeS_2) and the subsequent oxidation of dissolved Fe(II). Evidence of iron-sulfide-mineral oxidation was found also in the shallow part of the Magothy aquifer of eastern Suffolk County (Brown and others, 1999;

Brown, Schoonen, and Candela, 2000).
Concentrations of pore-water sulfate
were higher in shallow cores than in
deep cores and, thus, could indicate
localized pyrite oxidation. The uneven
distribution of Fe(III) concentrations,
carbon, total sulfur, and TEAPs in
Magothy aquifer sediments is consistent
with that in intermediate and deep parts
of the Magothy farther to the west in
Suffolk County (Brown and others,
1999). These geochemical data, together
with the varied distribution of TEAPs in
GB-1A sediments (table 1 and fig. 4A),
indicate that localized
microenvironments are prevalent in the
shallow parts of the Magothy aquifer.

     The TEAP assays indicated a
range from iron reduction to sulfate
reduction; the TEAPs in some samples
were undetermined (table 1).
Methanogenesis was not observed in any
of the samples, probably because sulfate
is ubiquitous in the pore water, and
methanogenic bacteria cannot proliferate
if preferred electron acceptors (Fe(III) or
sulfate) are present. The undetermined
TEAP results in samples can result from
several factors, including locally oxic
conditions (possibly sample C4-C), clay,
which can inhibit the transport of
nutrients and microbial waste
(possibly samples C5-A, C11-A, -B),
low concentrations of electron
acceptors, or the absence or
recalcitrance of an organic carbon
electron donor (possibly samples
C-5A); all of these factors can be
inhibitory to anaerobic bacteria.
Microbial activity, as measured in
the acetate-amended core sediments
by the rate of ^{14}C acetate oxidation
(% ^{14}C oxidation/h), generally was
highest in sediments with a high
percentage of organic carbon; figure
7 shows the square of the rate of ^{14}C
acetate oxidation in core sediment
as a function of the square of the
percentage of organic carbon. The
0.5M HCl-extractable Fe(III) is the
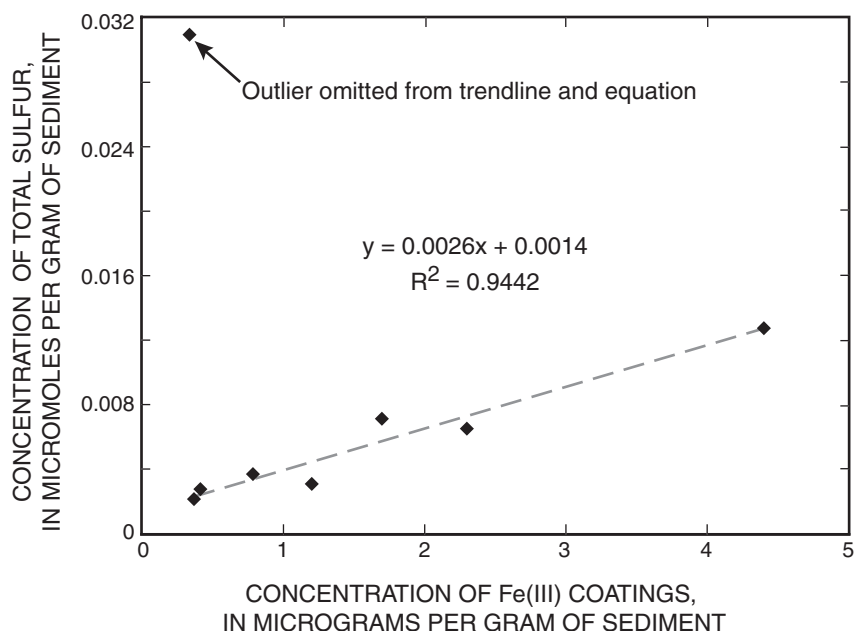
Figure 6. Concentration of total sulfur as a function of the concentration of
0.5M HCl-extractable Fe(III) coatings in Magothy aquifer core samples from
borehole GB-1A, Holbrook, N.Y. (Borehole location is shown in fig. 3.)
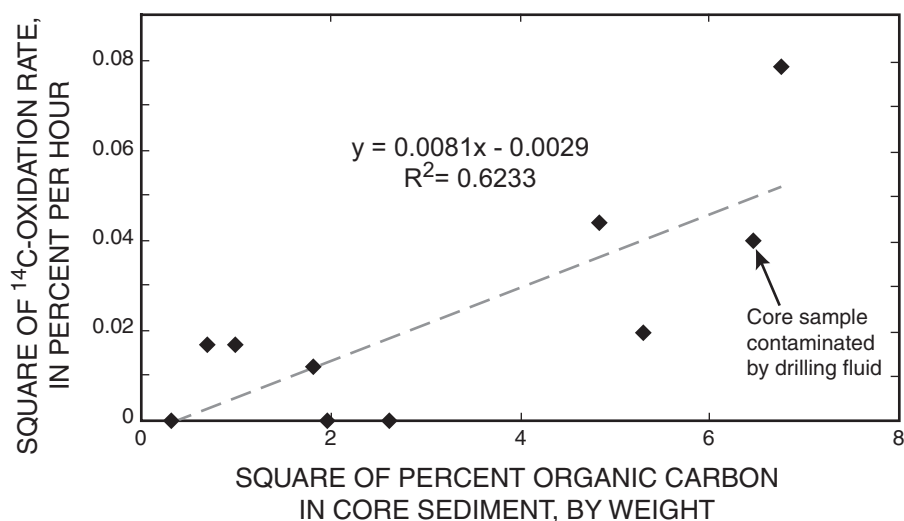
Figure 7. Square of the ^{14}C-oxidation rate in acetate-amended sediment as a
function of the square of the organic carbon concentration in sediment cores from
borehole GB-1A, Holbrook, N.Y. (Borehole location is shown in figs. 3 and 5).

most microbially reactive iron fraction (Lovley and Phillips, 1987) and, therefore, should be favorable for Fe(III)-reducing bacteria. No correlation was observed between this Fe(III) fraction and iron-reducing TEAPs in sediments; this indicates that iron-reducing bacteria are limited by the pool of electron donor (organic carbon) available, as observed in a previous study of borehole sediments from the middle part of the Magothy aquifer about 10 mi southeast of the GB-1A study area (Brown and others, 1999). The greatest anaerobic microbial activity (0.9 percent acetate oxidized/h) was in a sample from a 216-ft depth (core C5-B in table 1). This sample had a low SOM content (0.06 percent); however, the predominance of a sulfate-reducing TEAP, together with the high total sulfur concentration in these sediments, indicates that iron-sulfide minerals have formed at this horizon. Although the SOM content was low in sample C5-B, dissolved organic acids could leach from lignite in an overlying clayey sand (fig. 4A) and provide an organic-carbon source for the iron-reducing bacteria.

