Effects and Distribution of Iron-Related Well-Screen Encrustation and Aquifer Biofouling in Suffolk County, Long Island, New York

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FIGURES (continued)

TABLES

CONVERSION FACTORS, ABBREVIATIONS AND VERTICAL DATUM

Multiply	By	To Obtain
	Length	
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day
	Gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer

Other abbreviations used in this report

micrograms per liter (μg/L)
milligrams per liter (mg/L)
liters per minute per meter (L/min)/m

Sea level: 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.

Effects And Distribution of Iron-Related Well-Screen Encrustation and Aquifer Biofouling in Suffolk County, Long Island, New York

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Abstract

The process of iron-related well-screen encrustation and aquifer biofouling has led to significant decreases in the specific capacity of several wells in the Suffolk County Water Authority (SCWA) well network. Iron-related specific-capacity decreases from October 1990 through August 1992 prompted the SCWA to recondition 56 wells and to redrill an additional 3 wells from October 1990 through August 1992. The median decrease in specific capacity for SCWA wells screened in the Magothy aquifer was 3.4 percent per year, and the median decrease for wells screened in the upper glacial aquifer was 2.9 percent per year.

Most Magothy aquifer wells with annual specific-capacity decreases greater than or equal to 5.0 percent are in the southern and central parts of the county; most upper glacial aquifer wells with similar specific-capacity decreases are in the south-central part of the county. Most wells with large specific-capacity decreases are near ground-water-discharge zones along the coast and near streams.

Statistical comparisons of water-quality data from wells with annual specific-capacity decreases of at least 5.0 percent with data from wells having annual decreases of less than 5.0 percent indicated significant differences between the two groups in both aquifers. Water from Magothy aquifer wells with annual specific-capacity decreases of at least 5.0 percent had higher concentrations of total and dissolved iron, total and dissolved manganese, total phosphate, and dissolved sulfate than other Magothy aquifer wells, and lower concentrations of dissolved oxygen, nitrate, total alkalinity, and pH than water from other Magothy aquifer wells. Water from upper glacial aquifer wells with annual specific-capacity decreases of at least 5.0 percent had higher concentrations of total and dissolved manganese and dissolved sulfate, and lower pH, than water from other upper glacial aquifer wells.

Elevated concentrations of total and dissolved iron, total manganese, total phosphate, and dissolved sulfate, and the low concentrations of dissolved oxygen and nitrate, were detected primarily in samples from wells completed in ground-water discharge zones in the Magothy aquifer. Most of the Magothy aquifer wells with low pH were in the southwestern part of the county, and most of those with low total alkalinity were in the western part.

INTRODUCTION

The aquifer system underlying Suffolk County, Long Island, N.Y., (fig. 1) has been designated a sole-source aquifer by the U.S. Environmental Protection Agency. The largest water supplier on Long Island, and the primary water supplier for Suffolk County, is the Suffolk County Water Authority (SCWA). Declines in the specific capacity[1] of several wells in the SCWA well network since about 1970 have forced the SCWA to undertake a costly well-redevelopment and replacement program. The specific-capacity decreases are attributed to well-screen encrustation and biofouling by iron-related bacteria in the ground water, which are associated with elevated concentrations

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[1]Specific capacity of a well is the rate of discharge of the well per unit of drawdown from non-pumping water level.
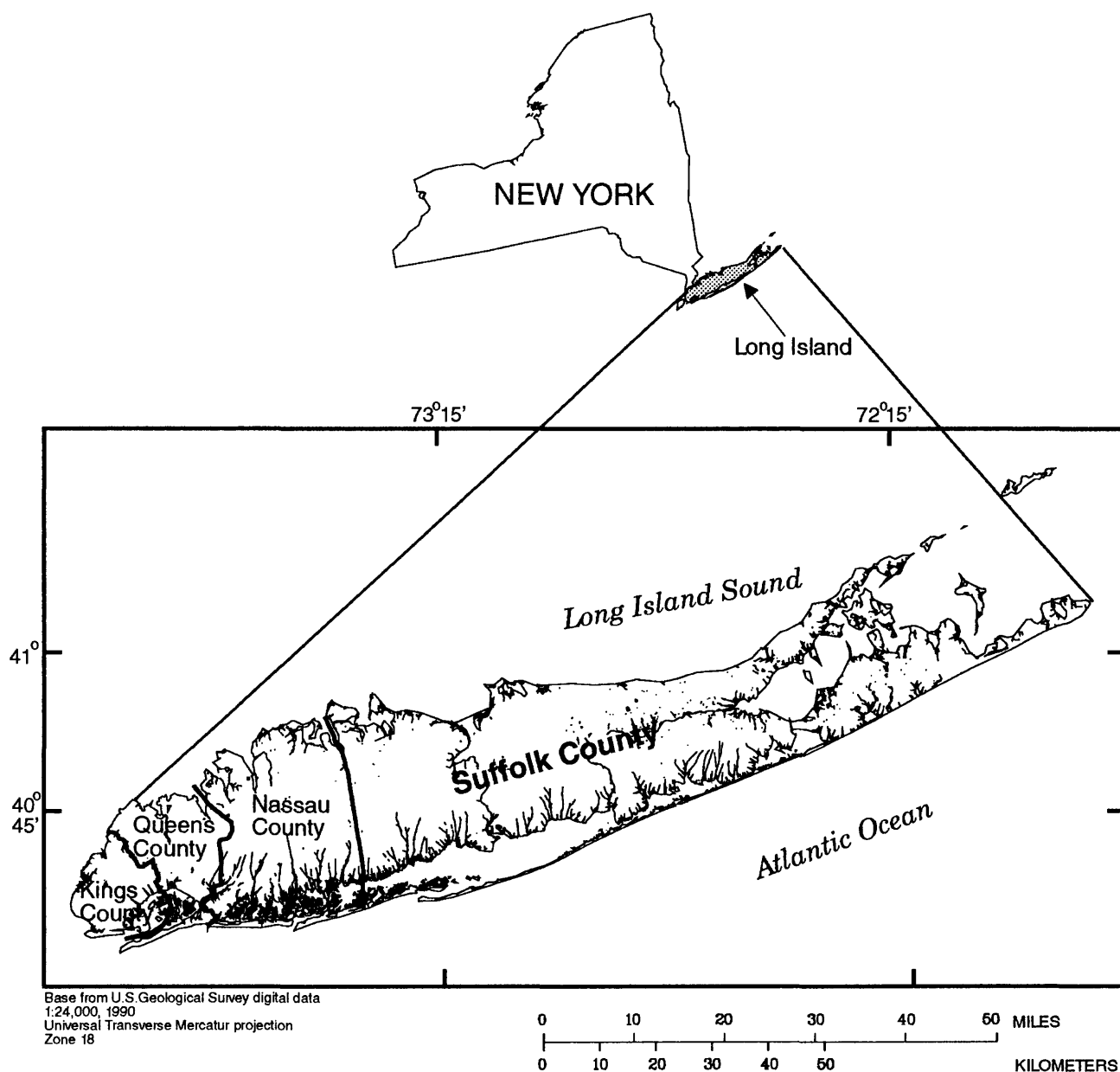
Figure 1. Location of Suffolk County, N.Y.

of iron. (In this report, the term "biofouling" refers to both the abiotic precipitation of ferric oxyhydroxides and the formation of biofilms by iron-oxidizing bacteria on well screens and in the pore spaces of the surrounding aquifer material.)

In 1990, the U.S. Geological Survey (USGS), in cooperation with the SCWA, began a 3-year study of iron-related well-screen encrustation in the two principal aquifers (upper glacial and Magothy) underlying Suffolk County. The investigation consisted of two components—a regional component that assessed the

effects of iron-related production decreases in Suffolk County, and a site-specific component that assessed the geochemical and microbiological processes that contribute to well-screen encrustation and aquifer biofouling. This report discusses the results of the regional component of the study.

Purpose and Scope

This report (1) describes the effects of iron-related well-screen encrustation on supply wells in the

SCWA network, (2) depicts, by aquifer, the spatial distribution of supply wells that have had significant specific-capacity decreases, (3) compares the quality of water from wells that have had large specific-capacity declines with that from wells that have had only small declines, and (4) depicts the spatial distribution of water constituents that could be related to the specific-capacity declines.

Iron-Related Well-Screen Encrustation and Biofouling

Decreases in specific capacity are commonly associated with elevated concentrations of dissolved iron and are attributed to (1) the oxidation of ferrous iron and the subsequent precipitation of iron oxyhydroxides on well screens and in the pore spaces of the gravel pack and the surrounding formation, and (2) the growth of iron-bacteria biofilms on well screens and in pore spaces (Cullimore, 1986). The iron-bacteria biofilms consist primarily of extracellular organic material and ferric oxyhydroxides. The iron-oxidizing bacteria involved in the biofouling process require oxygen and include both heterotrophic and chemoautotrophic species. Chemoautotrophic iron-oxidizing bacteria are able to use CO_2 as a carbon source and derive metabolic energy from the oxidation of ferrous iron. Heterotrophic iron-oxidizing bacteria require an organic carbon source and do not use ferrous iron oxidation as an energy source. Several taxonomic classes of iron bacteria have been identified as important biofouling agents (Cullimore, 1986). The species of iron-oxidizing bacteria in a given biofouled well depends on the physiochemical conditions in the ground water, such as concentrations of dissolved iron and dissolved oxygen, pH, and redox potential.

Iron-oxidizing bacteria grow in the vicinity of steep redox gradients and commonly are found in ground-water seeps and wetlands. A pumped well screened in a reducing environment can create an Eh gradient by mixing oxygenated water with water containing dissolved ferrous iron, and the resulting Eh gradient allows iron-oxidizing bacteria to grow within the zone of mixing around the well screen.

The decrease in specific capacity of wells through iron-related biofouling is of national and international concern (Cullimore, 1986). It can develop in a variety of hydrogeologic environments and is common in unconsolidated sediments such as those underlying Suffolk County (Driscoll, 1987).

Well Locations and Pumpage

The SCWA operated about 430 wells screened in the upper glacial aquifer and the underlying Magothy aquifer in 1992. The number of active wells fluctuates with periodic well shutdowns, abandonment, and the installation of new wells. Of the 430 wells, 216 are screened in the Magothy aquifer and 214 are screened in the upper glacial aquifer. In 1991, the SCWA withdrew 50.1 billion gallons of water for 1.2 million people. Locations of SCWA pumping centers that withdraw water from the Magothy and upper glacial aquifers are shown in figures 2A and 2B, respectively; each pumping center has from 1 to 6 wells.

SCWA pumpage data for 1970-89 were collected from the New York State Department of Environmental Conservation (NYSDEC). The distribution and magnitude of SCWA withdrawals from the upper glacial aquifer during 1970-79 and 1980-89 (fig. 3A, 3B) indicates that the largest withdrawals were in the central and northwestern parts of the county. The distribution and magnitude of withdrawals from the Magothy aquifer during the same periods is shown in figures 4A and 4B. The largest withdrawals from the Magothy aquifer are in the southwestern part of the county.

Pumpage data for 1985-89 from SCWA and other water suppliers in Suffolk County are summarized in table 1. The distribution of ground-water withdrawals from the upper glacial and Magothy aquifers by all water suppliers in Suffolk County during 1985-89 are shown in figures 5A and 5B, respectively.

Table 1. Pumpage by Suffolk County Water Authority and by other water suppliers, Suffolk County, N.Y., 1985-89

[Values are in billions of gallons. SCWA, Suffolk County Water Authority]

Aquifer	Total pumpage	SCWA Total	SCWA Percent	Others Total	Others Percent
Magothy	197,834	160,344	79.2	37,490	20.8
Upper glacial	100,120	79,878	79.8	20,242	20.2

A. Upper glacial aquifer

41°

40°
45'

EXPLANATION

● LOCATION OF SCWA PUMPING CENTER--
One or more Suffolk County Water Authority
public-supply wells screened in the upper
glacial aquifer.

73° 15'   72° 15'

B. Magothy aquifer

41°

40°
45'

EXPLANATION

● LOCATION OF SCWA PUMPING CENTER--
One or more Suffolk County Water Authority
public-supply wells screened in the Magothy
aquifer.

