Position of the Freshwater/Saltwater Interface in Southeastern Queens and Southwestern Nassau Counties, Long Island, New York, 1987-88

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CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	*By*	*To Obtain*
	Length	
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter

Other abbreviations used in this report

milligrams per liter (mg/L)
million gallons per day (Mgal/d)
feet per year (ft/yr)

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.

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Abstract

The landward movement of salty ground water in a 150-square-mile, south-shore area of southeastern Queens and southwestern Nassau Counties that includes the barrier beach has been indicated by an increase in chloride concentration at some production wells and observation wells since the 1960's. Of the 23 wells sampled in this study and in the late 1960's, only four (N6701, N3864, N6581, and Q1237) showed a change in chloride concentration; the latter three also showed increases during 1960-69.

The increase in chloride concentration at well N3864 in Woodmere by 1988, and the position of the 40-milligram-per-liter chloride front in 1958, indicate the rate of salt-front movement near the Mill Road well field to be about 100 feet per year. Graphs of chloride concentration through time for production wells in southeastern Queens County indicate that the interface is moving landward toward at least three pumping centers.

Water samples from most of the observation wells that were used to monitor movement of salty ground water do not indicate a significant change in chloride concentration since the wells were installed. This is probably because: (1) the rate of landward movement is relatively slow (about 100 feet per year in Woodmere), and (2) the wells are not close enough to the saltwater interface to detect landward movement.

INTRODUCTION

Ground water is the source of freshwater supply throughout southeastern Queens and all of Nassau Counties on Long Island, N.Y. (fig. 1). The aquifer system consists of a series of unconsolidated sand, silt, clay, and gravel units. Nearshore parts of the island have a potential for aquifer contamination from saltwater encroachment, particularly in (1) areas where the aquifers are hydraulically connected to the saltwater, and (2) areas of extensive pumping, where the head in the fresh ground-water system is less than

Figure 1. Location of study area, Long Island, N.Y.

that in the saltwater system. Both conditions prevail in parts of Long Island and are resulting in a slow advance of seawater into the aquifers.

The three main aquifers used for public water supply in southeastern Queens and southwestern Nassau Counties are the Jameco, Magothy, and Lloyd aquifers (fig. 2). Extensive pumping of these aquifers in adjacent parts of Kings and Queens Counties during the 1930's and 1940's caused elevated chloride concentrations in large areas (Buxton and others, 1981), and salty ground water was detected as early as 1958 in southwestern Nassau County (Lusczynski and Swarzenski, 1960).

In 1986,the U.S. Geological Survey (USGS), in cooperation with the Nassau County Department of Public Works (NCDPW), began a study to (1) evaluate the position of the freshwater/saltwater interface (the boundary between fresh ground water and salty ground water) in a 150-mi^2 area of southeastern Queens and southwestern Nassau Counties (fig. 1), and (2) document vertical and horizontal migration of the interface within these aquifers.

Ground water having a chloride concentration between 40 and 16,000 mg/L is defined as salty ground water, and ground water having a chloride concentration less than 40 mg/L is referred to as freshwater (Lusczynski and Swarzenski, 1966). A maximum chloride concentration of 250 mg/L is a recommended guideline for drinking water established by the U.S. Environmental Protection Agency (1986). Buxton and Shernoff (1995) found that high concentrations of chloride within the study area generally were not associated with elevated nitrate concentrations and concluded, therefore, that the source of chloride was the encroachment of sea water, not contamination from land surface or sewage. The mixing of freshwater and saltwater from fluctuations in tides, and from pumping and recharge, creates a transition zone between fresh ground water and saltwater. The location, size, and shape of this mixing vary locally.

Purpose and Scope

This report provides information on the location and degree of saltwater encroachment in the three major aquifers being used for public water supply in southwestern Nassau and southeastern Queens Counties. It (1) describes the hydrologic setting and the observation-well network, (2) tabulates ground-water levels and chloride concentrations in selected wells, and (3) depicts the position and movement of the freshwater/saltwater interface in maps, vertical sections, and "chloride-breakthrough" curves.