Sulfate concentrations in pore water from GB-1A (table 3) were from 2 to 50 times greater than in water from nearby wells (OW-1B and OW-1C) screened in the Magothy aquifer (table 4). High concentrations of sulfate in pore water have been observed in Magothy borehole sediments from other parts of Suffolk County and probably result from a seawater transgression in the past (Brown, 1998). These locally high sulfate concentrations can result in localized microbial and geochemical reactions that are not apparent in large-scale aquifer studies that depend solely on well-water analyses. Similar results were observed in this study and probably reflect the thin (<0.5-ft) interval from which pore-water samples were obtained, unlike the much wider (10- to 50-ft) screened intervals from which ground-water samples were obtained. Furthermore, the disturbance of the sediment samples, and the ion desorption that probably occurs during sediment dilution with deionized water, result in the release of pore water that is not represented in well-water samples because it is not removed by pumping (Brown, 1998).

Dissolved iron concentrations in pore water ranged from below the detection limit (<1.8 μmol/L) in several cores to 6.5 μmol/L in sample C4-C. The low pH (4.93) and the absence of anaerobic microbial activity in sample C4-C may result from the local presence of dissolved oxygen in pore water and subsequent oxidation of pyrite, which would release dissolved iron and acidity.

Ground-Water Quality

Water quality in the upper glacial aquifer in the study-site vicinity differs from that in the Magothy aquifer. Water from both aquifers generally can be characterized as a low ionic strength, sodium-chloride type, but the upper glacial aquifer is more prone to point- and nonpoint-source contamination. The Magothy aquifer at this location is confined by silt and clay layers at the top of the Cretaceous surface and at the bottom of the Pleistocene deposits (upper glacial aquifer). Water in the Magothy aquifer generally is older, contains more reduced species, such as dissolved (ferrous) iron, manganese, and sulfide, and contains less dissolved oxygen, than water in the upper glacial aquifer.

Local water quality in the upper glacial aquifer and the upper part of the Magothy aquifer at the study site is reflected in the chemistry of samples from the pumping well (GB-1A) and the adjacent observation-well cluster (OW-1A, OW-1B, and OW-1C; fig. 8; table 4). Concentrations of ions in the upper glacial aquifer (OW-1A) reflect effects of human activities and generally are higher than those in the Magothy aquifer (OW-1B, OW-1C, and GB-1A; fig. 8), although the concentrations of nitrogen species at Magothy wells GB-1A and OW-1C also reflect human activity (table 4). The presence of nitrate in GB-1A and OW-1C probably results from the downward flow of shallow water induced by pumping of supply wells in the Magothy aquifer. The presence of nitrate in GB-1A (6.3 μmol/L) during a static period of nonpumping (April 20, 1999) indicates that ground water that contributes to this well is from a less reducing environment than that in OW-1C, where nitrate concentrations were below the detection limit (<3.6 μmol/L). The part of the aquifer from which OW-1C obtains water is small compared to the part tapped by GB-1A, which has a much longer screen, is pumped at large rates, and, therefore, obtains much larger volumes of water. The low concentrations of nitrate in OW-1C, therefore, probably reflect local conditions.

Table 3. pH and concentrations of selected constituents in pore-water samples from borehole GB-1A in Holbrook, Suffolk County, N.Y.

[Concentrations in micromoles per liter. Diss, dissolved. NM, not measured. <dl, below detection limit. Borehole location is shown in fig. 3.]

Sample identifier	Sample depth, in feet below (-) land surface	Sample altitude, in feet below (-) sea level	pH	Iron, dissolved	SO_4^{2-}	Cl^-
C1-A	180	-102	NM	NM	NM	NM
C2-A	185	-107	5.7	0.46	2.5	410
C2-B	185.7	-107.7	5.9	NM	NM	NM
C2-C	186.5	-108.5	5.6	1.3	230	190
C3-A	195	-117	5.6	.67	2,800	240
C3-B	196	-118	5.2	<dl	1,000	200
C4-A	205	-127	5.3	<dl	1,300	200
C4-B	205.6	-127.6	5.3	NM	NM	NM
C4-C	206.2	-128.2	4.9	6.5	100	190
C5-A	215	-137	6.1	<dl	660	310
C5-B	216	-138	5.7	2.1	510	220
C6	225	-147	5.6	<dl	590	120
C7	235	-157	5.8	<dl	820	180
C8	245	-167	5.1	<dl	770	240
C9	255	-177	5.4	<dl	1,500	200
C10-A	265	-187	6.2	.71	760	310
C10-B	266	-188	5.4	<dl	570	98
C11-A	285	-207	NM	<dl	810	84
C11-B	286.5	-208.5	6.8	<dl	210	110

Table 4. Concentrations of major elements and chemical species, and δ^{13}C, and δ^{34}S of sulfate in water samples from wells at Green Belt Parkway well field in Holbrook, Suffolk County, N.Y., 1999.

[Dissolved concentrations in milligrams per liter (and micromoles per liter). Diss, dissolved. TOC, total organic carbon; DOC, dissolved organic carbon. δ^{13}C and δ^{34}S in ‰. Screen interval in feet (and meters) above or below (-) sea level. Dashes indicate data not available. Locations shown in fig. 1.]