Base from U.S Geological Survey digital data
1:24,000, 1990
Universal Transverse Mercatur projection
Zone 18

0   20 MILES

0   20   KILOMETERS

Figure 2. Location of Suffolk County Water Authority (SCWA) pumping centers, Long Island, N.Y., in (A) upper glacial aquifer, and (B) Magothy aquifer. (Location is shown in fig. 1.)
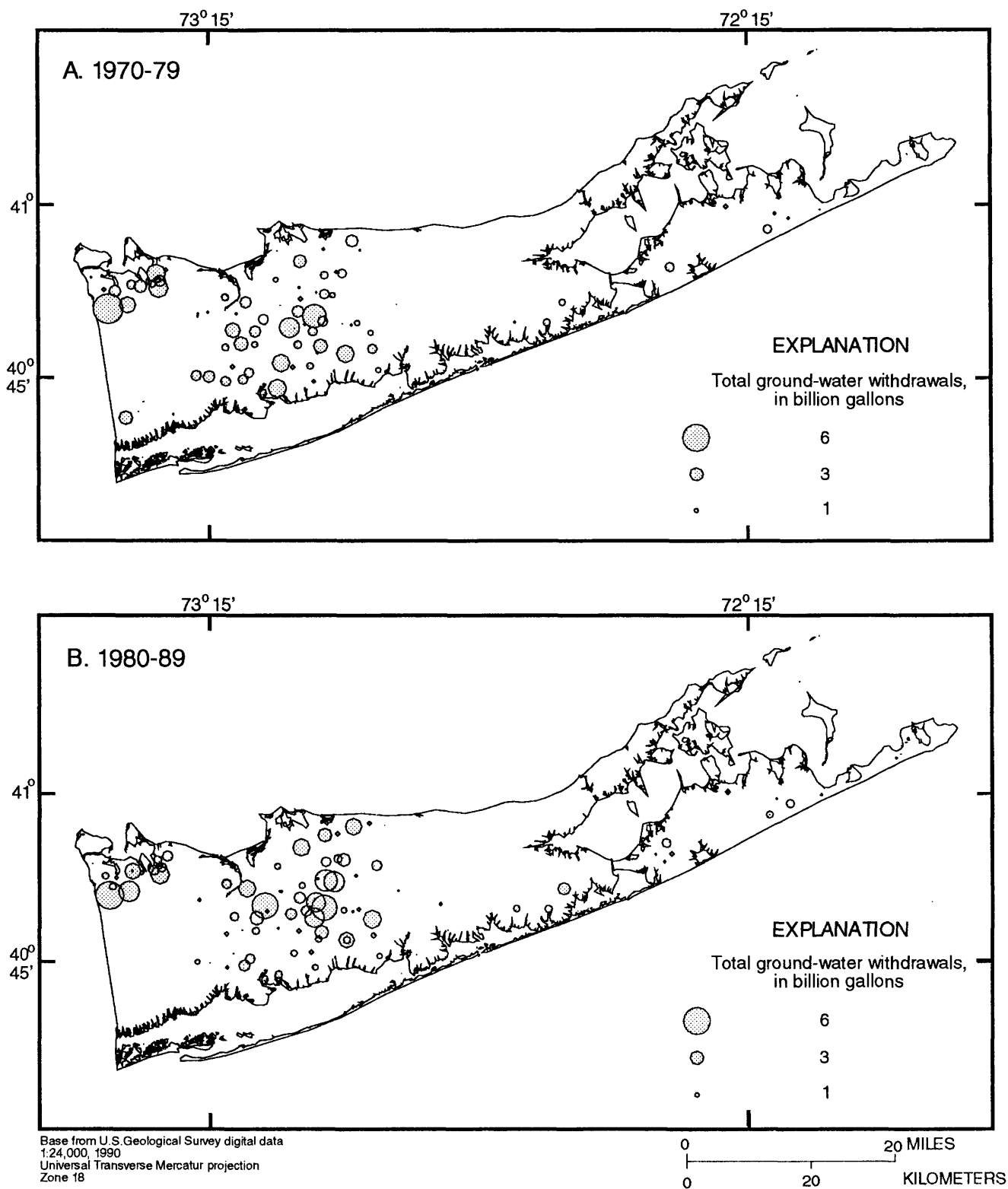
Figure 3. Areal distribution of ground-water withdrawals by the Suffolk County Water Authority from the upper glacial aquifer, Long Island, N.Y., in (A) 1970-79, and (B) 1980-89.
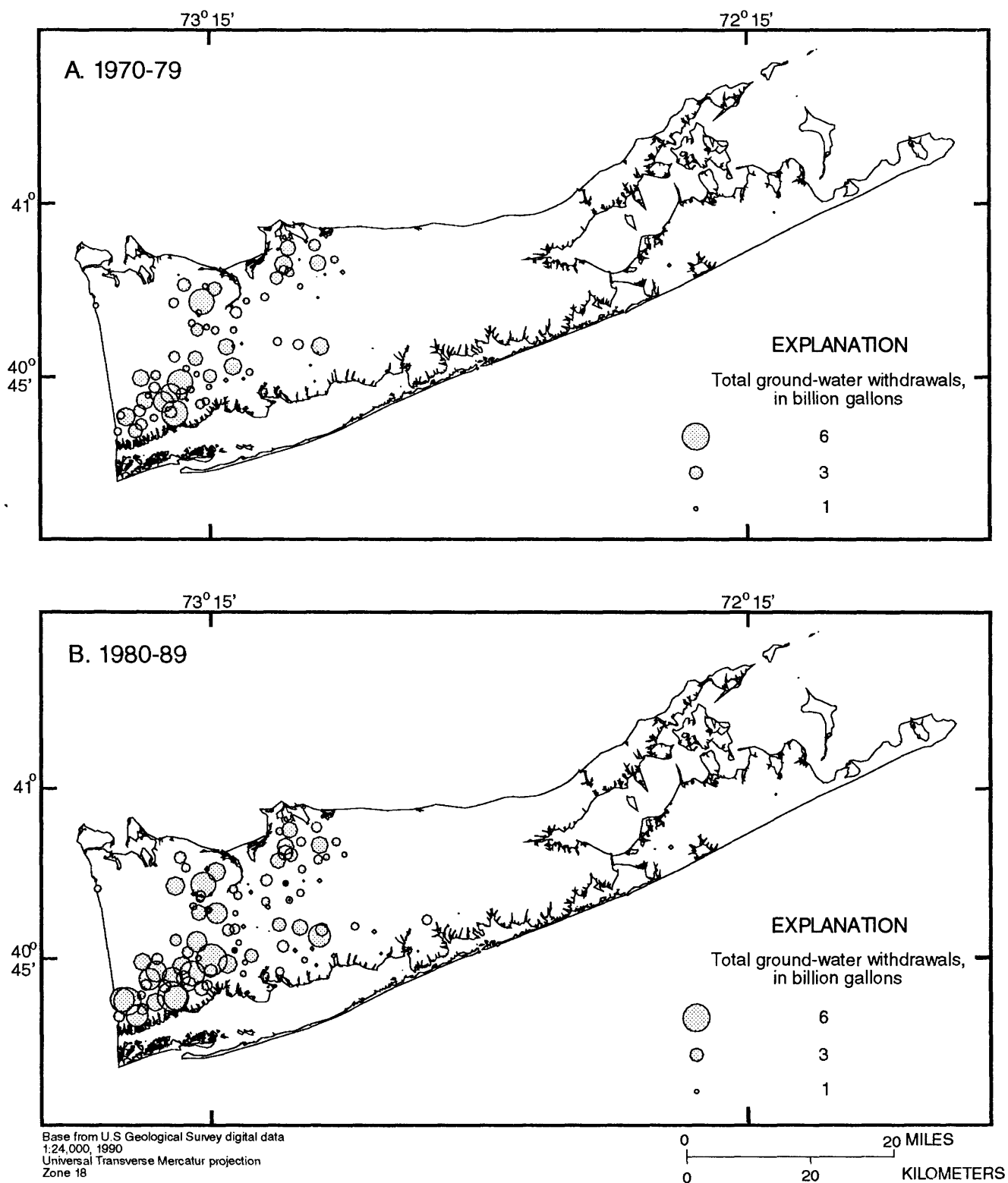
Figure 4. Areal distribution of ground-water withdrawals by the Suffolk County Water Authority from the Magothy aquifer, Long Island, N.Y., in (A) 1970-79, and (B) 1980-89.

A. Upper glacial aquifer

73° 15'   72° 15'

41°

40°
45'

EXPLANATION

Total ground-water withdrawals,
in billion gallons

6

3

1

B. Magothy aquifer

73° 15'   72° 15'

41°

40°
45'

EXPLANATION

Total ground-water withdrawals,
in billion gallons

6

3

1

Base from U.S.Geological Survey digital data
1:24,000, 1990
Universal Transverse Mercatur projection
Zone 18

0   20 MILES

0   20   KILOMETERS

Figure 5. Areal distribution of ground-water withdrawals by all Suffolk County, Long Island, N.Y., water suppliers during 1985-89 from (A) upper glacial aquifer, and (B) Magothy aquifer.

Acknowledgments

HYDROGEOLOGIC SETTING

Long Island lies at the northern extent of the Atlantic Coastal Plain and consists of unconsolidated Pleistocene and Late Cretaceous sediments underlain by Precambrian(?) crystalline bedrock; the bedrock consists of muscovite-biotite schist, gneiss, and granite of Precambrian(?) age (Smolensky and others,

1989). Suffolk County is in the eastern half of Long Island and encompasses about 1,200 mi^2 (fig. 1).

Hydrogeologic Framework

The unconsolidated sediments of Long Island overlie a southeastward dipping bedrock surface and thicken from 0 ft in northwest Queens County to more than 2,000 ft beneath the barrier beach in south-central Suffolk County. The minimum thickness in Suffolk County, about 500 ft, is in the northwestern part of the county.

The unconsolidated sediments consist of Pleistocene till, moraine, and outwash deposits overlying Cretaceous nonmarine and deltaic deposits. Characteristics of the major hydrogeologic units in Suffolk County are summarized in table 2; the stratigraphy of

Table 2. Generalized description of major hydrogeologic units underlying Suffolk County,N.Y.

[Modified from Jensen and Soren, 1971, table 1]

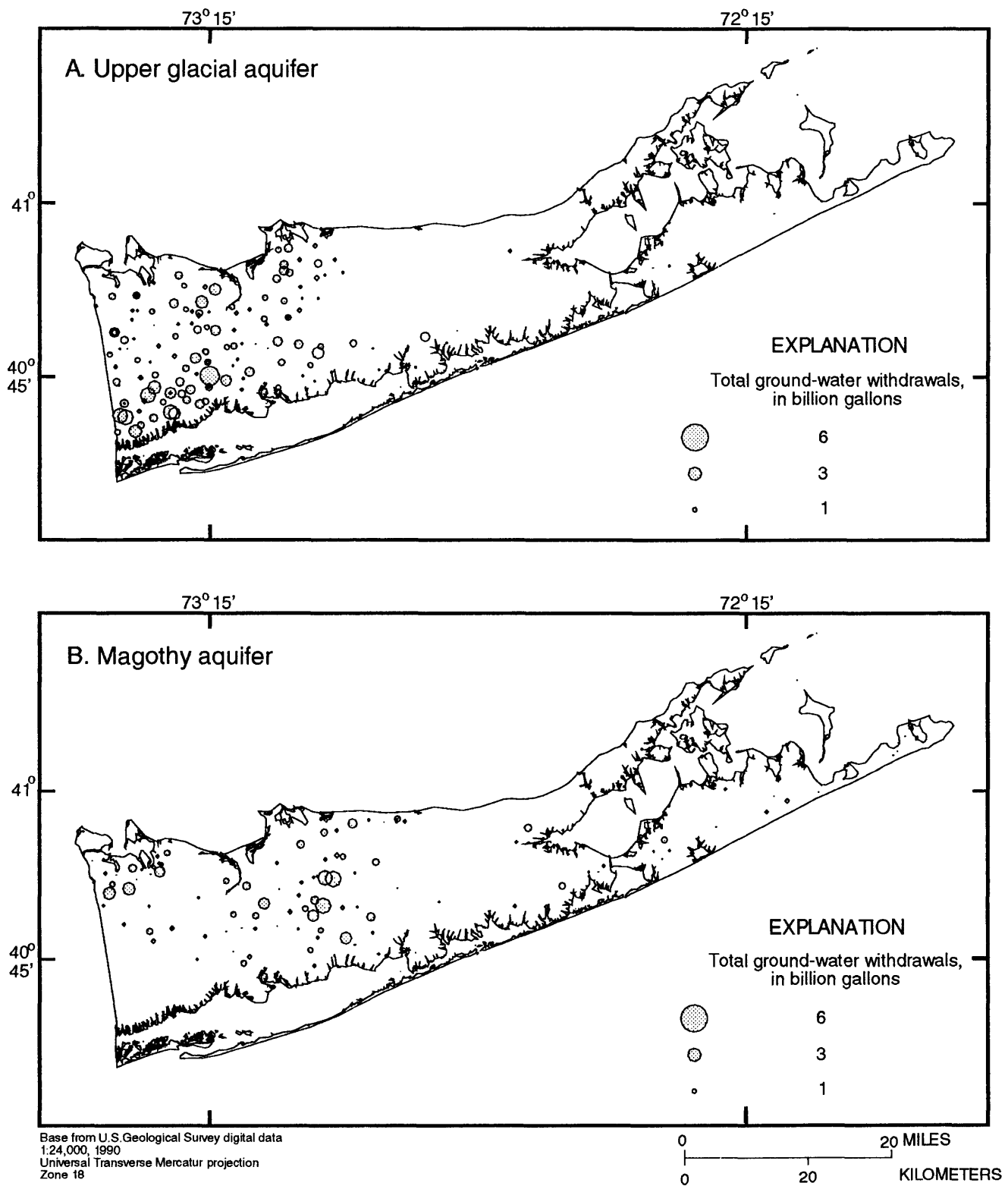| Hydrogeologic unit	Geologic name	Description and water-bearing characteristics
Upper glacial aquifer	Holocene and upper Pleistocene deposits	Mainly brown and gray sand and gravel of moderate to high hydraulic conductivity; also includes deposits of clayey till and lacustrine clay of low hydraulic conductivity. A major aquifer.
Gardiners Clay	Gardiners Clay	Green and gray clay, silt, clayey and silty sand, and some interbedded clayey and silty gravel; low hydraulic conductivity. Unit tends to confine water in underlying aquifer.
Monmouth greensand	Monmouth Group, undifferentiated	Interbedded marine deposits of dark-gray, olive-green, dark-greenish-gray, and greenish-black glauconitic and lignitic clay, silt, and clayey and silty sand. Unit has low hydraulic conductivity and tends to confine water in underlying aquifer.
Magothy aquifer	Matawan Group and Magothy Formation, undifferentiated	Gray and white fine to coarse sand of moderate hydraulic conductivity. Generally contains sand and gravel beds of low to high hydraulic conductivity in basal 100 to 200 feet. Contains much interstitial clay and silt, and beds and lenses of clay of low hydraulic conductivity. A major aquifer.
Raritan clay	Unnamed clay member of the Raritan Formation	Gray, black, and multicolored clay and some silt and fine sand. Unit has low hydraulic conductivity and tends to confine water in underlying aquifer.
Lloyd aquifer	Lloyd Sand Member of the Raritan Formation	White and gray fine-to-coarse sand and gravel of moderate hydraulic conductivity and some clayey beds of low hydraulic conductivity.
Bedrock	Undifferentiated crystalline rocks	Mainly metamorphic rocks of low hydraulic conductivity; surface generally weathered; considered to be the bottom of the ground-water reservoir.

the hydrogeologic units along a generalized north-south section near the boundary between Nassau and Suffolk Counties is shown in figure 6.