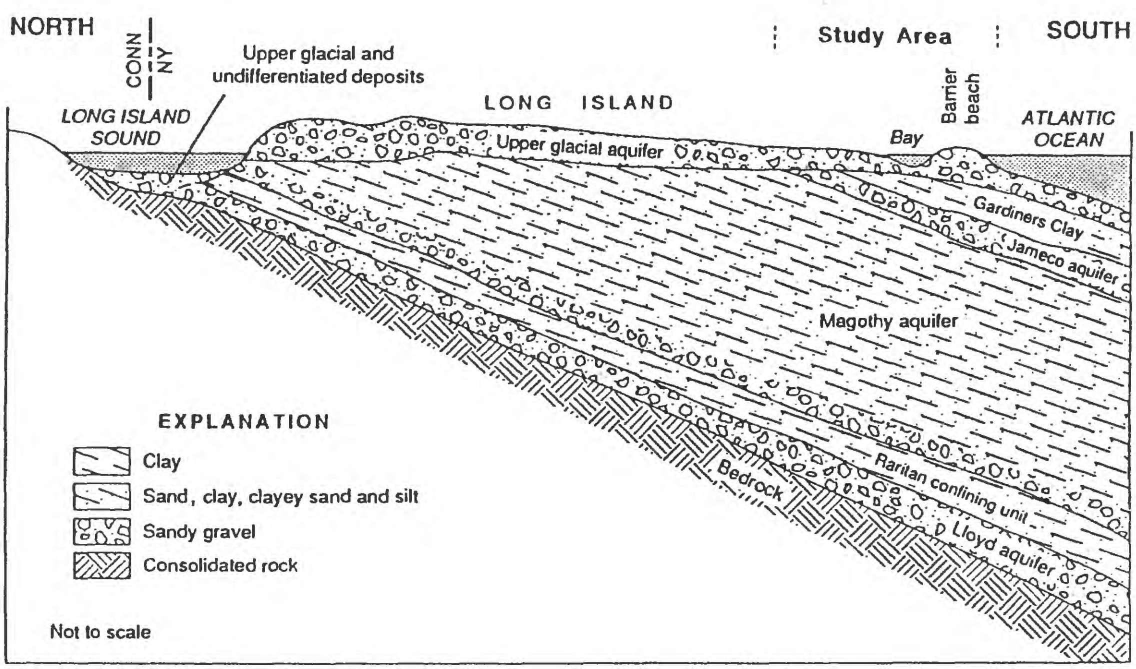


Figure 2. Generalized hydrogeologic section of Long Island, N.Y., aquifers. (Modified from McClymonds and Franke, 1972, fig. 3.)

Previous Studies

Field methods and water-quality data from wells in the study area that were used for comparison with 1988 data are described by Perlmutter and Crandell (1959), Perlmutter and others (1959), Lusczynski and Swarzenski (1960, 1962, 1966), Lusczynski (1961a, b), Perlmutter and Geraghty (1963), and Cohen and Kimmel (1971). Hydrologic conditions in Queens and Nassau Counties are described by Soren (1971, 1978), and Buxton and Shernoff (1995). The stratigraphy of southern Nassau County is described by Doriski and Wilde-Katz (1983) and Krulikas (1989). The stratigraphy of Long Island is described by Smolensky and others (1989).

Hydrologic Setting

The 150-mi^2 study area encompasses the southern shore of Long Island and the barrier-beach system. The area is underlain by a sequence of unconsolidated deposits of sand, silt, clay, and gravel overlying southeastward dipping bedrock surface. These deposits range in thickness from 300 ft in the northwestern part of the study area to 1,200 ft in the southeastern part. The deposits are separated into stratigraphic units on the basis of their depositional history and water-bearing properties and are summarized in table 1; their positions and sequence are depicted in figure 2.

The major aquifers in the study area are, from youngest to oldest, the upper glacial aquifer, Jameco aquifer, Magothy aquifer, and Lloyd aquifer. The upper glacial aquifer is under water-table conditions. The Magothy and Jameco aquifers are mostly confined, especially within the study area. The Lloyd aquifer is completely confined.

The major confining units are the Raritan confining unit (also called the Raritan clay) and the Gardiners Clay. The 20-foot clay (not shown in fig. 2), which is interbedded within the upper glacial aquifer, also acts as a discontinuous confining unit within the study area. The 20-foot clay can be difficult to differentiate from the Gardiners Clay where the two are near or in contact with each other. Discontinuous clay beds within the aquifers significantly affect ground-water flow patterns, which in turn affect the distribution of salty ground water within the study area.

The upper glacial aquifer is in direct hydraulic contact with saltwater and is generally not used as a source of potable water within the study area. The upper glacial aquifer is underlain by the Gardiners Clay and (or) the 20-foot clay in most places.