Well site screen interval	Date time	Water temp. (°C)	pH	O_2	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	H_2S	SO_4^{2-}	Cl^-	Silica	NH_4^+ as N	NO_3^- as N	P Total	P Diss	PO_4^{2-}	Fe Total	Fe Diss	Mn Total	Mn Diss	TOC	DOC	δ^{13}C	δ^{34}S
GB-1A (S113812) -154 to -204 (-47.0 to -62.2)	4/8/99[1] 12:40	10.7	5.8	0.21 (6.6)	3.8 (95)	1.5 (62)	4.3 (190)	0.56 (14)	8.2 (140)	--	10 (100)	5.9 (170)	15 (250)	<.02 (<1.1)	<.05 (<3.6)	<.05 (<1.6)	<.05 (<1.6)	0.007 (0.23)	0.30 (5.3)	0.27 (4.8)	0.016 (0.29)	0.017(0.29)	0.1 (8.3)	0.2 (17)	--	--
	4/20/99[2] 16:00	10.5	6.0	<.1 (<3.1)	4.0 (100)	1.8 (74)	4.7 (200)	.5 (13)	10 (166)	<.004 (<.1)	10 (100)	6.8 (190)	15 (250)	.024 (1.3)	.088 (6.3)	<.05 (<1.6)	<.05 (<1.6)	.006 (.19)	.19 (3.4)	.20 (3.6)	.022 (.39)	.022 (.40)	.3 (25)	.2 (17)	--	--
	4/22/99[3] 16:30	10.6	6.0	.18 (5.6)	3.5 (87)	1.6 (66)	4.4 (190)	.43 (11)	11 (180)	.004 (.12)	10 (100)	6.0 (170)	15 (250)	.034 (1.9)	.051 (3.6)	<.05 (<1.6)	<.05 (<1.6)	.013 (.42)	.35 (6.3)	.36 (6.4)	.018 (.32)	.018 (.33)	.1 (8.3)	.1 (8.3)	-19.8	-0.1
OW-1A (S114872) -51.7 to -61.7 (-15.8 to -18.8)	4/20/99 10:00	12.1	6.2	4.8 (150)	5.5 (140)	5.8 (240)	20 (870)	1.2 (31)	29 (470)	--	8.8 (92)	32 (900)	10 (170)	.042 (2.3)	2.3 (16)	.44 (14)	.48 (15)	.49 (16)	.26 (4.6)	.28 (5.0)	.51 (9.2)	.48 (8.8)	.8 (67)	.8 (67)	-22.4	6.4
	4/22/99 14:00	11.4	6.1	5.5 (170)	5.5 (140)	5.7 (230)	20 (870)	1.8 (46)	19 (310)	--	9.3 (97)	34 (960)	10 (170)	.055 (3.0)	2.3 (160)	.30 (9.7)	.30 (9.7)	.32 (10)	.23 (4.1)	.22 (3.9)	.44 (8.0)	.42 (7.7)	.4 (37)	.4 (33)	--	--
OW-1B (S114874) -111.7 to -121.7 (-34.1 to -37.1)	4/19/99 15:00	11.5	6.1	3.1 (97)	6.6 (160)	3.0 (120)	5.7 (250)	.54 (14)	28 (460)	--	6.4 (67)	8.8 (250)	17 (280)	.059 (4.2)	.79 (56)	<.05 (<1.6)	<.05 (<1.6)	.015 (.48)	<.012 (<.22)	<.010 (<.18)	.0078 (.14)	<.003 (<.05)	.9 (75)	.2 (17)	-22.3	3.8
	4/22/99 13:00	11.4	6.1	5.5 (170)	8.3 (207)	3.6 (150)	6.3 (270)	.95 (24)	32 (520)	--	5.0 (52)	11 (310)	17 (290)	.033 (2.4)	1.2 (86)	<.05 (<1.6)	<.05 (<1.6)	.001 (.03)	<.012 (<.22)	<.010 (<.18)	<.003 (.14)	<.003 (<.05)	.2 (17)	.1 (8.3)	--	--
OW-1C (S97070) -166.7 to -176.7 (-50.3 to -53.9)	4/19/99 11:45	11.0	5.9	<.1 (<3.1)	3.0 (75)	1.3 (53)	4.3 (190)	.39 (10)	8.0 (130)	.010 (.29)	11 (110)	5.0 (140)	15 (250)	.059 (1.7)	.79 (56)	<.05 (<1.6)	<.05 (<1.6)	.008 (.26)	.16 (29)	.17 (30)	.032 (.59)	.032 (.58)	.3 (25)	.3 (25)	-21.1	2.4
	4/19/99[4] 11:46	--	--	--	3.0 (75)	1.3 (53)	4.3 (190)	.40 (10)	8.2 (130)	.010 (.29)	11 (110)	5.0 (140)	16 (260)	.059 (1.8)	.79 (56)	<.05 (<1.6)	<.05 (<1.6)	.008 (.26)	.16 (28)	.17 (31)	.031 (.56)	.034 (.62)	.2 (17)	.2 (17)	--	--
	4/22/99 10:00	11.0	5.9	<.1 (<3.1)	3.2 (80)	1.3 (54)	4.4 (190)	.42 (11)	7.2 (120)	.012 (.35)	12.1 (120)	5.3 (150)	15 (250)	.031 (1.7)	<.05 (<3.6)	<.05 (<1.6)	<.05 (<1.6)	.022 (.71)	.16 (28)	.16 (29)	.028 (.52)	.029 (.53)	.1 (8.3)	<.1 (<8.3

[1] Sample collected after well development; nearby supply wells were pumped intermittently at this time
[2] Sample collected during static conditions
[3] Sample collected during pumping conditions
[4] Replicate analysis