Pleistocene Deposits

Upper Pleistocene sediments underlie all of Suffolk County and unconformably overlie Cretaceous deposits. The maximum thickness of the Pleistocene unit in Suffolk County is about 700 ft. The 20-foot clay is present only along the southwestern shore of Long Island and generally is not an important hydrogeologic

unit in Suffolk County. The Smithtown clay is present only in central Suffolk County. The Gardiners Clay extends along the southern shore of most of Long Island; its thickness ranges from 0 to 75 ft (Smolensky and others, 1989).

The upper Pleistocene deposits in northern Long Island consist of sand, gravel, silt, and clay (Smolensky and others, 1989) that form the Harbor Hill and Ronkonkoma terminal moraines (fig. 6). The upper Pleistocene deposits south of the terminal moraines are glacial outwash deposits of sand and gravel with some interbedded silt and clay. The sediments consist
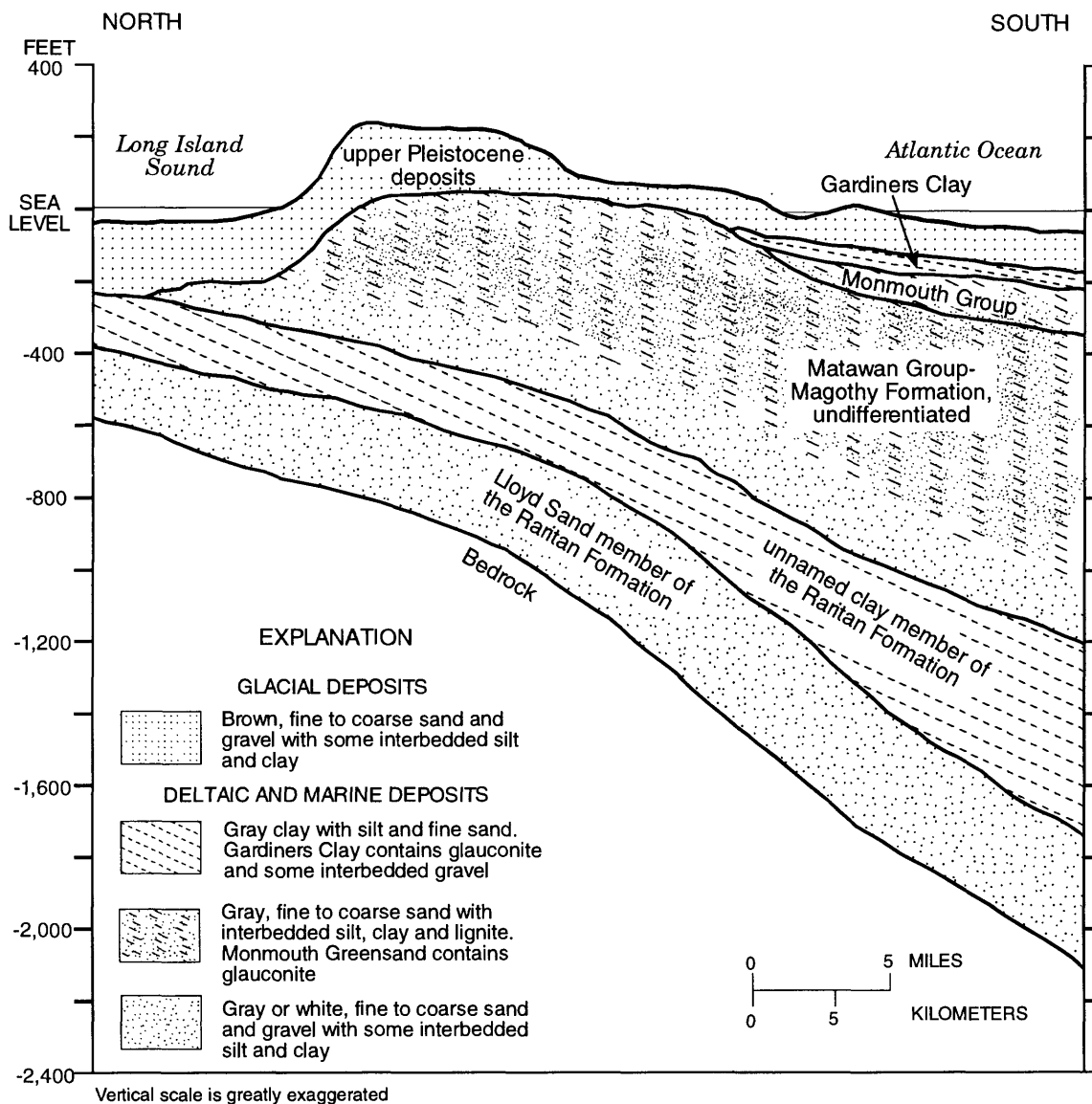

Figure 6. Major hydrogeologic units along a generalized north-south vertical section near the Nassau-Suffolk County border, Long Island, N.Y. (Modified from McClymonds and Franke, 1972, fig. 3.)

of quartz, feldspar, and rock fragments. Iron oxide stains are common. The unit also contains glaciolacustrine clay lenses (Jensen and Soren, 1974).

Cretaceous Deposits

The upper surface of the Matawan Group-Magothy Formation, undifferentiated was severely eroded by meltwater streams before Pleistocene deposition. The unit consists of Late Cretaceous nonmarine and deltaic deposits that were part of a system of coalescing deltas (Smolensky and others, 1989). The Matawan Group-Magothy Formation is absent in northwestern Suffolk County, where it was removed by erosion during the Pleistocene; the northern extent of the unit is indicated in figure 8 (further on). The thickness of the unit in Suffolk County ranges from 0 to 1,100 ft.

The Magothy Formation consists of gray sand and silt interbedded with clay lenses that generally are gray or black. The sand is fine to medium and contains interstitial silt or clay. A zone of coarse sand and gravel forms the base of the unit. The sand consists mainly of quartz and contains lesser amounts of feldspar, biotite, and rock fragments. Lignite is common and is present as beds and disseminated in the sediments. Pyrite and marcasite are common along the southern shore and commonly are present in association with lignite. The Monmouth greensand of Cretaceous age overlies the Matawan Group-Magothy Formation along the southern shore of Long Island. The unit consists of glauconitic marine clays interbedded with greenish-black lignitic and glauconitic silty or clayey sand. Thickness of the unit ranges from 0 to 200 ft (Smolensky and others, 1989).

The upper surface of the underlying Raritan Formation was eroded before deposition of the Matawan Group-Magothy Formation. The Raritan Formation is divided into the unnamed clay and Lloyd Sand members. It is a deltaic deposit with a depositional history similar to that of the Matawan Group-Magothy Formation, undifferentiated (Smolensky and others, 1989) and underlies all of Suffolk County. The unnamed clay member lies conformably on the Lloyd Sand member and ranges in thickness from 0 to 200 ft. The unit consists primarily of clay with interbedded silty sand. Lignite and pyrite are common. The unit is typically gray but can be white or red (Smolensky and others, 1989). The underlying Lloyd Sand member has a maximum thickness of 500 ft. The unit consists of medium to coarse quartz sand and gravel with interbedded gray, white, or red clay and contains thin beds of lignite (Smolensky and others, 1989). The Raritan Formation typically is underlain by a zone of weathered bedrock that has a maximum thickness of 70 ft.

Ground Water

The upper Pleistocene and the Matawan Group-Magothy Formation constitute the upper glacial and Magothy aquifers, respectively. The Lloyd Sand member of the Raritan Formation constitutes the Lloyd aquifer, which is not an important source of potable water in Suffolk County. All but four wells in the SCWA well network obtain their water from the upper glacial and Magothy aquifers; the remaining four wells obtain water from the Lloyd aquifer.

Ground-Water Flow

The upper glacial aquifer is moderately to highly permeable, and the Magothy aquifer is moderately permeable (Smolensky and others, 1989). McClymonds and Franke (1972) reported an average horizontal hydraulic conductivity of 254 ft/d for the upper glacial aquifer in central Suffolk County and 48 ft/d for the Magothy aquifer. Smolensky and others (1989) reported average horizontal hydraulic conductivities of 270 and 50 ft/d for the upper glacial and Magothy aquifers, respectively.

Recharge to the ground-water system is derived solely from precipitation. About 50 percent of total precipitation reaches the water table; the remainder is lost through evapotranspiration and as surface runoff (Warren and others, 1968). Recharge near the coast flows through the upper glacial aquifer in shallow subsystems and discharges to the bays and ocean; farther inland, it enters shallow-flow subsystems that discharge to streams and lakes as well as the surrounding bays and ocean. Precipitation that falls close to the ground-water divide flows downward and recharges the deep aquifers, and water that enters directly at or near the divide flows downward into the Lloyd aquifer. A generalized section showing ground-water-flow patterns in the Long Island aquifer system is shown in figure 7.

The water table is within the upper glacial aquifer throughout Suffolk County. Water in the upper glacial aquifer in central Suffolk County can be locally confined by the Smithtown clay, and water in the Mag-
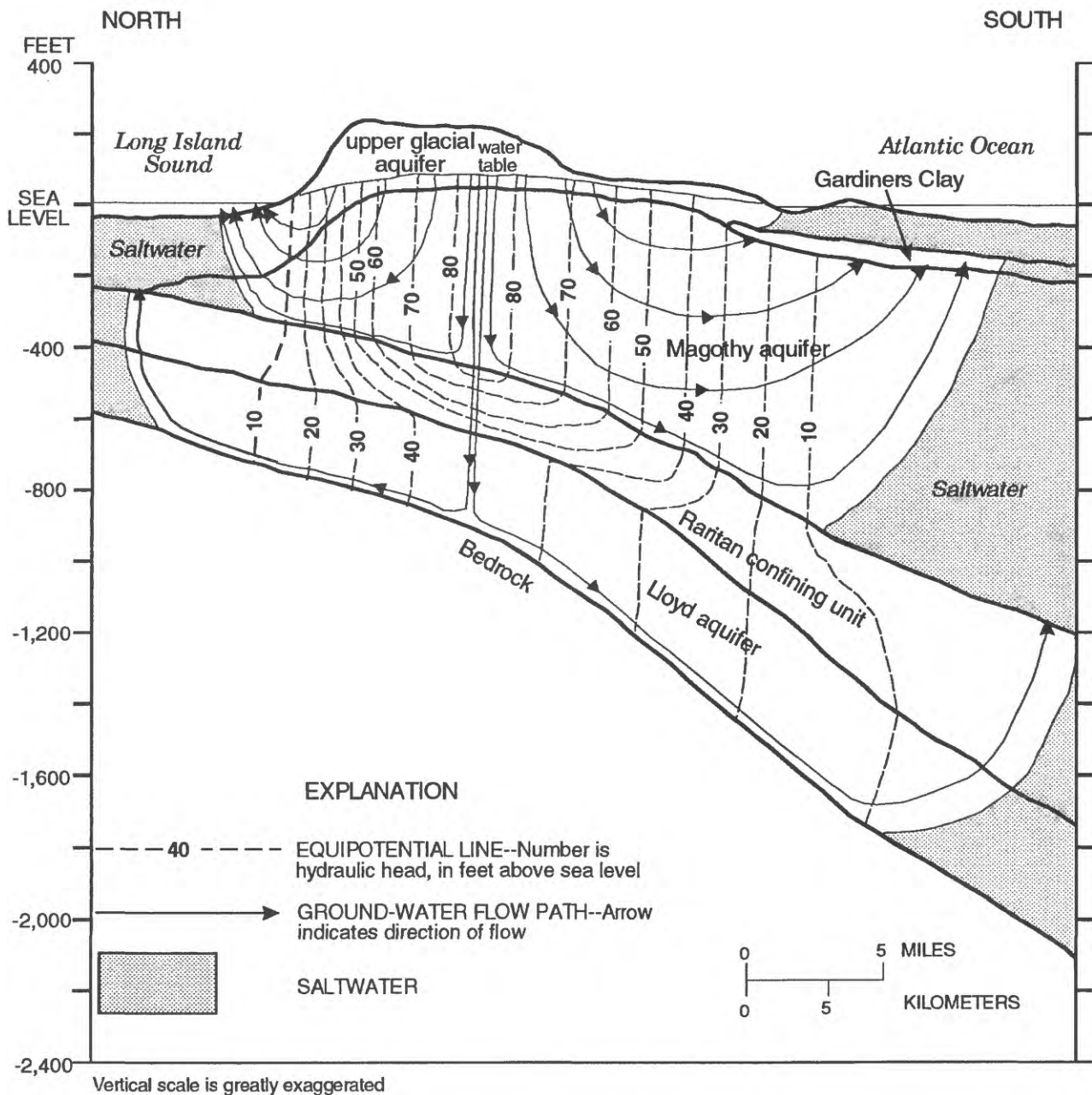
Figure 7. Hydraulic heads and ground-water flow paths along a generalized north-south vertical section near the Nassau-Suffolk County border, Long Island, N.Y. (Modified from Reilly and others, 1983, fig. 4.)