In this report, the Magothy and Jameco aquifers and other reworked Matawan-Magothy channel deposits (table 1) are treated as a single stratigraphic unit because they are not separated by a confining unit. Differentiation of the Magothy aquifer from Jameco and other channel-fill deposits can be difficult because the Magothy composition varies locally (Ku and others, 1975). The Magothy and Jameco aquifers are a major source of water for communities within the study area. These aquifers are confined in most places but are unconfined (under water-table conditions) where the Gardiners Clay and 20-foot clay are absent. The base of the Magothy aquifer is the Raritan clay.

The Lloyd aquifer is confined by the Raritan clay and is a major source of water to communities on the barrier islands. It overlies the weathered crystalline bedrock surface; this weathered zone is reported to be 100 ft thick in test holes cored near Bergen Basin in Queens (fig. 5, further on) (B.E. Russell, Fenix and Scisson, Inc., written commun., 1989).

A generalized vertical section showing flow patterns within the regional ground-water system under natural (nonpumping) conditions is given in figure 3. Under natural conditions, the source of all fresh ground water in the study area is recharge from precipitation. Water that enters the water table at the ground-water divide flows downward; elsewhere it flows seaward and discharges into the saltwater bodies that bound the system. Flow within the system is three dimensional and is affected by the hydraulic characteristics of the aquifers and the confining units, the local variability of recharge, proximity and type of discharge points, and the distribution of hydraulic head throughout the system (Nemickas and others, 1989).

Recent Hydrologic Conditions

Human activities, primarily sewer construction, have altered the rate and spatial distribution of recharge to the ground-water system (Ku and others, 1992). Storm sewers route runoff from impervious surfaces such as streets and parking lots to recharge basins and streams; sanitary sewers also have decreased recharge to the ground-water system. In the study area, however, sewer construction and the redistribution of recharge were largely completed by 1964, and little new construction has occurred since 1970; thus, recharge patterns in the study area probably have remained unchanged.

Table 1. Summary of the hydrostratigraphic units underlying southwestern Nassau and southeastern Counties, N.Y., and their waterbearing properties

System	Series	Age	Stratigraphic unit	Hydro-strati-graphic unit	Approxi-mate range in thick-ness (feet)	Character	Water-bearing properties
Quaternary	Holocene	Holocene	Recent deposits	Upper glacial aquifer	0-40	Beach sand and gravel and dune sand, tan to white; black, brown, and gray bay-bottom deposits of clay and silt; artificial fill. Beach and dune deposits are mostly stratified and well sorted. Fill includes earth and rocks, concrete fragments, ashes, rubbish, and hydraulic fill.	Sandy beds of moderate to high permeability beneath barrier beaches, locally yield fresh or salty water from shallow depths. Clayey and silty beds beneath bays retard salt-water encroachment and confine underlying aquifers.
	Pleis-tocene	Wisconsinan	Upper Pleistocene deposits		30-300	Outwash consisting mainly of brown fine to coarse sand and gravel, stratified. Interbedded with "20-foot" clay.	Sand and gravel part of outwash highly permeable; yields of individual wells are as much as 1,700 gal/min. Specific capacities of wells as much as 109 gal/min per foot of drawdown. Water fresh except near shorelines.
			unconformity	"20-foot" clay	0-40	Clay and silt, gray and grayish green; some lenses of sand and gravel. Contains shells, foraminifera, and peat. Altitude of top of unit about 20 ft below mean sea level. Interbedded with outwash in southern part of area.	Relatively impermeable confining unit. Retards salt-water encroachment in shallow depths. Confines water in underlying outwash deposits when present.
		Sangamon interglaciation	Gardiners Clay unconformity	Gardiners Clay	0-40	Clay and silt, grayish-green; some lenses of sand and gravel. Contains lignitic material, shells, glauconite, foraminifera, and diatoms. Interglacial deposit. Altitude of surface about 50 ft or more below mean sea level.	Relatively impermeable confining layer above Jameco aquifer. Locally contains moderately to highly permeable sand and gravel lenses. Confines water in underlying Magothy aquifer in most of study area.
		Illinoisan(?)	Jameco Gravel	Jameco aquifer	0-250	Sand, coarse, granule to cobble gravel, generally dark brown and dark gray. Found mainly in Queens and Kings County. A stream deposit in a valley cut in Matawan Group-Magothy Formation undifferentiated deposits. Buries valley of ancestral Hudson River.	Highly permeable. Yields as much as 1,500 gal/min to individual wells. Specific capacities as high as 135 gal/min per foot of drawdown. Contains water under artesian pressure. Water commonly has high iron content and is salty near shoreline.
unconformity		Illinoisan(?) to Upper Cretaceous(?)	Reworkd Matawan-Magothy channel deposits	Upper glacial or Magothy aquifer	0-260	Sand, fine to coarse, dark-gray and brown; gravel. Contains some thin beds of silt and clay. Often called Jameco aquifer in Nassau County; however these channel deposits have different source material.	Moderate to highly permeable. Provides a high degree of interconnection between Magothy aquifer and upper glacial aquifer when Gardiners Clay is not present.