GB-1A
4/20/99

Na — HCO₃
Ca — SO₄
Mg — Cl

1 .5 .5 1

OW-1B
4/19/99

Na — HCO₃
Ca — SO₄
Mg — Cl

1 .5 .5 1

OW-1A
4/20/99

Na — HCO₃
Ca — SO₄
Mg — Cl

1 .5 .5 1

OW-1C
4/19/99

Na — HCO₃
Ca — SO₄
Mg — Cl

1 .5 .5 1

CONCENTRATION, IN
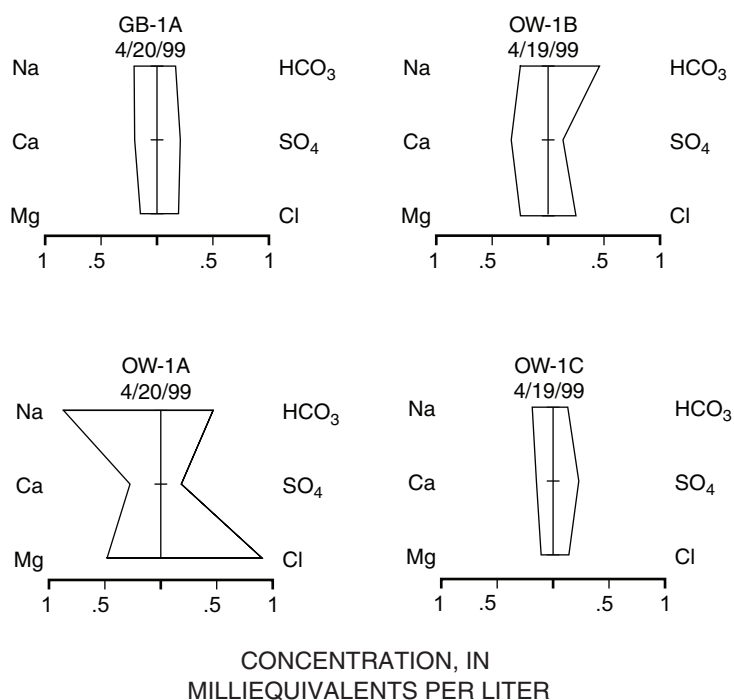MILLIEQUIVALENTS PER LITER

Figure 8. Stiff diagrams representing ion concentrations in water samples from public-supply well GB-1A and observation wells OW-1A, OW-1B, and OW-1C, at Green Belt Parkway well field, Holbrook, N.Y., during static, nonpumping conditions of April 19-20, 1999 (Well locations are shown in fig. 3.)

EFFECTS OF PUMPING ON GROUND-WATER QUALITY

Pumping of supply well GB-1A lowered water levels in nearby observation wells and altered the water quality. All supply-well pumping at the site was stopped on April 17, 1999 for 2 days to achieve static water-level conditions. Well GB-1A was then turned on and pumped for 2 days at a rate of about 700 gal/min. Water samples were collected from GB-1A and from OW-1 wells A, B, and C during the nonpumping period (GB-1A was sampled about 20 min. after its pump was turned on), and at the end of the 2-day pumping period. Water levels in all nine observation wells were monitored before, during, and after the test (fig. 9). The water level in GB-1A generally was stable at 37.2 ft above sea level before the test, then declined to 3.4 ft above sea level once pumping began (fig. 9). Water levels in nearby Magothy aquifer observation wells OW-1B and -1C and OW-3B and -3C also were steady before the test, then declined almost immediately in response to pumping in GB-1A. Water levels in wells screened in the upper glacial aquifer

(OW1-A, -2A, and -3A) showed little, if any, decline in response to the pumping—the water levels in OW-1A and -2B did not decline at all, and the water level in OW-3A declined from 38.46 ft above sea level before pumping to 38.33 ft above sea level during the pumping. This indicates that extended pumping in the Magothy aquifer during the nonsummer months has little or no effect on water levels in the upper glacial aquifer. The summer demand often requires pumping of more than one supply well, however. For example, total combined pumpage from wells GB-1 through GB-4 for July 1999 ranged from 1.4 to 6 Mgal/d, whereas the combined pumpage for the preceding January ranged from 0.02 to 0.17 Mgal/d. Water levels measured in Magothy wells OW-1C and OW-3C on July 20, 1999, at a time when GB-1, - 2, and -3 were pumping simultaneously, were 26.96 and 31.71 ft above sea level, respectively—nearly 3 ft lower than water levels measured during the pumping of GB1A alone on April 22, 1999. Water levels measured in upper glacial wells OW-1A and OW-3A on July in 1999 were 35.20 and 35.75 ft above sea level, respectively, and also were nearly 3 feet lower than water levels measured on April 22. Water-table fluctuations generally are caused by variations in the amount of water entering or discharging from the aquifer, such as from precipitation or pumping (Busciolano and others, 1998). Precipitation had been low in the 4 months preceding the test and probably provided little ground-water recharge and, thus, led to water-level declines. Intensive pumping of the Magothy aquifer during the summer probably lowered water levels in the upper glacial aquifer as well.