othy aquifer along the southern shore is confined by the Gardiners Clay. Maps of the water table and the potentiometric surface of the Magothy aquifer in March 1991 are shown in figure 8. Mounds in the water table and in the Magothy potentiometric surface are present in western and central Suffolk County. Locations of areas of ground-water recharge and dis-

charge on the main body of Long Island are shown in figure 9. The line separating recharge zones from discharge zones in the Magothy aquifer represents the line along which heads in the upper glacial and Magothy aquifers are equal (the component of vertical flow is zero). In discharge zones, the direction of flow is upward, and water flows from the Magothy aquifer
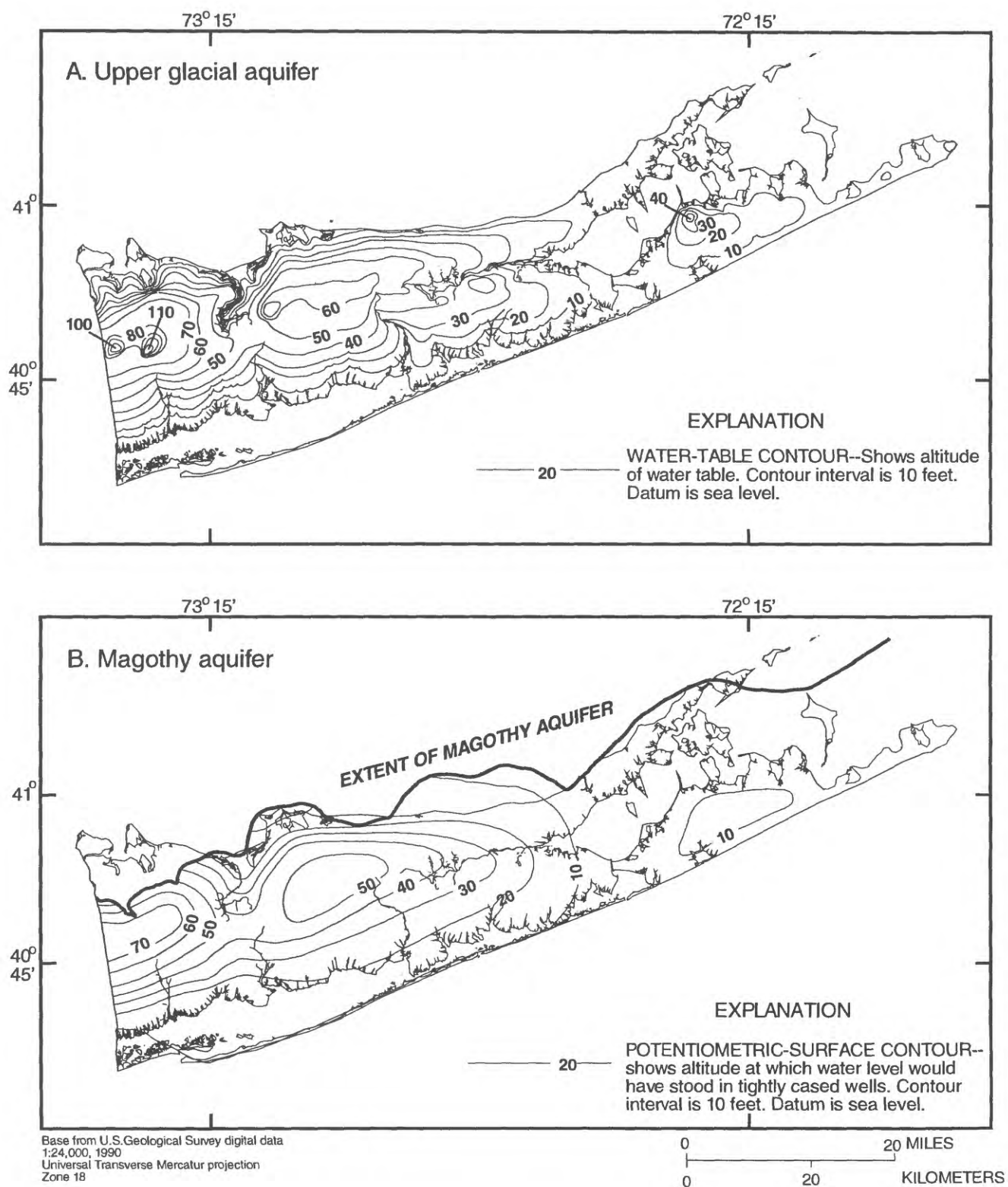
Figure 8. Ground-water levels in Suffolk County, N.Y., March 1991. A. Upper glacial (water-table) aquifer. B. Magothy aquifer.
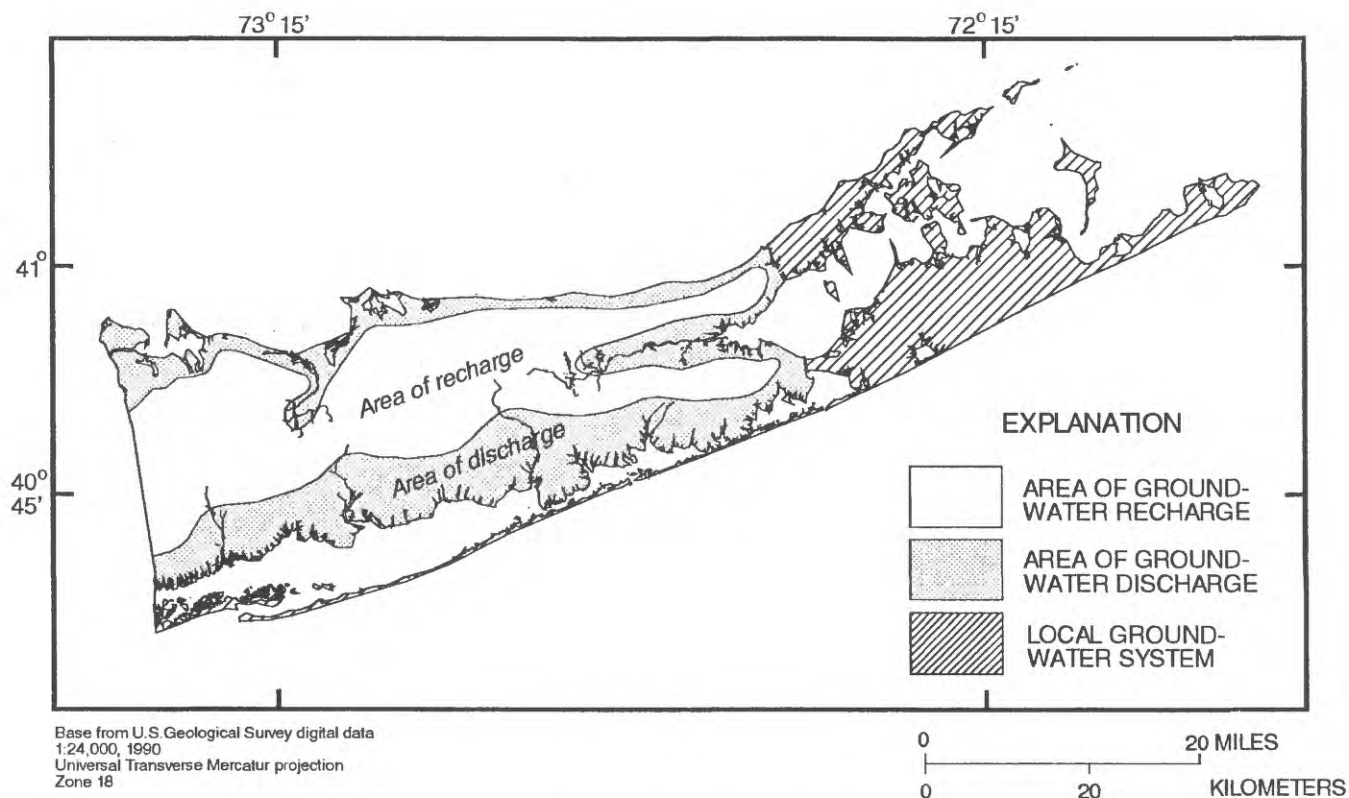
Figure 9. Location of ground-water recharge and discharge areas in Suffolk County, N.Y.

to the upper glacial aquifer. In recharge zones, the direction of flow is downward, and water flows from the upper glacial aquifer to the Magothy aquifer. The locations of the lines indicate that discharge from the Magothy to the upper glacial aquifer occurs primarily along the southern shore and the inland bend between the water-level mounds in the Magothy aquifer.

Ground-Water Quality

Water quality in the upper glacial and Magothy aquifers is affected by natural and human- related processes. Natural (predevelopment) water quality in Long Island's ground-water system reflects the chemistry of natural precipitation, the mineralogy of the aquifer sediments, and prevailing redox conditions in the ground water. As oxygenated water flows through the aquifer from the water table to areas of discharge, O_2 is consumed by the oxidation of organic matter, primarily in the form of lignite, by aerobic bacteria. As oxygen is consumed and conditions become more reducing, nitrate reduction and denitrification occur. After the reduction of nitrate, lignite oxidation, coupled with the

reduction and dissolution of manganese and iron oxide coatings, releases Mn^{2+} and Fe^{2+} into solution; the process of iron oxide reduction is the cause of high-iron environments elsewhere in the Atlantic Coastal Plain (Chapelle and Lovley, 1992). Depletion of available iron oxide allows the reduction of sulfate to sulfide and the subsequent precipitation of authigenic pyrite (FeS_2). Pyrite is commonly found in association with lignite in fine-grained Magothy aquifer sediments along the southern shore of the island (Steven Colobufo, Suffolk County Water Authority, oral commun.). The oxidation of authigenic pyrite can also be a cause of high-iron environments in the Magothy aquifer; the predominant geochemical processes governing water quality in the Magothy aquifer in Maryland are discussed in Knobel and Phillips (1988).

Native (predevelopment) water quality is difficult to characterize because (1) the effects of human activities are evident in most parts of the upper glacial and Magothy aquifers, and (2) geochemical conditions vary locally, and those in areas of ground-water recharge differ from those in areas of discharge. Native water as described by de Laguna (1964),

Eckhardt and others (1988), and Pearsall (1996) is summarized in table 3. De Laguna (1964) summarized native quality of ground water in the upper gla-

Table 3. Native water quality in Suffolk County, N.Y., as indicated by data from three previous studies

[All values are medians; concentrations are in milligrams per liter; <, less than; dashes indicate no data]

Constituent or characteristic	Data source		
	de Laguna (1964)[1]	Eckhardt and others (1988)[2]	Pearsall (1996)[3]
Iron (dissolved)	--	<0.05	<0.05
Manganese (dissolved)	--	<.05	<.05
Calcium	2.0	4.0	1.2
Magnesium	1.5	1.6	0.6
Sodium	4.0	5.0	3.3
Potassium	.6	.8	.4
Nitrate	.50	.24	.20
Sulfate	8.0	9.0	1.6
Phosphate	--	0.02	--
Chloride	5.0	8.3	4.0
Alkalinity (as $CaCO_3$)	7.0	7.0	6.0
pH (units)	6.0	--	--
Dissolved solids	36	70	25

[1] Upper glacial aquifer in central Suffolk County.
[2] Upper 40 feet of upper glacial aquifer in eastern Suffolk County.
[3] Lower Magothy aquifer in Suffolk County.

cial aquifer in central Suffolk County; Eckhardt and others (1988) summarized the effects of land use on water quality at wells screened within 40 ft of the water table in several areas; and Pearsall (1996) compared the amounts of several major ions derived from human activities in ground water from residential areas with those in ground water from agricultural areas. The data from Pearsall (table 2) are from the lower part of the Magothy aquifer in areas of ground-water recharge in central Suffolk County, and are assumed to be representative of predevelopment conditions.

Data assembled from the USGS WATSTORE database were used to determine the ranges and median concentrations of several constituents that could be related to biofouling in the Magothy and upper glacial aquifers (table 4); the methods used in assembling the data are described further on. The values in table 4 represent only the median values of concentrations stored in the WATSTORE database and thus might not be representative of the true median concentrations at a given well.

IRON-RELATED WELL-SCREEN ENCRUSTATION AND AQUIFER BIOFOULING

Iron-related well-screen encrustation and biofouling of wells has necessitated the routine recondi-

Table 4. Ranges and median concentrations of selected constituents from NWIS[1] data base for Magothy and upper glacial aquifers, Long Island, N.Y.

[All concentrations are in milligrams per liter; <, less than]

Constituent or characteristic	Magothy aquifer			Upper glacial aquifer		
	Minimum	Median	Maximum	Minimum	Median	Maximum
Total iron	<0.01	0.27	8.5	<0.01	0.15	40
Dissolved iron	<.003	.08	8.8	<.003	.2	40
Total manganese	<.01	.02	.52	<.01	.03	11
Dissolved manganese	<0.00	.01	.86	<.001	.06	22
Dissolved sulfate	<.2	3.0	72	<.2	12	2,600
Nitrate (as N)	<.01	.08	8.7	<.01	2.2	49
Total phosphate	<.10	.13	2.0	<.06	.03	37
Dissolved oxygen	<.3	3.1	12	<1.0	7.0	12
Total alkalinity	1	10	63	1	13	325
pH (units)	4.7	6.0	8.5	4.4	6.0	8.6

[1] U.S. Geological Survey National Water Information System

tioning, redrilling, and replacement of affected wells. From October 1990 through September 1992, the SCWA abandoned and replaced 12 wells, reconditioned 56 wells, and redrilled 3 wells.

The most common reconditioning procedure is to (1) remove the pump and treat the screen with sulfamic acid, which remains in the casing for 72 hours, (2) surge the well to remove encrusting and biofouling material, (3) pump the well until all acid has been removed and ambient water quality is observed, and (4) test the specific capacity to ensure that recovery has been successful. Poor recoveries require a second acid treatment. If recovery is sufficient, the pump column is steam cleaned and replaced, and the well operation is resumed. If the recovery is inadequate, well casings may be removed, and the borehole redrilled to remove biofouled gravel packs.

Effect of Iron Biofouling on Specific Capacity of Wells

The specific capacity (Sc) of a well is a function of the hydraulic conductivity of the surrounding gravel pack and formation, the well-screen slot size, well diameter, and flow rate. The Sc is determined by the equation

$$Sc = Q/\Delta h,$$

where Q is the discharge of the well (volume per time unit) and Δh is the change in head. Specific capacity commonly is given in units of gallons per minute per foot of drawdown. Initial specific-capacity measurements are made after the installation of new wells, and subsequent measurements are made annually to monitor well efficiency. Wells with a rapidly declining specific capacity are selected for reconditioning. In this study, specific-capacity measurements for 357 of the SCWA's wells through 1990 were obtained from the SCWA Engineering Department (data from an additional 52 wells were incomplete) and used to calculate average specific-capacity declines. The medians, means, standard deviations, and ranges of initial specific capacities for the upper glacial and Magothy aquifer wells, and specific-capacity decreases, are presented in table 5.