Table 1. (continued) Summary of the hydrostratigraphic units underlying southwestern Nassau and southeastern Counties, N.Y., and their waterbearing properties

System	Series	Age	Stratigraphic unit		Hydro-strati-graphic unit	Approxi-mate range in thickness (feet)	Character	Water-bearing properties
Cretaceous	Upper Cretaceous		Matawan Group-Magothy Formation, undifferentiated unconformity		Magothy aquifer	0-850	Sand, fine to medium gray; interfingered with lenses of coarse sand, sandy clay, silt, and solid clay. Generally contains gravel in bottom 50 to 100 ft. Lignite and pyrite abundant.	Slightly to highly permeable. Principal source of public-supply water in Nassau County. Individual wells yield as much as 2,200 gal/min. Specific capacities as high as 80 gal/min per foot of drawdown. Water mainly under artesian pressure; some wells in southern part of area flow. Water generally is of excellent quality except where contaminated by salty water in southwestern part of area or by dissolved constituents associated with human activities.
			Raritan Formation	Unnamed clay member	Raritan clay	100-300	Clay, gray, white, and some red and purple; contains interbedded layers of sand and gravel. Lignite and pyrite occur widely throughout.	Relatively impermeable confining unit. Local lenses and layers of sand and gravel, moderate to high permeability.
				Lloyd Sand Member	Lloyd aquifer	150-300	Sand, fine to coarse, gray and white, and gravel; some lenses of solid sandy clay, and clayey sand. Thin beds of lignite locally.	Relatively impermeable. Yields as much as 2,000 gal/min to individual wells. Specific capacities as high as 44 gal/min per foot of drawdown. Water under artesian pressure; some wells flow. Water of good quality except for high iron content.
unconformity								
Paleozoic (or) Precambrian			Undifferentiated gneiss, schist, pegmatite		Bedrock	--	Crystalline metamorphic and igneous rocks. Soft, clayey weathered zone at top, as thick as 100 ft.	Relatively impermeable. Contains water along joints and fault zones. No wells used for water supply in report area.