Chemical analyses of ground-water samples collected from well GB-1A during pumping indicate that the water originated from a wide range of depths. Dissolved oxygen concentrations increased from <3.1 μmol/L on April 20 to 5.6 μmol/L on April 22, and phosphate concentrations increased from 0.19 to 0.42 μmol/L as P (fig. 10A); these increases probably resulted from the induced inflow of water from shallow depths, such as near the well screens of OW-1A and 1B (fig. 9A). Phosphate concentrations in OW-1C increased also (fig. 10A). Dissolved iron
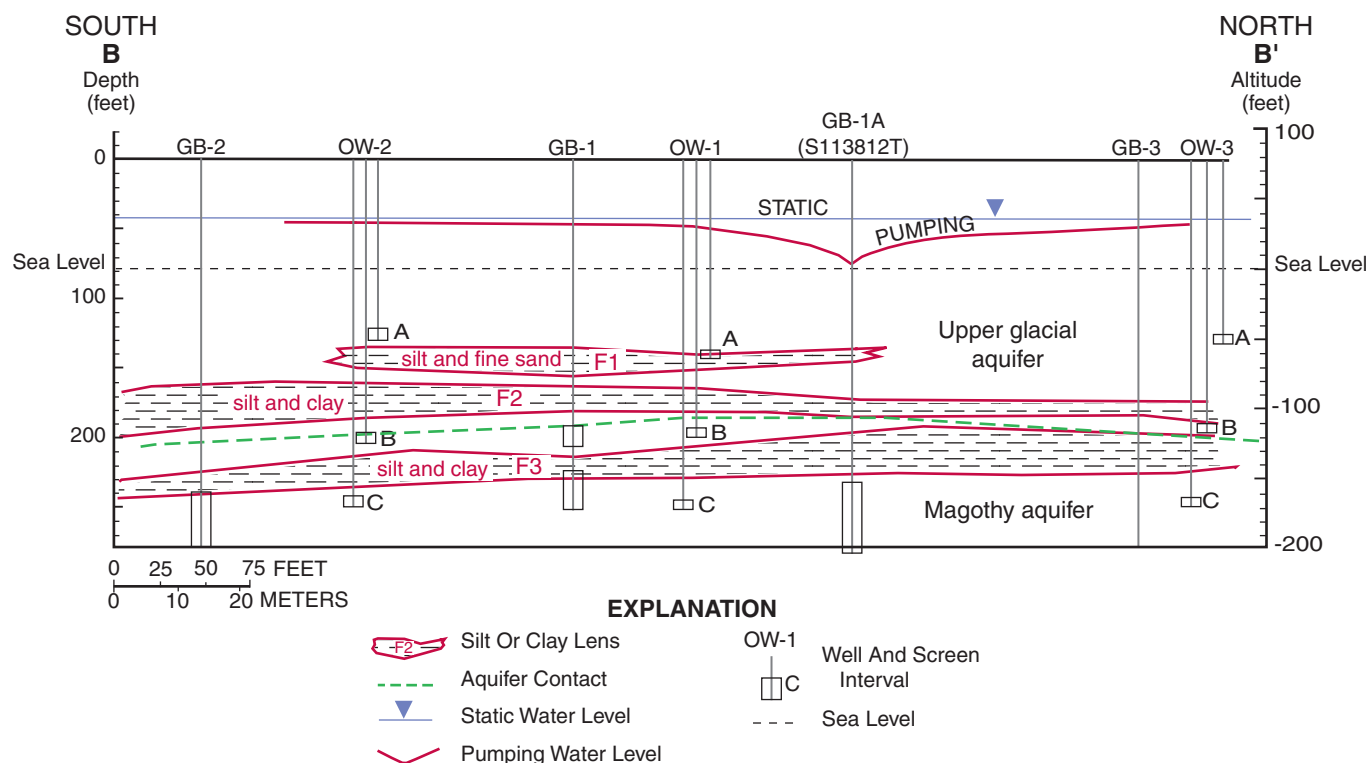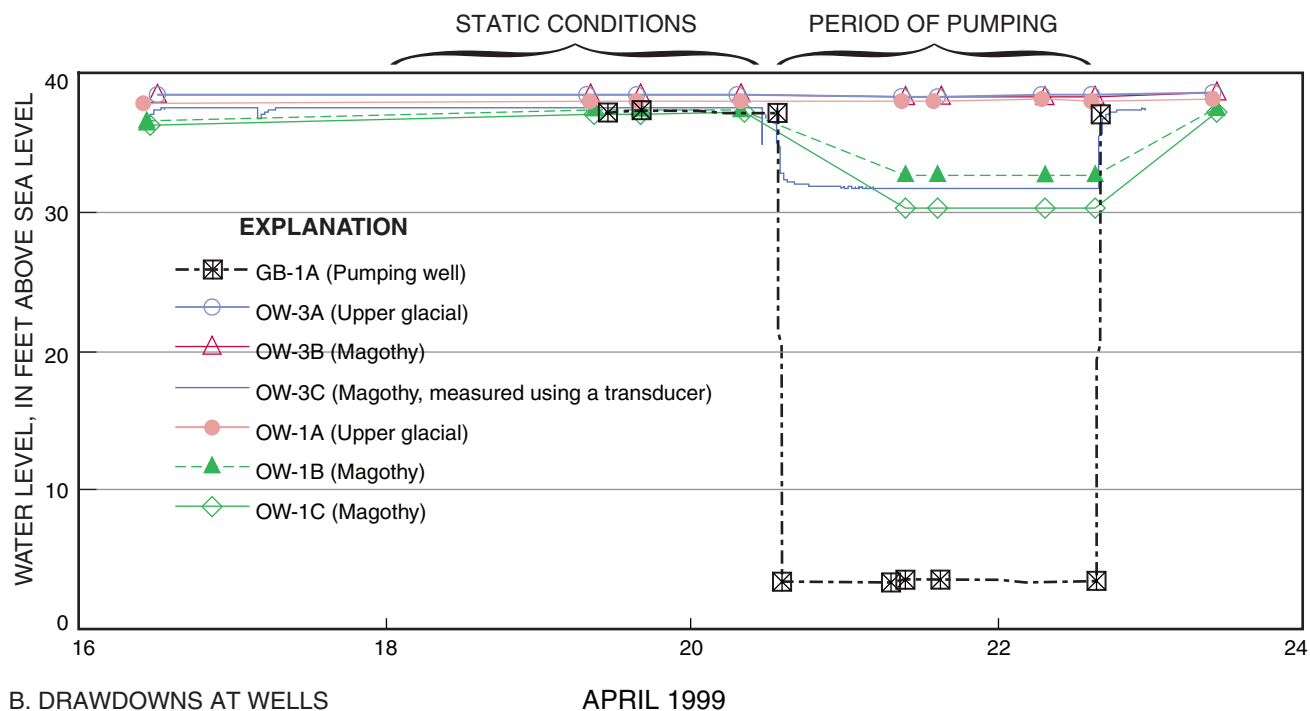
Figure 9. Water levels in the Magothy aquifer (for wells screened below clay lens F3) along Section B-B´ at the Green Belt Parkway well field, Holbrook, N.Y., during static, prepumping conditions and the pumping period, April 19-22, 1999: A. Drawdowns along B-B´. B. Water levels in pumping well (GB-1A) and two observation-well clusters (OW-1 and OW-3). (Trace of Section B-B´ is shown in fig. 3.)
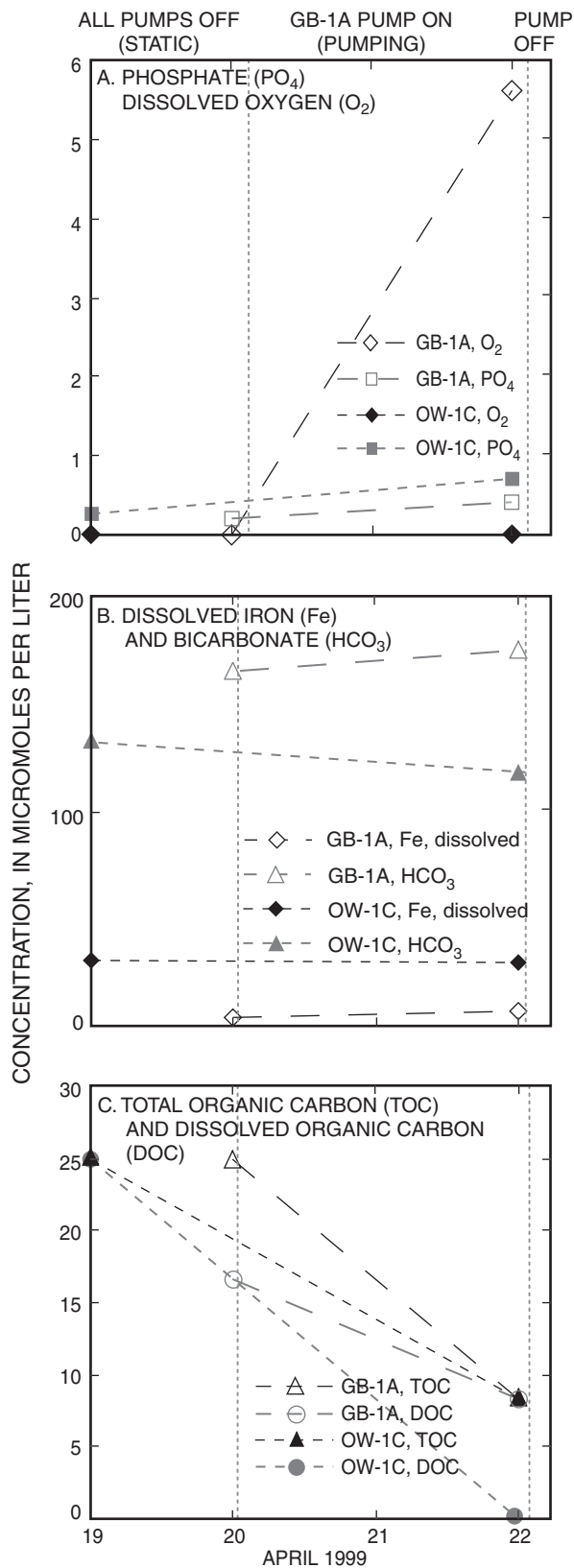
Figure 10. Concentrations of selected constituents in water samples from pumping well GB-1A and observation well OW-1C, Holbrook, N.Y., during static, prepumping conditions and the pumping period, April 19-22, 1999: A. Phosphate and dissolved oxygen. B. Dissolved iron and bicarbonate. C. Total organic carbon (TOC) and dissolved organic carbon (DOC). (Well locations are shown in fig. 3.)
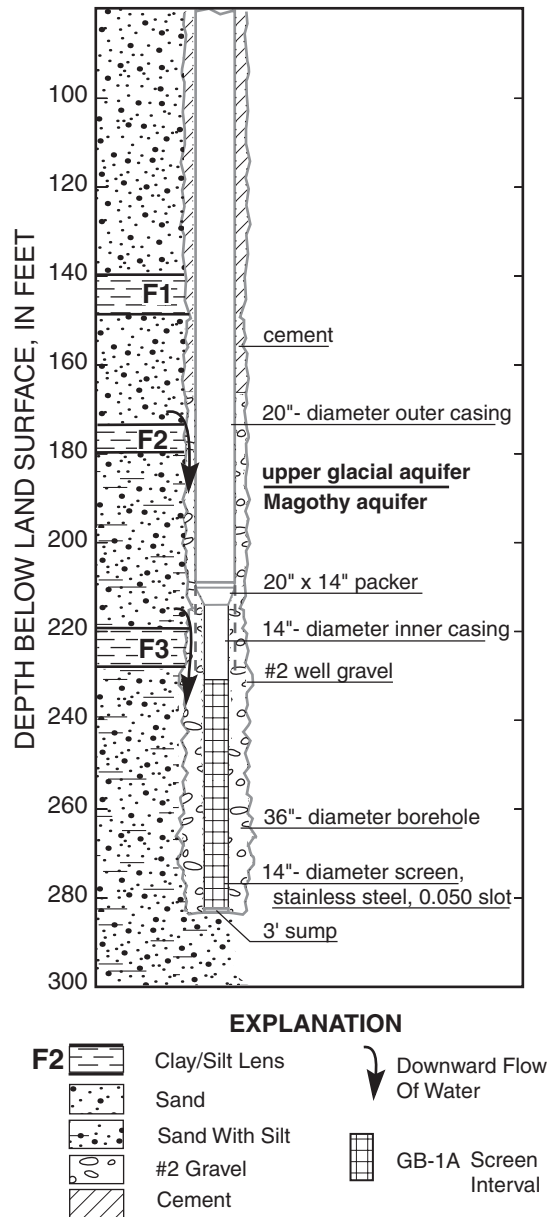
ALL PUMPS OFF (STATIC) GB-1A PUMP ON (PUMPING) PUMP OFF