The initial specific capacity of a well is a function of the hydraulic conductivity of the gravel pack and the surrounding formation before any biofouling of the screen and gravel pack. Histograms showing the

Table 5. Specific-capacity data from 357 Suffolk County Water Authority wells, Suffolk County, N.Y.,1990-92

[Sc, specific capacity; Sc values are in gallons per minute per foot of drawdown]

Statistic	Magothy aquifer (200 wells)			Upper glacial aquifer (157 wells)		
	Initial Sc	Percent total decrease	Percent annual decrease	Initial Sc	Percent total decrease	Percent annual decrease
Mean	44.5	21	3.4	61.5	24	3.0
Median	41.2	20	1.4	51.3	22	1.5
Minimum	8.3	-48	-16	5.4	-33	-5.5
Maximum	150	69	47	229	85	33
Standard deviation	18.9	21	7.6	37.3	23	4.9

statistical distribution of initial specific capacities of 157 wells screened in the upper glacial aquifer and 200 wells screened in the Magothy aquifer are shown in figures 10A and 10D. The data indicate that initial specific capacities of wells screened in the upper glacial aquifer were higher and had a wider range than those of wells screened in the Magothy aquifer; the higher hydraulic conductivity of the upper glacial aquifer could be the reason.

Decreases in specific capacities of the wells were calculated from current and initial specific-capacity data. For wells with a history of reconditioning, specific-capacity changes between each reconditioning procedure were averaged. The statistical distribution of specific-capacity decreases in the Magothy and upper glacial aquifers is shown in figures 10B and 10E. Decreases of less than 0 percent (negative values in the graphs) indicate specific-capacity increases and can be attributed to the removal of fine particles by continued pumping of the wells or to corrosion of the well screens and the subsequent widening of screen slots. A total of 23 Magothy aquifer wells and 18 upper glacial aquifer wells had specific-capacity increases. The percentage of wells with specific-capacity increases is 12 percent for both aquifers.

The data show that total specific-capacity decreases in both aquifers ranged widely and had similar mean and median values. Specific-capacity decreases in the upper glacial aquifer ranged from 0 to 85 percent. The median decrease was 22 percent, the mean decrease was 24 percent, and the standard deviation was 23. Specific-capacity decreases in the Magothy aquifer ranged from 0 to 69 percent. The median
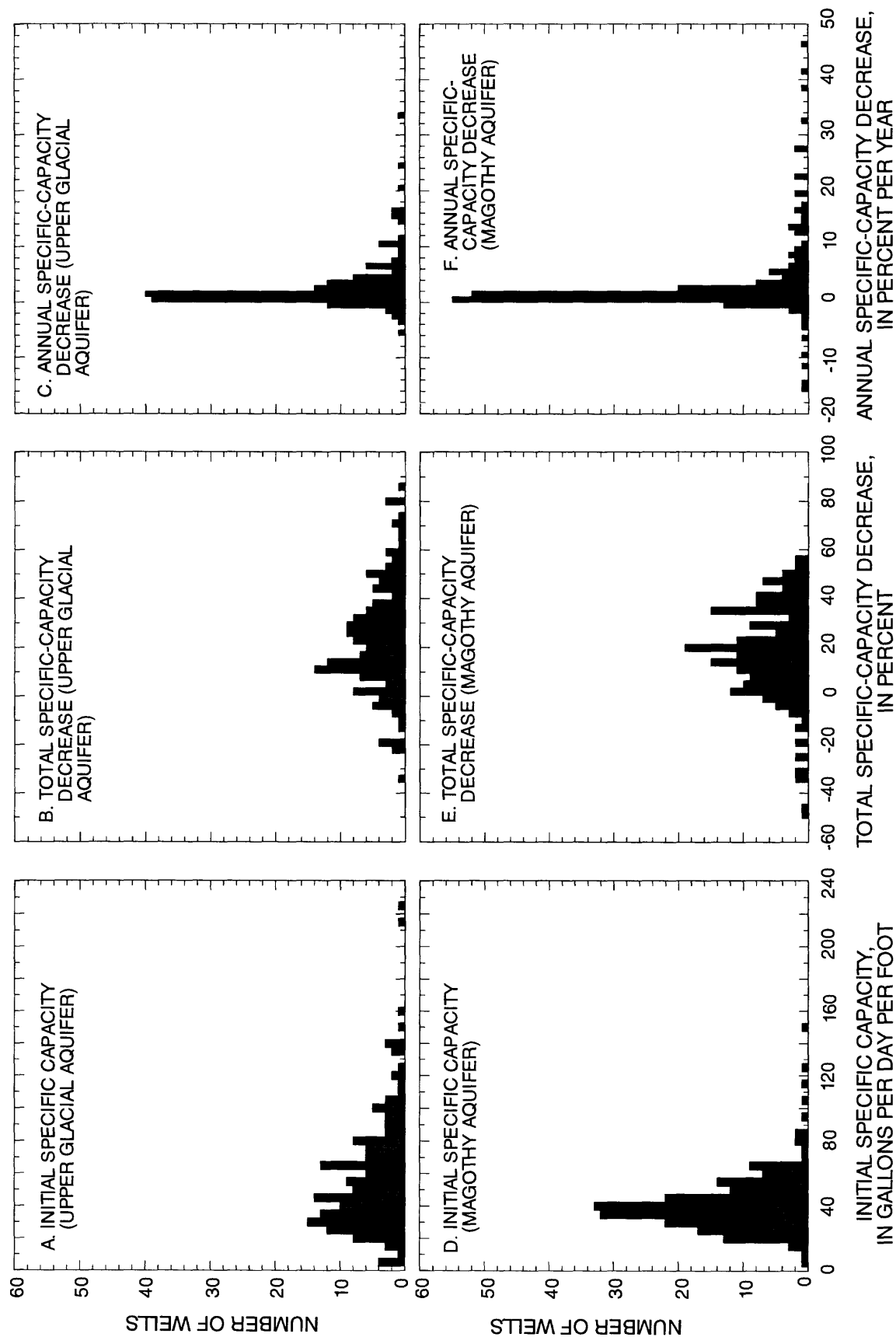
Figure 10. Distribution of specific-capacity data for the upper glacial and Magothy aquifers, Suffolk County, N.Y.: A, D. Initial specific-capacity values. B, E. Total specific-capacity decreases. C, F. Mean annual specific-capacity decreases.

and mean for specific-capacity decreases in the Magothy aquifer were 20 and 22 percent, respectively, and the standard deviation was 21.

The average annual specific-capacity decreases of the 357 wells were estimated by normalizing total specific-capacity decreases to operating time. The statistical distribution of annual specific-capacity decreases (in percent) for the two aquifers is shown in figures 10C and 10F. Annual specific-capacity decreases for upper glacial aquifer wells ranged from -5.5 to 33 percent per year; the median and mean annual decreases were 3.0 and 1.5 percent, respectively, and the standard deviation was 4.9. Annual decreases in the Magothy aquifer ranged from 0 to 47 percent; the median and mean annual decreases were 1.4 and 3.4 percent, respectively, and the standard deviation was 7.6. The histograms (fig. 10) indicate that the annual rates of specific-capacity decrease were similar in both aquifers.

In this study, an average annual specific-capacity decrease of 5 percent was used to separate "unaffected" wells from "affected" wells. The 5.0-percent value is based on the statistical distribution of specific-capacity decreases (figs. 10E, 10F). Annual decreases greater than 5.0 percent are assumed to differ significantly from the remaining population; the percentage of upper glacial and Magothy aquifer wells with average annual specific-capacity decreases between 0 and 5.0 percent was 73 and 70 percent, respectively. Of the 200 Magothy aquifer wells, 37 (19 percent) had annual specific-capacity decreases greater than 5.0 percent, and, of the 157 upper glacial aquifer wells, 25 (16 percent) had annual specific-capacity decreases greater than 5.0 percent.

Spatial Distribution of Affected Wells

The specific-capacity data were entered into a Geographic Information System (GIS) data base, which was then used to identify spatial trends among wells with large annual specific-capacity decreases (greater than 5.0 percent per year). The spatial distribution of affected wells and of chemical constituents related to biofouling could be useful in future well siting. The locations of Magothy aquifer and upper glacial aquifer wells with annual specific-capacity decreases greater than and less than 5 percent per year are shown in figure 11; locations of other water suppliers' wells in western Suffolk County are included to

compensate for the lack of data in the west-central part of the county. The other water suppliers have reported no iron-related specific-capacity declines; thus, their wells are classified as unaffected.

Upper glacial aquifer wells with an average annual specific-capacity decrease of greater than 5.0 percent per year are mostly in south-central Suffolk County (fig. 11A). Their location between the water-table mounds delineated in figure 8A suggests that affected upper glacial aquifer wells are associated with ground-water discharge zones. The distribution of affected upper glacial aquifer wells is similar to that of affected Magothy aquifer wells. Few SCWA wells are screened in the upper glacial aquifer in the populated sections of southwestern Suffolk County, where several Magothy aquifer wells are affected.

Magothy aquifer wells with specific-capacity decreases greater than 5.0 percent per year are mostly along the southern shore and in central Suffolk County (fig. 11B). Many of the affected Magothy aquifer wells in central Suffolk County are between the two ground-water mounds in the Magothy aquifer, in or near the area of ground-water discharge shown in figure 9. Magothy aquifer wells classified as unaffected are distributed throughout the western half of the county, whereas most of the affected wells are primarily in south-shore discharge zones. The geochemical reasons for this are discussed later.

Relation of Ground-Water Quality to Specific-Capacity Decreases

Water-quality data bases were assembled to evaluate water-quality differences between unaffected and affected wells. SCWA wells that had annual specific-capacity decreases of less than 5 percent and a history of reconditioning were included with the affected-well group. This classification resulted in a total of 64 affected Magothy aquifer wells and 46 affected upper glacial aquifer wells. Data bases for unaffected and affected wells were assembled from the National Water Information System (NWIS) data base. A total of 5,119 analyses were assembled for unaffected and affected Magothy aquifer wells, and 3,999 analyses were assembled for unaffected and affected upper glacial aquifer wells. Medians for the selected water-quality constituents were computed for each well. Medians for wells with censored data were computed by using the computer program AUTOMDL
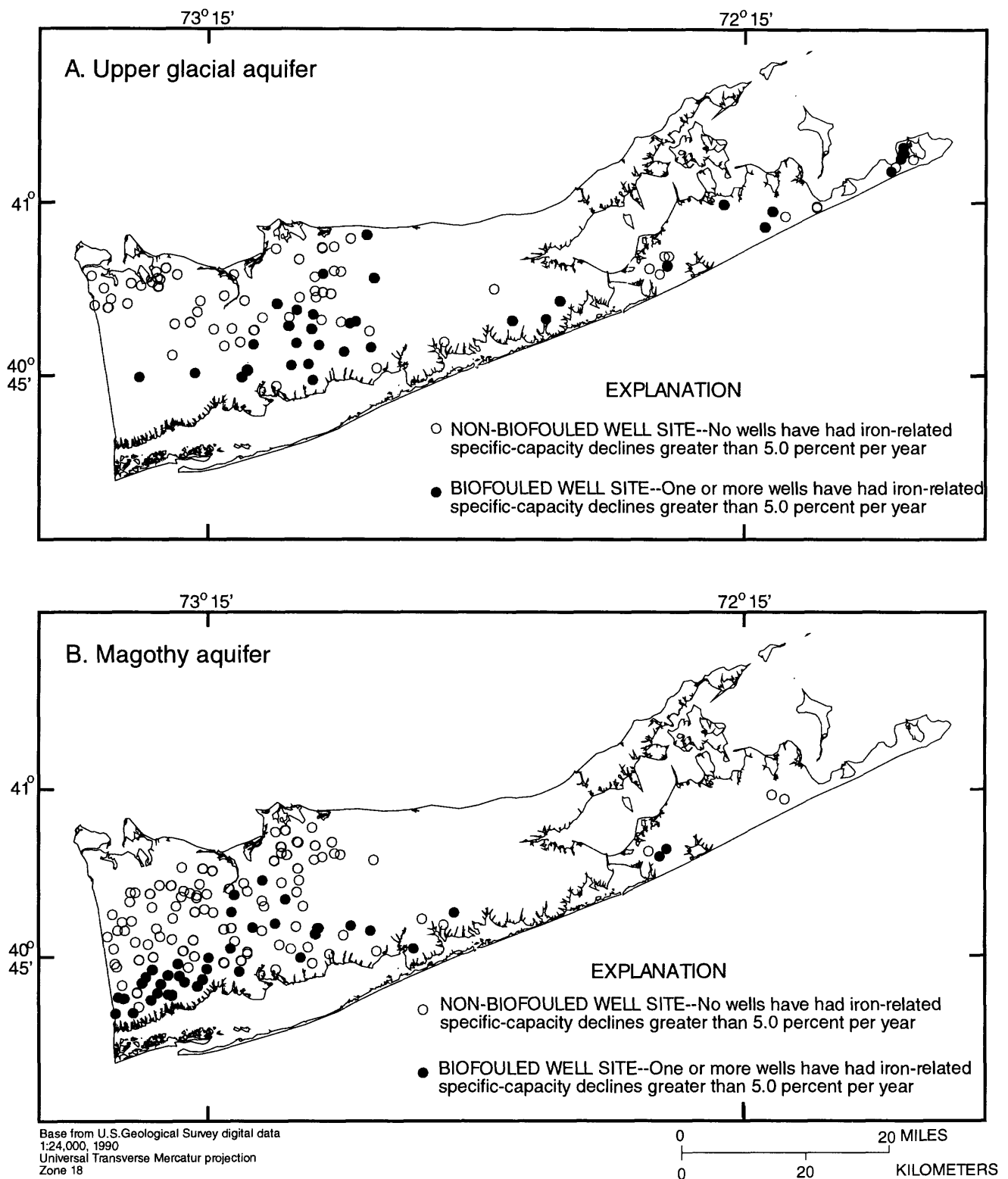
Figure 11. Areal distribution of wells with iron-related specific-capacity declines in Suffolk County, N.Y., in (A) upper glacial aquifer, and (B) Magothy aquifer.