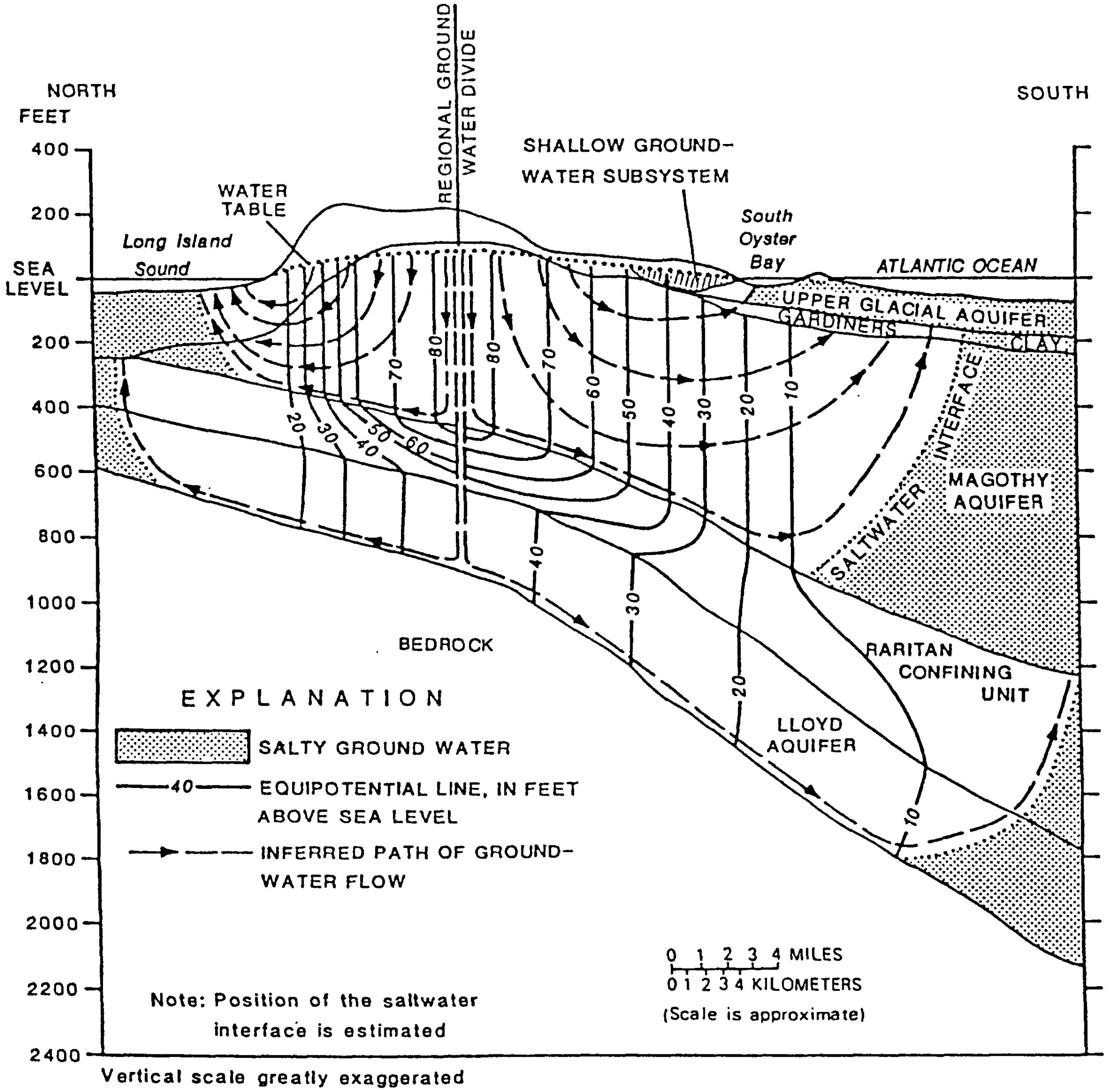


Figure 3. Generalized flow lines in the ground-water system of Long Island, N.Y. (Modified from Reilly and others, 1983, fig. 4.)

Most of the public water supply in the study area is obtained from pumping centers north of the study area; pumping centers within the study area are the Mill Road well field in Woodmere and those on the barrier island in Long Beach and Lido Beach (fig. 5, further on). Public-supply wells in the Mill Road well field are screened in the Jameco aquifer; public-supply wells on the barrier island are screened in the Lloyd aquifer. Data on public-supply pumpage in Nassau County, Queens County, the study area, and at Mill Road and the barrier island are given in figure 4. Reported 1968-87 pumpage for the study area has been fairly constant and is consistent with the gross 1968 pumpage reported by Cohen and Kimmel (1971), although pumpage for Nassau County shows an increasing trend for 1968-86. Pumpage in Queens County has decreased since 1982, but this is a due to of an increase in supply from upstate reservoirs rather than a decrease in demand. Annual pumpage at the Mill Road well field has remained fairly constant since 1970. Annual pumpage from the Lloyd aquifer has decreased from a high of 10 Mgal/d in 1970 to a level similar to that of the Mill Road well field (about 5 Mgal/d) in 1986.

Sanitary sewers and storm sewers have caused a decrease in aquifer recharge, and pumping has decreased the amount of fresh ground water in storage in the aquifer system. The imbalance between recharge to, and discharge from, the Jameco and Magothy aquifers has resulted in a decrease in the amount of freshwater and an increase in the amount of saltwater in storage (Cohen and others, 1968).