A. PHOSPHATE (PO_4) DISSOLVED OXYGEN (O_2)

GB-1A, O_2
GB-1A, PO_4
OW-1C, O_2
OW-1C, PO_4

B. DISSOLVED IRON (Fe) AND BICARBONATE (HCO_3)

GB-1A, Fe, dissolved
GB-1A, HCO_3
OW-1C, Fe, dissolved
OW-1C, HCO_3

CONCENTRATION, IN MICROMOLES PER LITER

C. TOTAL ORGANIC CARBON (TOC) AND DISSOLVED ORGANIC CARBON (DOC)

GB-1A, TOC
GB-1A, DOC
OW-1C, TOC
OW-1C, DOC

19   20   21   22
APRIL 1999

DEPTH BELOW LAND SURFACE, IN FEET

100
120
140
F1
cement
160
180   F2
20"- diameter outer casing
upper glacial aquifer
Magothy aquifer
200
20" x 14" packer
220
14"- diameter inner casing
F3
#2 well gravel
240
260
36"- diameter borehole
280
14"- diameter screen, stainless steel, 0.050 slot
3' sump
300

EXPLANATION

F2 Clay/Silt Lens
Sand
Sand With Silt
#2 Gravel
Cement

Downward Flow Of Water

GB-1A Screen Interval

Figure 11. Construction diagram for well GB-1A at Green Belt Parkway wellfield, Holbrook, N.Y., showing gravel-filled annulus that could provide a downward flow path from the upper glacial aquifer through clay unit F3 to the well screen. (Well location is shown in fig. 3.)