(Helsel and Cohn, 1988), which uses log-probability regression and maximum-likelihood methods to compute descriptive statistics for data sets containing multiple detection limits. Wells for which reliable medians could not be computed were omitted from the data sets. The nonparametric Mann-Whitney rank sum test was used to test for differences between unaffected and affected wells. A p-value (α) of 0.05 was used to identify significant statistical differences between the two groups of wells for each constituent at a confidence interval of 95 percent. Wherever the number of nondetections exceeded 30 percent in either group, additional tests were done with contingency tables, which provide a measure of association between variables.

Results of the statistical tests for affected and unaffected upper glacial aquifer wells are presented in table 6A. Statistically significant differences between unaffected and affected wells were found only for total and dissolved manganese, dissolved sulfate, and pH. The Mann-Whitney p-values for the remaining constituents were less than 0.05, indicating no statistical differences in total and dissolved iron, nitrate, phosphate, total sulfate, and field alkalinity between the two groups of upper glacial aquifer wells.

Results of the statistical tests for unaffected and affected Magothy aquifer wells are summarized in table 6B. All constituents tested differed significantly between the two groups of wells, and Mann-Whitney tests gave p-values less than 0.00001 (which indicates significant differences between unaffected and affected wells) for total iron, total manganese, nitrate, sulfate, dissolved oxygen, and pH. Tests for dissolved iron and total field alkalinity gave p-values of 0.001 and 0.0001, respectively. The largest p-values were for phosphate and dissolved manganese (0.002 and 0.0179, respectively); p-values from contingency tables for these constituents were less than 0.001 and less than 0.05, respectively. Medians for the constituents in the two groups of wells screened in the Magothy are included in table 6B.

The difference in concentration of a particular constituent between unaffected and affected wells is not necessarily due to the biofouling process. Average specific-capacity decreases greater than 5 percent per year at wells in discharge zones could cause spurious correlation between large specific-capacity decreases and high concentration of constituents found naturally in discharge zones even without a direct relation. The spatial distributions of major constituents and their

possible role in the biofouling process are discussed in the next section.

Spatial Distribution of Selected Chemical Constituents and Properties

Water-quality data for 1970-90 on constituents of possible significance to the biofouling process were assembled from the WATSTORE data base. The assembled data include 13,632 analyses from 858 observation wells and supply wells screened in the upper glacial aquifer and 8,706 analyses from 356 observation wells and supply wells screened in the Magothy aquifer. All data were collected and analyzed by the USGS or by laboratories in Suffolk County that follow recommended sampling procedures and participate in USGS quality-assurance programs. Medians were computed for each individual well and entered into a GIS data base. Medians for wells with censored data were computed through AUTOMDL. Wells for which reliable medians could not be computed were omitted from the GIS data bases. Additional data on total iron and manganese were obtained from the SCWA test-boring program and used to construct an additional GIS data base. Water-quality analyses for an additional 330 test zones from 119 test boreholes were assembled. A total of 265 water-quality data points were added to the Magothy data base, and 65 data points were added to the upper glacial data base. The GIS data bases were used to identify spatial trends of major constituents. No clear spatial trends were observed in data from the upper glacial aquifer. Maps showing the distribution of selected constituents in the Magothy aquifer are shown in figures 12A-12H. The importance of the geochemical processes discussed below, particularly in relation to iron, manganese, oxygen, phosphorus, sulfate, and pH in the biofouling process in Suffolk County, is addressed in a companion report describing the site-specific component of the study (Walter, in press).

Iron

Total or unfiltered iron concentrations greater than 0.5 mg/L in wells screened in the Magothy aquifer (fig. 12A) are found primarily along the southern shore and in central and east-central Suffolk County; dissolved-iron concentrations above 0.25 mg/L follow

Table 6. Statistical summary of water-quality data from unaffected and affected wells in Suffolk County, N.Y.

[Median values of values of all constituents in milligrams per liter; <, less than; >, greater than; dashes indicate no data]

Constituent or characteristic	Unaffected wells		Affected wells		Mann-Whitney p-value	Chi-squared p-value
	Number of wells	Median	Number of wells	Median		
A. UPPER GLACIAL AQUIFER						
Total iron	101	0.015	43	0.014	0.7683	--
Dissolved iron	11	0.005	17	0.007	0.3486	>0.1
Total manganese	87	0.004	42	0.020	<0.00001	--
Dissolved manganese	11	0.003	15	0.030	<0.00001	<0.001
Dissolved sulfate	108	6.70	45	9.35	0.0006	--
Nitrate	108	1.507	45	2.36	0.1379	--
Total phosphate	61	0.042	21	0.027	0.2362	>0.1
Dissolved oxygen	13	10.00	19	9.40	0.7735	--
Total alkalinity	83	14.00	38	13.00	0.1267	--
pH (units)	83	6.20	38	6.00	0.0126	--
B. MAGOTHY AQUIFER						
Total iron	128	0.023	60	0.300	<0.00001	--
Dissolved iron	33	0.009	24	0.225	0.001	--
Total manganese	105	0.005	57	0.010	<0.00001	--
Dissolved manganese	31	0.002	24	0.013	0.0179	<0.05
Dissolved sulfate	132	2.10	61	3.30	<0.00001	--
Nitrate	116	0.263	36	0.005	<0.00001	--
Total phosphate	70	0.082	49	0.565	0.0002	<0.001
Dissolved oxygen	43	8.000	29	0.500	<0.00001	--
Total alkalinity	93	10.000	49	4.000	0.0001	--
pH (units)	95	6.08	49	5.40	<0.00001	--

a similar trend. Comparison of the total- and dissolved-iron concentration maps (fig. 12A, 12B) with the location of discharge areas (fig. 9) suggests that elevated total- and dissolved-iron concentrations in the Magothy aquifer are in or near discharge zones. Water in discharge zones has interacted with the aquifer material for a longer time than in recharge areas, and the consumption of O_2 by the bacterially mediated oxidation of lignite has resulted in an anoxic (reducing) environment. As water moves along a flow path, consumption of O_2 and the subsequent reduction of iron oxyhydroxides releases ferrous iron into solution. The microbially mediated reduction of Fe^{3+} oxides (Chapelle and Lovley, 1992) and the oxidation of authigenic pyrite (Kno-

bel and Phillips, 1988) explain the presence of high-iron environments elsewhere in the Atlantic Coastal Plain. These processes would be expected to increase iron concentrations along flow paths and can explain the elevated iron concentrations in discharge zones.

Elevated concentrations of ferrous iron facilitate the growth of iron-oxidizing bacteria by providing an energy source for the autotrophic iron bacteria commonly found in biofouled wells (Cullimore, 1986). The inorganic precipitation of iron oxyhydroxides at the anoxic-oxic interface also contributes larger volumes of iron oxide precipitate in wells with elevated iron concentrations than in wells characterized by lower concentrations of dissolved ferrous iron. This

A. Total iron

73° 15'

72° 15'

41°

40° 45'

EXPLANATION

o LOW-TOTAL-IRON SITE--One or more wells or test borings where the median total iron concentration was less than 0.5 milligrams per liter at all sampling points

● HIGH-TOTAL-IRON SITE--One or more wells or test borings where the median total iron concentration was greater than or equal to 0.5 milligrams per liter at at least one sampling point

B. Dissolved iron

73° 15'

72° 15'

41°

40° 45'

EXPLANATION

o LOW-DISSOLVED-IRON SITE--One or more wells where the median dissolved iron concentration was less than 0.25 milligrams per liter at all sampling points

● HIGH-DISSOLVED-IRON SITE--One or more wells where the median dissolved iron concentration was greater than or equal to 0.25 milligrams per liter at at least one sampling point

Base from U.S.Geological Survey digital data
1:24,000, 1990
Universal Transverse Mercatur projection
Zone 18

0   20 MILES

0   20   KILOMETERS

Figure 12. Areal distribution of median values of selected constituents in wells screened in the Magothy aquifer, Suffolk County, N.Y. A. Total iron concentrations greater than 0.5 milligrams per liter. B. Dissolved iron concentrations greater than 0.25 milligrams per liter.

Figure 12 continued. Areal distribution of median values of selected constituents in wells screened in the Magothy aquifer, Suffolk County, N.Y. C. Total manganese concentrations greater than 0.01 milligrams per liter. D. Total phosphate concentration greater than 0.13 milligrams per liter.

73° 15'　　　　　　　　　　　　　　**72° 15'**

E. Dissolved oxygen

41°

40°
45'

EXPLANATION

o HIGH-DISSOLVED-OXYGEN SITE--One or more wells where
  the median dissolved oxygen concentration was greater than
  2.0 milligrams per liter at all sampling points

● LOW-DISSOLVED-OXYGEN SITE--One or more wells where
  the median dissolved oxygen concentration was less than
  or equal to 2.0 milligrams per liter at at least one
  sampling point

73° 15'　　　　　　　　　　　　　　**72° 15'**

F. pH

41°

40°
45'

EXPLANATION

o HIGH-pH SITE--One or more wells where the median pH was
  greater than 5.5 at all sampling points

● LOW-pH SITE--One or more wells where the median pH was
  less than or equal to 5.5 at at least one sampling point

Base from U.S.Geological Survey digital data
1:24,000, 1990
Universal Transverse Mercatur projection
Zone 18

0　　　　　　　　　　　　　20 MILES

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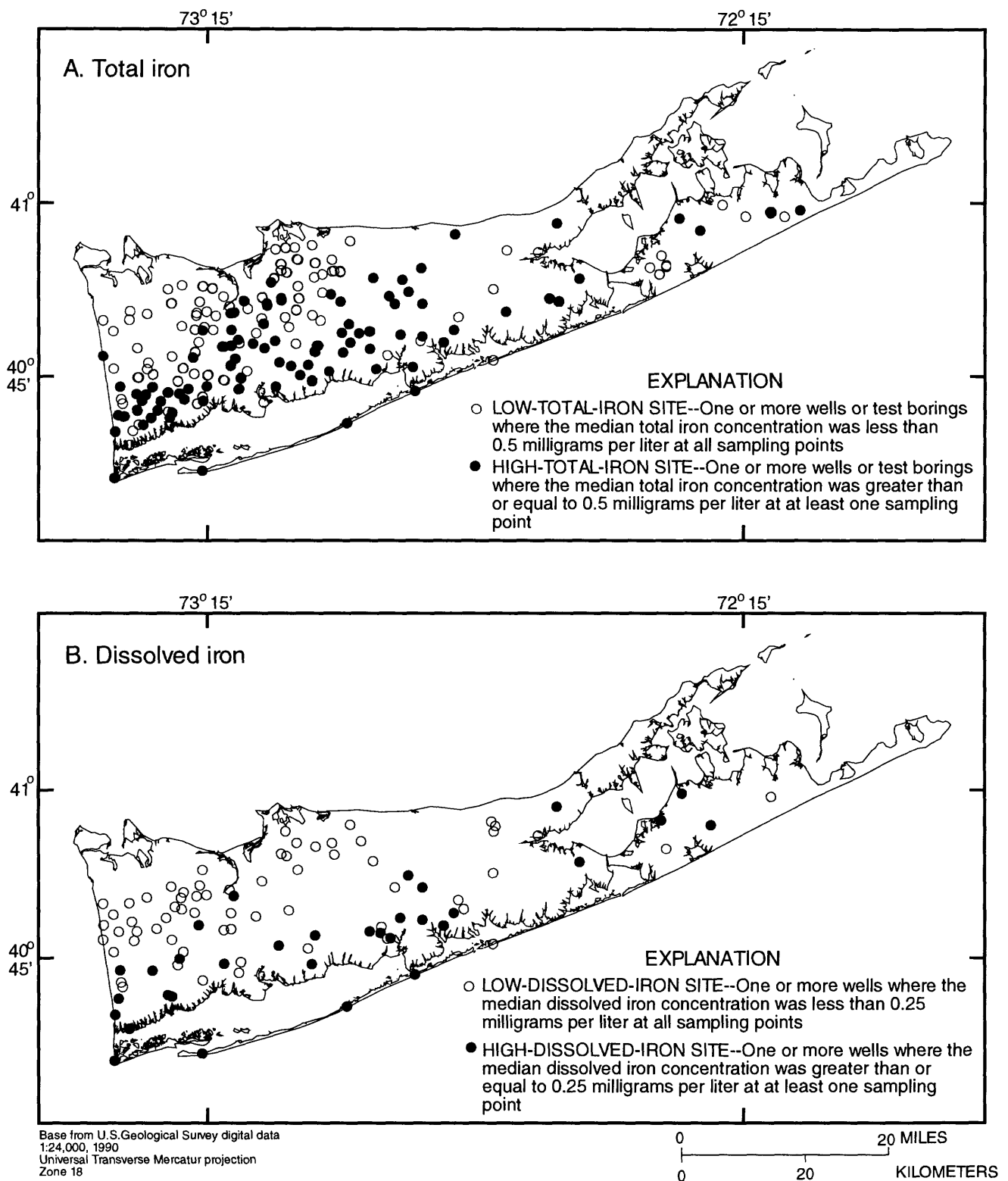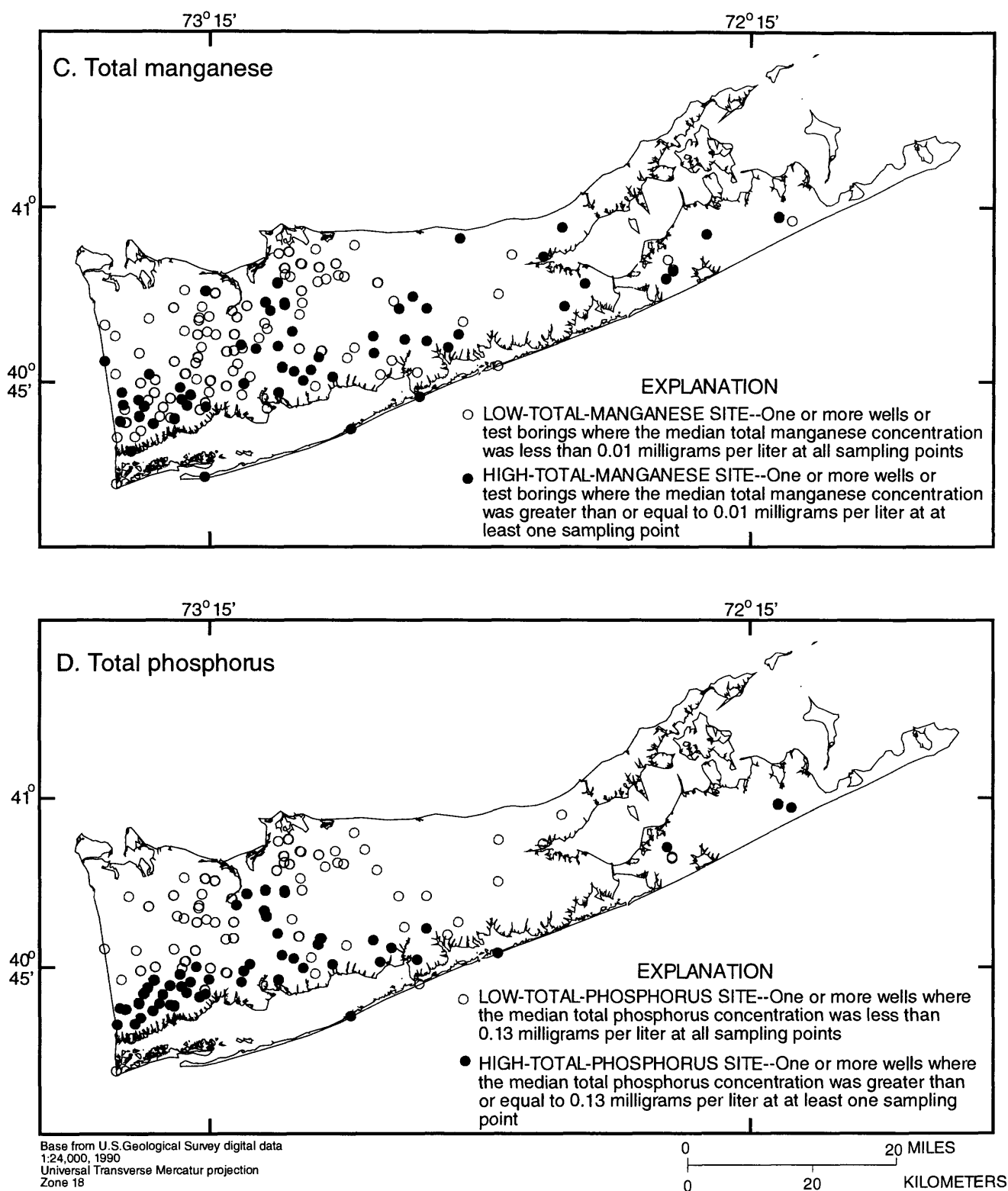**Figure 12 continued.** Areal distribution of median values of selected constituents in wells screened in the Magothy aquifer,
Suffolk County, N.Y. E. Dissolved-oxygen concentrations greater than 2.0 milligrams per liter. F. pH values less than 5.5.

G. Total alkalinity

EXPLANATION

○ LOW-TOTAL-ALKALINITY SITE--One or more wells where the median total alkalinity was less than 10 milliggrams per liter at all sampling points

● HIGH-TOTAL-ALKALINITY SITE--One or more wells where the median total alkalinity was greater than or equal to 10 milligrams per liter at at least one sampling point

H. Total nitrate

EXPLANATION

○ LOW-TOTAL-NITRATE SITE--One or more wells where the median total nitrate concentration was less than 0.25 milligrams per liter at all sampling points

● HIGH-TOTAL-NITRATE SITE--One or more wells where the median total nitrate concentration was greater than or equal to 0.25 milligrams per liter at at least one sampling point

Base from U.S.Geological Survey digital data
1:24,000, 1990
Universal Transverse Mercatur projection
Zone 18

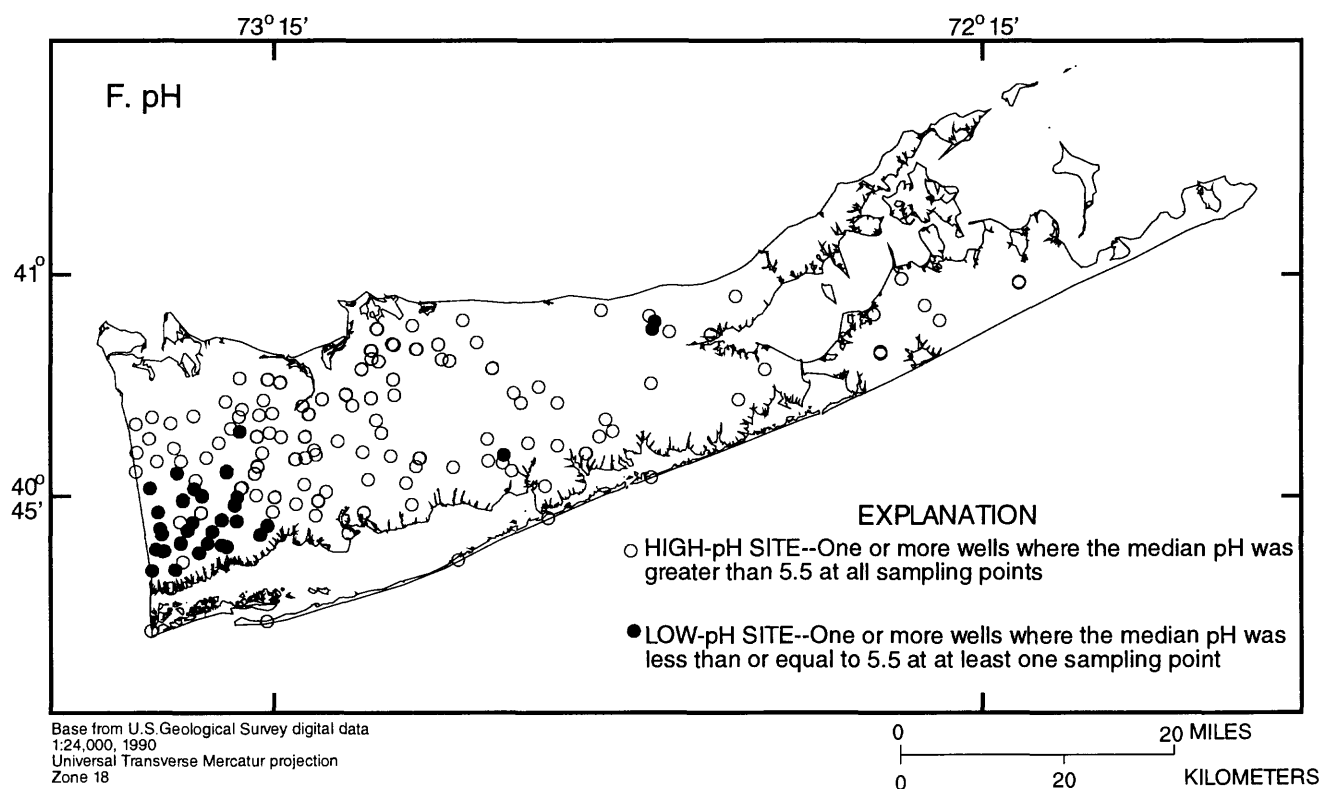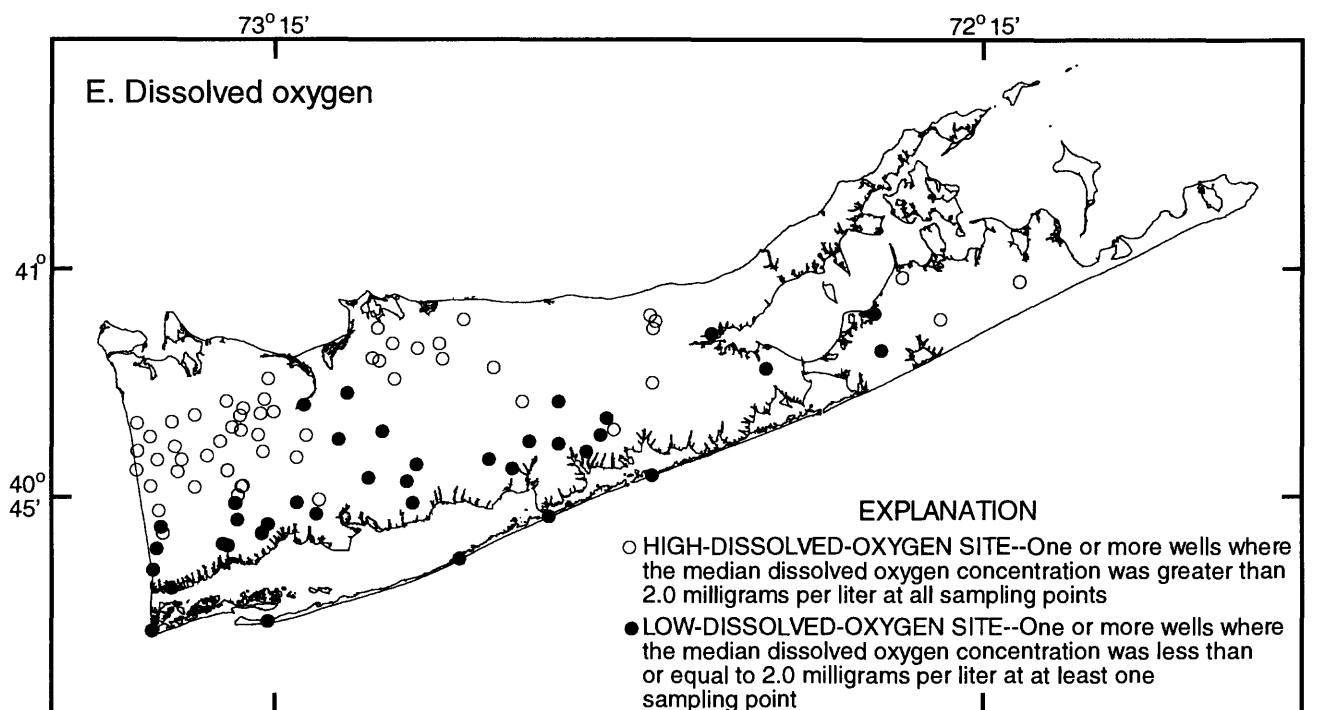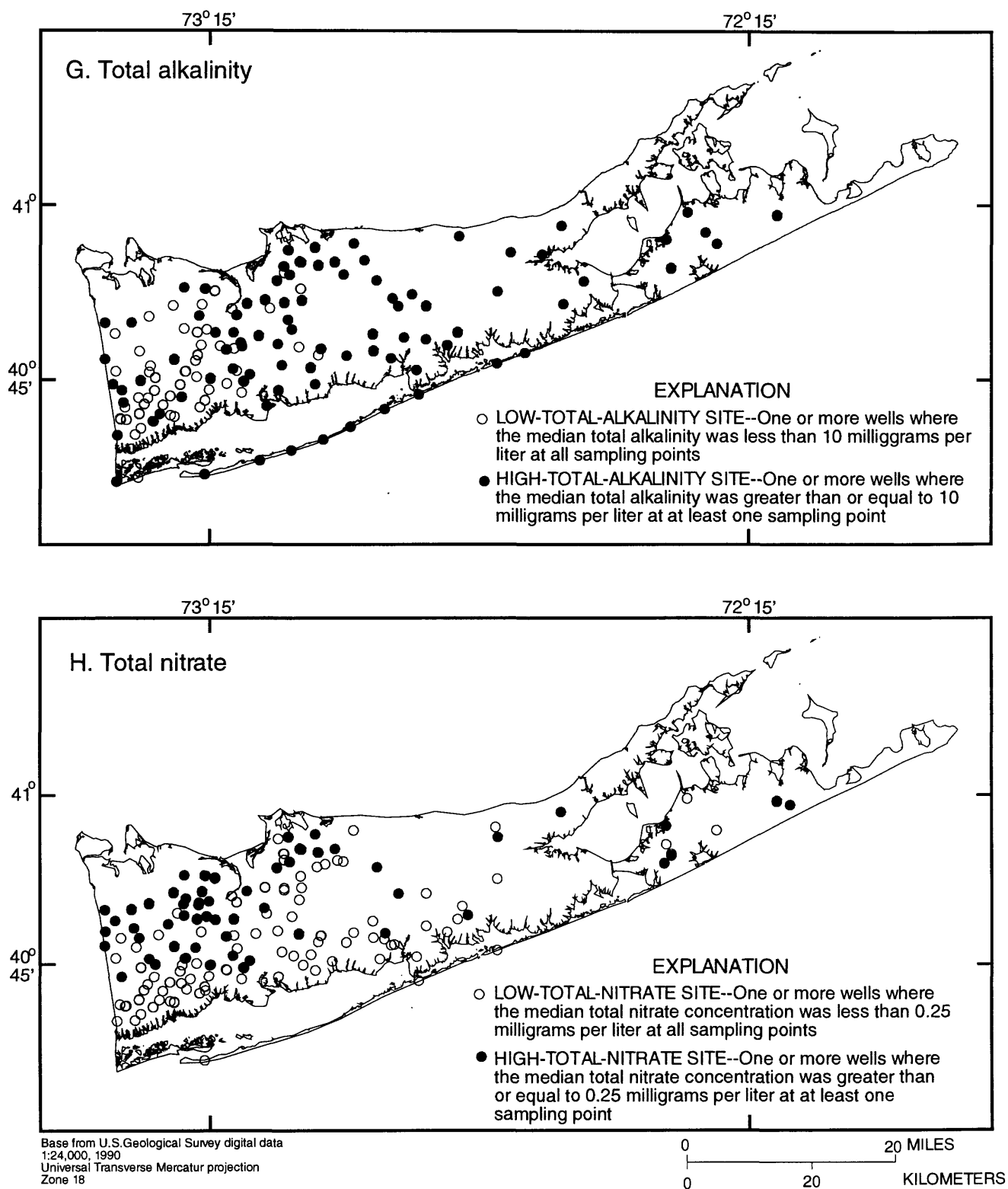0   20 MILES

0   20   KILOMETERS

Figure 12 continued. Areal distribution of median values of selected constituents in wells screened in the Magothy aquifer, Suffolk County, N.Y. G. Total alkalinity less than 10 milligrams per liter as $CaCO_3$. H. Nitrate concentration less than 0.25 milligrams per liter.

explains the statistically higher concentration of total and dissolved iron in affected Magothy aquifer wells and also explains the tendency of iron-related specific-capacity decreases to occur in discharge zones, where total- and dissolved-iron concentrations are higher.