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concentrations in samples from GB-1A (fig. 10B) increased during the pumping and may reflect inflow from anoxic, high-iron horizons such as near the screen zone of OW-1C; this trend is consistent with the increase in other reduced species such as ammonium and sulfide during pumping. Bicarbonate concentrations in GB-1A also increased during pumping, possibly from an increase in the percentage of water pumped from shallow depths, such as near the screen zones of OW-1A and OW-1B (fig. 9A), where bicarbonate concentrations are much higher than in the Magothy and (or) in pristine settings (table 4).

Water from the upper glacial aquifer could flow downward to the Magothy aquifer through gaps in the confining units or through coarse parts of the confining unit. The downward flow of shallow ground water could be enhanced by the sand pack around the outside of the screen and casing and the gravel-filled annulus, which continues from around the screen upward to a depth of 215 ft (fig. 11); together, these could provide a direct pathway for water from the upper glacial aquifer to flow downward through clay unit F3.

The $\delta^{13}C$ of DIC and the $\delta^{34}S$ of sulfate generally were measured in the observation wells before the pumping test and in the supply well (GB-1A) at the end of the pumping test. The stable-isotope values were not measured in GB-1A before pumping, but the available $\delta^{34}S$ data were sufficient to identify changes in the contribution of water to GB-1A from the depths represented by the observation-well screens. The $\delta^{13}C$ values of DIC in ground water at the site ranged from -22.4 ‰ to -19.8 ‰ (table 4) and were heavier than the $\delta^{13}C$ of a lignite sample (-22.9 ‰) from 280 ft below land surface (shallow Magothy). The $\delta^{13}C$ of lignite from the intermediate and deep parts of the Magothy aquifer elsewhere in Suffolk County range from -24.3 ‰ to –22.5 ‰ (Brown, Schoonen, and Candela, 2000). The relatively light $\delta^{13}C$ of -22.4 ‰ in DIC from OW-1A may be caused by aerobic heterotrophs, which can deplete ^{13}C through oxidation of organic carbon (Blair and others, 1985). The $\delta^{13}C$ of DIC became enriched with increasing depth in samples from OW-1B (-22.3‰), OW-1C (-21.1‰), and GB-1A (-19.8‰) (fig. 12A). Similar trends in ^{13}C enrichment were observed in the Magothy aquifer in western Suffolk County (Brown, Schoonen, and Candela, 2000) and in deep coastal-plain aquifers in South Carolina and probably result from some form of fractionation associated with lignite oxidation (McMahon and others, 1992). TOC

and DOC, which probably had built up from the oxidation of SOM and detritus released from microbial activity, decreased in all wells during pumping as the organic carbon was evacuated from the vicinity of the redox gradients around well screens.