Statistical analysis of total- and dissolved-iron data indicate no statistical difference between unaffected and affected wells screened in the upper glacial aquifer. Biofouling in the upper glacial aquifer could occur while the wells are shut down because, during idle periods, water from the local distribution system is pumped into the well casing for lubrication, and water taken for this purpose from nearby wells that yield water high in iron thereby could introduce dissolved iron into an upper glacial well that yields water with a low iron concentration. This, in turn, could lead to biofouling of the well, even though iron concentrations are low while the well is in operation. This process could explain the lack of significant water-quality differences between unaffected and affected wells screened in the upper glacial aquifer.

Manganese

The spatial distribution of total manganese concentrations above 10 μg/L in the Magothy aquifer (fig. 12C) is similar to that of total iron. Wells with median total manganese concentrations greater than 10 μg/L are mostly along the southern shore and in central and east-central Suffolk County. No distribution map for dissolved manganese is presented because data were insufficient. Manganese chemistry in ground-water systems is similar to that of iron—the consumption of O_2 and the subsequent reduction and dissolution of manganese oxyhydroxides along the flow path would introduce manganese into solution and, in turn, could cause elevated manganese concentrations in and near discharge zones.

Statistical analysis of total- and dissolved-manganese data indicate higher concentrations in affected wells than in unaffected wells in both aquifers. The chemical similarities between iron and manganese suggest that the biofouling process could also involve manganese. Iron bacteria that oxidize dissolved ferrous iron are also capable of oxidizing reduced manganese (Cullimore, 1986). The statistical differences between unaffected and affected wells suggests that manganese could participate in the biofouling process in both aquifers.

Total Phosphorus

The distribution of total phosphorus concentrations above 0.13 mg/L in the Magothy aquifer (fig. 12D) indicates that phosphate concentrations greater than 0.13 mg/L are mainly in the vicinity of discharge zones along the southern shore and in central Suffolk County. Phosphorus commonly is coprecipitated with iron and manganese oxyhydroxides. Adsorption onto, or coprecipitation, with iron and manganese oxyhydroxides is an important control on the solubility of phosphorus (Hem, 1985). The reduction and dissolution of iron and manganese oxyhydroxides in reducing environments such as those typically found in discharge zones would release phosphorus into solution.

Statistical analysis of total-phosphorus data from the Magothy aquifer indicate that the concentration of phosphate is significantly higher in affected wells than in unaffected wells. Phosphate is an important nutrient in ground-water systems and can be a limiting nutrient for the growth of iron-bacteria biofilms (Cullimore, 1986). The elevated concentrations of phosphate in affected wells suggests that phosphorus could be a limiting nutrient in the biofouling process in the Magothy aquifer. Also, the addition of phosphate as a chelating agent for iron directly into the casings of wells with high iron concentrations has led to rapid decreases in the specific capacities of those wells (Steven Colabufo, Suffolk County Water Authority, oral commun., 1989); this is further evidence that phosphate could be a limiting nutrient in the biofouling process. The lack of a statistically significant difference between concentrations of phosphate at unaffected wells and those at affected wells screened in the upper glacial aquifer suggests either that phosphate is not a limiting nutrient in the biofouling process in that aquifer, or that biofouling is occurring only while the wells are idle, as previously discussed.

Dissolved Oxygen

The distribution of dissolved oxygen concentrations below 2.0 mg/L in the Magothy aquifer (fig. 12E) is similar to the distribution of elevated concentrations of iron, manganese, and phosphate. Dissolved-oxygen concentrations less than 2.0 mg/L are mainly along the southern shore and in central Suffolk County; low concentrations in discharge zones indi-

cates that conditions are more reducing than in recharge zones. The consumption of O_2 by aerobic bacteria and by the oxidation of lignite lowers O_2 concentrations in discharge zones.

Statistical analysis of dissolved-oxygen data indicate that dissolved-oxygen concentrations are significantly lower in affected wells than in unaffected wells. Oxygen is an important constituent in the biofouling process because the iron bacteria that form biofilms are aerobic. The growth of aerobic iron bacteria can begin at dissolved-oxygen concentrations between 0.02 and 0.2 mg/L (Cullimore, 1986). The most common and effective filamentous iron bacteria involved in the biofouling process in Suffolk County is the genus *Gallionella*, a microaerophile that prefers low-oxygen environments (Driscoll, 1987). The significantly lower concentrations of dissolved oxygen in affected wells than in unaffected wells could reflect the affinity of *Gallionella* for low-oxygen environments. There was no significant difference between dissolved-oxygen concentrations in unaffected wells and affected wells screened in the upper glacial aquifer. The median concentrations of dissolved oxygen at unaffected wells screened in both aquifers and affected wells screened in the upper glacial aquifer are above the upper limit of the optimum dissolved-oxygen range for *Gallionella*. The presence of affected wells in discharge zones, where reducing conditions predominate and iron concentrations are elevated, could indicate a correlation between large specific-capacity decreases and low concentrations of dissolved oxygen.

pH

The distribution of pH values above and below 5.5 in the Magothy aquifer (fig. 12F) indicates that pH values lower than 5.5 are mainly in the southwestern part of the county, where the largest withdrawals from the Magothy aquifer are made. The low pH values in this area could be the result of the drawdown of oxygenated water and the subsequent oxidation of authigenic pyrite, which is commonly found in the Magothy aquifer along the southern shore and would decrease the pH of ground water. Knobel and Phillips (1988) used the oxidation of pyrite to explain increases in the concentrations of iron and sulfate along flow paths in the Magothy aquifer in Maryland.

Statistical analysis of pH data indicate significantly lower pH values in affected wells screened in both aquifers than in unaffected wells. The kinetics of

inorganic iron oxidation are second order with respect to pH; the rate of iron oxidation would be faster at elevated pH values (Stumm and Morgan, 1981). In addition, most iron-oxidizing bacteria commonly found in supply wells prefer neutral pH environments (pH 6 to 7.6) (Cullimore, 1986); thus, water from affected wells in an acidic ground-water system could be expected to have higher pH values than water from unaffected wells. The lower pH of ambient ground water at affected wells is due to the location of most of the affected wells in southwestern Suffolk County, where pH values are low.

Alkalinity

The distribution of total field alkalinity (as $CaCO_3$) above 10 mg/L in the Magothy aquifer (fig. 12G) indicates that water with total alkalinity less than 10 mg/L as $CaCO_3$ is primarily in western Suffolk County. As water moves along a flow path, the oxidation of organic carbon such as lignite can increase concentrations of HCO_3^- and cause increased alkalinity. The microbially mediated oxidation of lignite, coupled with the reduction of iron and manganese, has been used to explain the origin of high concentrations of HCO_3^- in aquifers containing little or no carbonate minerals (Chapelle and Knobel, 1985; Pearson and Friedman, 1970). The natural presence of elevated alkalinity in discharge zones could explain the lack of wells in eastern Suffolk County, where flow paths are shallow and the degree of interaction with aquifer materials is less, at which alkalinities were less than 10 mg/L as $CaCO_3$. The presence of alkalinities less than 10 mg/L in the southwestern part of Suffolk County could contribute to the low pH values observed there.

Statistical analysis of alkalinity data indicate that alkalinity is significantly lower in affected wells screened in the Magothy aquifer than in unaffected wells. Chemoautotrophic iron bacteria such as *Gallionella* use inorganic carbon as a carbon source (Cullimore, 1986), which suggests that biofouling could be more common in wells with elevated alkalinity than in other wells. The significantly lower alkalinity in affected wells could be the result of a spatial bias. Almost all of the affected wells screened in the Magothy aquifer (fig. 2) are in western and central Suffolk County, where low alkalinity (less than 10 mg/L) is common.

Nitrate

Nitrate concentrations (as nitrogen) greater than 0.25 mg/L are found primarily in the inland recharge area in western Suffolk County (fig. 12H). Nitrate in ground water can undergo denitrification in low-oxygen environments; thus, the reducing environments associated with discharge zones contain lower concentrations of nitrate than the recharge areas.

Statistical analysis of nitrate data indicates that nitrate concentrations are significantly lower in affected wells in the Magothy aquifer than in unaffected wells. Nitrate is an important nutrient in many ground-water systems. High nitrate concentrations allow nitrate respiration by aerobic bacteria in low-oxygen environments, a process that can lead to significant biofouling (Cullimore, 1986). Thus, nitrate concentrations would be higher in affected wells than in unaffected wells if nitrate respiration is an important factor in the biofouling process. The lower concentrations of nitrate in the affected wells screened in the Magothy aquifer than in unaffected wells could be due to low nitrate concentrations along the southern shore, where most of the affected wells are located.

Sulfate

Median sulfate concentrations computed from the data base showed no significant spatial trends in the Magothy aquifer. Sulfate data collected from the Magothy aquifer throughout Suffolk County as part of an investigation into natural geochemical processes on Long Island indicate that dissolved sulfate concentrations greater than 3.0 mg/L are found primarily along the southern shore (Pearsall, 1996). The oxidation of authigenic pyrite has been used to explain increased sulfate concentrations along flow paths elsewhere in the Magothy aquifer (Knobel and Phillips, 1988). This process could explain the elevated concentrations of sulfate in discharge zones along the southern shore.

Statistical analysis of sulfate data indicate that dissolved sulfate was significantly higher at affected wells than at unaffected wells screened in both aquifers. Sulfate could be a nutrient in the biofouling process (Cullimore, 1986), and the reduction of sulfate by sulfate-reducing bacteria and the precipitation of iron sulfides also could be an important factor in the biofouling process. Iron-sulfide mineral phases are commonly found in iron biofilms and are attributed to the formation of microredox environments within the bio-

films (George Alford, ARCC Inc., oral commun., 1992).

SUMMARY AND CONCLUSIONS

The Suffolk County Water Authority (SCWA) is the largest water supplier on Long Island and in 1992 operated a network of 430 wells screened in the Magothy and upper glacial aquifers. Iron-related well-screen encrustation and aquifer biofouling has affected many of the wells and has forced the SCWA to adopt a costly well-reconditioning and replacement program. The specific-capacity decreases are attributed to the growth of iron-bacteria biofilms composed of extracellular material and iron oxyhydroxides on well screens, in the gravel packs of wells, and in the surrounding formation in areas with elevated concentrations of iron in the ground water.

Specific-capacity decreases forced the SCWA to recondition 56 wells from October 1990 through August 1992. Initial specific capacities of SCWA wells screened in the upper glacial aquifer ranged from 5.4 to 229 (gal/min)/ft; the total decreases ranged from 0 to 85 percent. Initial specific capacities of SCWA wells screened in the Magothy aquifer ranged from 8.3 to 15 (gal/min)/ft; the total specific-capacity decreases ranged from 0 to 69 percent.

Magothy aquifer wells with annual specific-capacity decreases greater than 5 percent are mostly along the southern shore and in central Suffolk County, whereas upper glacial aquifer wells with annual specific-capacity decreases greater than 5 percent are mostly in south-central Suffolk County. These wells are primarily in ground-water discharge zones and are associated with elevated concentrations of iron.

Specific-capacity data and water-quality data for affected and unaffected wells screened in the Magothy aquifer indicate higher median concentrations of total and dissolved iron, total and dissolved manganese, total phosphate, and dissolved sulfate in samples from biofouled wells than in unaffected wells, and lower median concentrations of dissolved oxygen, total alkalinity, and pH. Data from the upper glacial aquifer indicate higher median concentrations of total and dissolved manganese and dissolved sulfate in biofouled wells than in unaffected wells and lower median pH.

No spatial trends in the median values of constituents possibly related to the biofouling process were evident in the upper glacial aquifer, possibly because

they were masked by the effects of human activities. Data from the Magothy aquifer show that concentrations of total and dissolved iron, total manganese, and total phosphate were higher along the southern shore and in central Suffolk County, in and near ground-water discharge zones, than elsewhere. Concentrations of dissolved oxygen less than 2.0 mg/L showed a similar distribution. Sulfate data from another investigation indicated that dissolved-sulfate concentrations were also higher along the southern shore than elsewhere. The spatial distribution of these concentrations is similar to that of wells with specific-capacity decreases greater than 5.0 percent per year in the Magothy aquifer, suggesting that ground-water quality affects the rate of biofouling. The biofouling of wells in areas with high concentrations of iron and manganese could be due to the presence of these metals as an energy source for the autotrophic iron bacteria that act as a biofouling agent. The elevated phosphate concentrations in biofouled wells suggest that phosphate could be a limiting nutrient in the biofouling process. The low dissolved-oxygen concentrations in biofouled wells screened in the Magothy aquifer could be due to the affinity of certain iron bacteria for low-oxygen environments. The high percentage of biofouled wells in discharge zones, where reducing conditions prevail, indicates a correlation between specific-capacity decreases greater than 5.0 percent per year and water-quality constituents associated with reducing environments, although no direct relation is defined.

Elevated nitrate concentrations are found mainly in northwestern Suffolk County. Biofouled wells commonly are in or near ground-water discharge zones in southern and southwestern Suffolk County, where nitrate reduction has occurred and nitrate concentrations are low. A zone of low pH was observed in southwestern Suffolk County, and a zone of low total alkalinity in western Suffolk County. Of the 64 wells used to create the biofouled-well data set, 44 are in water districts in southwestern Suffolk County, suggesting that the lower pH and total alkalinity values in affected wells may be due to a spatial bias.

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