The $\delta^{34}S$ of sulfate in ground water at the well field ranged from –0.1 ‰ to 6.4 ‰ (table 4). Sulfate in shallow ground water collected from OW-1A during nonpumping conditions had a $\delta^{34}S$ of 6.4 ‰, which is the heaviest of the samples collected and reflects the high $\delta^{34}S$ values in atmospheric deposition (0 ‰ to 20 ‰; Coplen, 1993) and in shallow ground water in areas of recharge on Long Island (13 ‰; Brown, Schoonen, and Candela, 2000). The $\delta^{34}S$ values in ground water from deeper wells (OW-1B and OW-1C) during prepumping conditions indicated a decrease with depth—3.8 ‰ and 2.4 ‰, respectively (fig. 12B). The $\delta^{34}S$ of sulfate in OW-1C increased to 3.3 ‰ after pumping and indicates that sulfate of heavier $\delta^{34}S$ was drawn down from shallower depths by the pumping of GB-1A. Water from well GB-1A, which was sampled only once after the 2-day pumping period, had the lightest $\delta^{34}S$ (–0.1 ‰) and indicates FeS_2 oxidation. The $\delta^{34}S$ of sulfate along a southward flow path farther west in Suffolk County becomes "lighter" with depth through the oxidation of FeS_2, but gradually becomes "heavier" with distance from the recharge area and at depths greater than 350 ft along deep Magothy flow paths as a result of (1) mixing with "heavier" sulfate that originates from seawater anion complexes sorbed in poorly permeable sediments, and (2) sulfate reduction and the subsequent formation of FeS_2 (Brown, 1998). The depths of wells sampled at the Green Belt Parkway site are less than 300 ft below land surface, and the lightest $\delta^{34}S$ value-in water from GB-1A-is equivalent to that at a depth of about 500 ft below the zone of deep recharge in wells in southwestern Suffolk County (Brown, Schoonen, and Candela, 2000). The $\delta^{34}S$ of iron-sulfide cemented sand, which was collected from a depth of 280 ft below land surface at GB-1A, was –41.3 ‰. The $\delta^{34}S$ of iron-sulfide minerals at other depths (intermediate and deep) in the Magothy aquifer elsewhere in Suffolk County ranged widely-from -44.1 ‰ to 10.6 ‰. The $\delta^{34}S$ ranges of iron sulfide minerals typically are "heavy" in isolated aquifer environments, where sulfate reduction and the formation of iron-sulfide minerals leave the remaining sulfate enriched in ^{34}S, which subsequently forms heavy iron-sulfide minerals
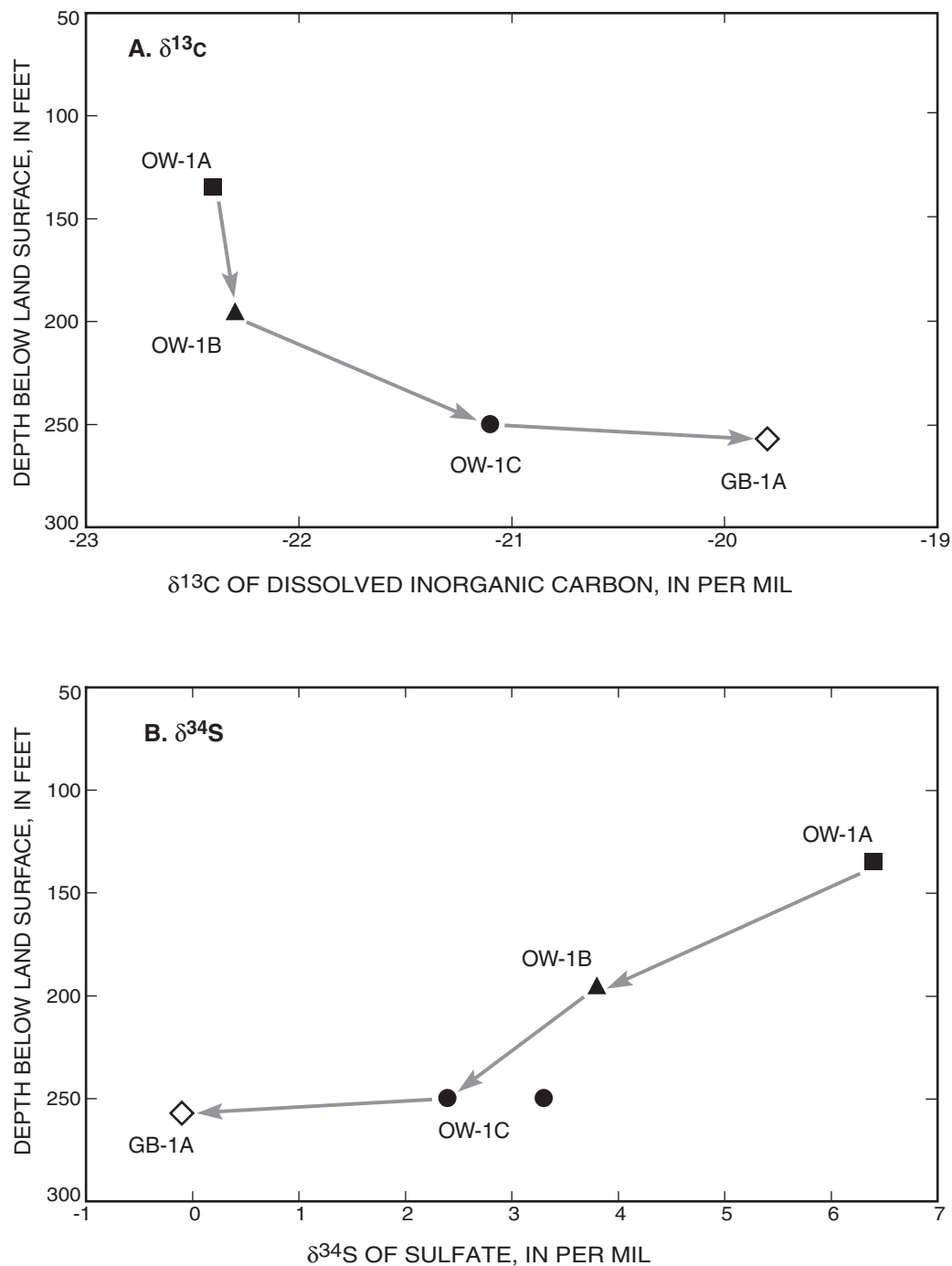
Figure 12. Isotopic composition of water from the Green Belt Parkway well field, Holbrook, N.Y.: A. $\delta^{13}C$ of dissolved inorganic carbon. B. $\delta^{34}S$ of sulfate. (Well locations are shown in fig. 3.)

(Canfield and others, 1992; Brown, Schoonen, and Candela, 2000).

Supply-well pumping in the Magothy aquifer probably causes downward flow of oxygenated water from the upper glacial aquifer and contributes to biofouling at the site by promoting the oxidation of ferrous iron and the growth of iron-oxidizing and heterotrophic bacteria. This is supported by the increased concentrations of oxygen and phosphate in the sample from GB-1A after the 2-day pumping period, despite the locally confined nature of the Magothy aquifer at this site.

CONCLUSIONS

Aquifer lithology, geochemistry, microbiology, and water quality at a new supply well screened in the Magothy aquifer at the Green Belt Parkway well field in Holbrook were studied to help identify factors that can contribute to iron-related biofouling and well-screen encrustation. Concentrations of sedimentary organic matter, and the terminal electron-accepting processes (TEAPs), in core-sample sediments from the screen zone varied from well to well. The principal TEAPs were iron reduction, sulfate reduction, and undetermined (possibly oxic); microbial activity was positively correlated with organic carbon content. Water quality was monitored at the supply well and in nearby observation wells screened in the upper glacial and Magothy aquifers.

Ground-water quality in the supply well (GB-1A) and in an adjacent observation-well cluster indicates that pumping of the supply well can cause downward flow of shallow, oxygenated water from overlying aquifers; this, in turn, probably contributes to iron-related biofouling and well-screen encrustation at the site. Concentrations of dissolved oxygen and phosphate were higher after 2 days of pumping of GB-1A than before the pumping, probably as a result of the downward flow of shallow water, which contains high concentrations of dissolved oxygen and phosphate. The $\delta^{34}S$ of sulfate in the nearby deep observation well (OW-1C) increased from 2.4 ‰ before pumping to 3.3 ‰ after pumping; this confirms that water with heavier $\delta^{34}S$ was drawn down from shallower depths by the pumping of GB-1A. The gravel-filled annulus, which extends from around the screen upwards to a depth of 215 ft, provides a potential flowpath downward through clay unit F3. The increase in the iron concentration of water from GB-1A during pumping may reflect an increased contribution from the deep, anoxic, iron-rich horizons, such as those near the screen zone of well OW-1C. Extended pumping from the Magothy aquifer in April 1999, when water demand was low, had little effect on water levels in the upper glacial aquifer, but the increased water-supply pumping of more than one supply well at a time during the summer could lower water levels in the upper glacial aquifer. The induced downward flow of shallow ground water by intensive pumping probably aggravates iron-related biofouling and well-screen encrustation.

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