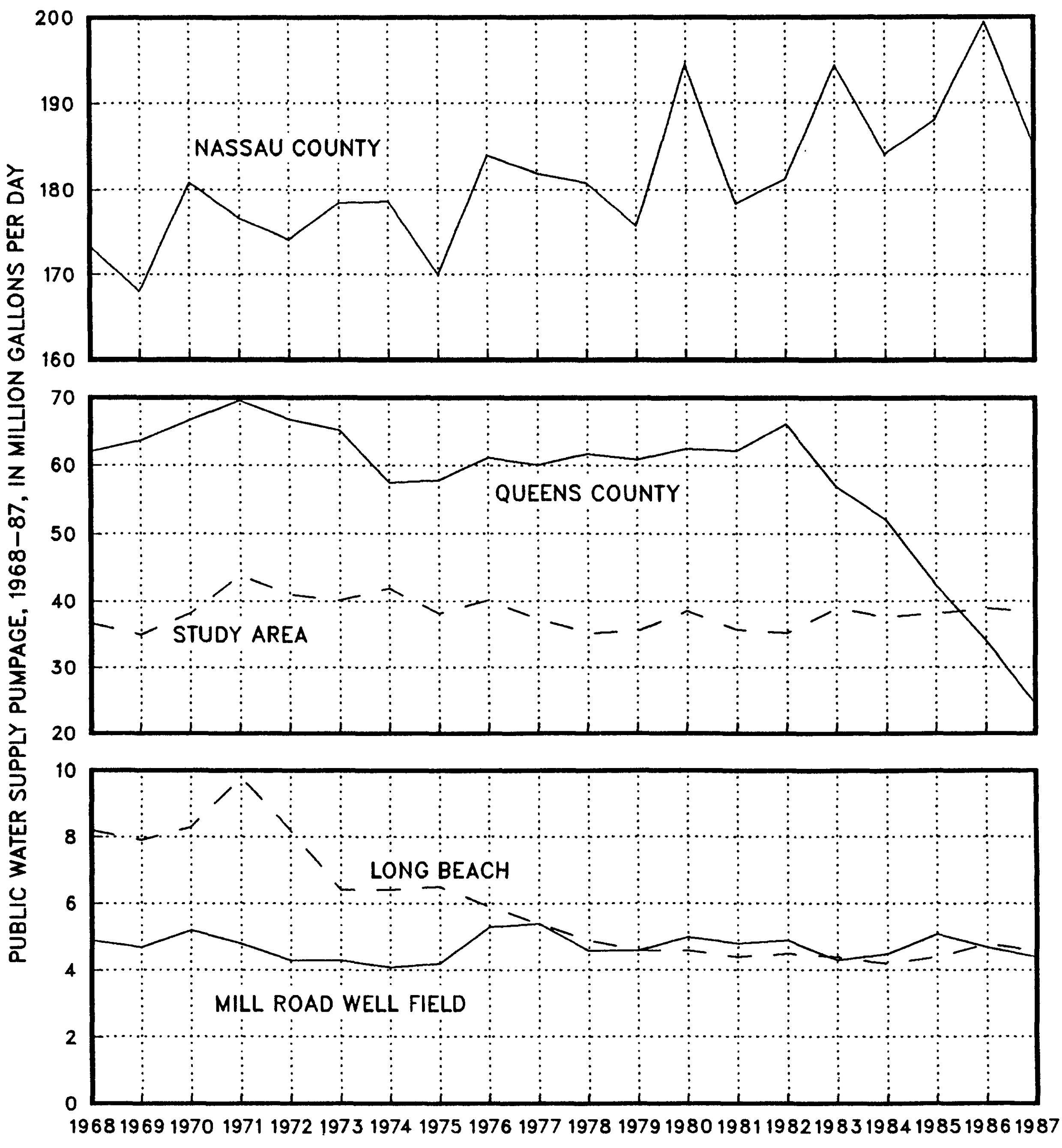


Figure 4. Reported yearly public-water-supply pumpage from five areas, Long Island, N.Y., 1968-87. (Locations are shown in figs. 1 and 5.)

METHODS OF INVESTIGATION

The study entailed (1) identifying observation wells that could be used for water-level measurements and ground-water sampling, (2) installing new wells as needed for delineation of the interface, and (3) measuring water levels in all available wells and sampling each well for chloride concentration.

An attempt was made to locate all wells that had been identified by Cohen and Kimmel (1971) for monitoring saltwater encroachment in southern Nassau and southeastern Queens Counties. Additional wells in this area were sought by searching the USGS Long Island database. Identified wells were (1) visually inspected for holes in the surface casing, (2) measured for depth, and (3) pumped with a centrifugal pump to determine suitability for sampling. Wells that had holes in the surface casing or were obstructed, or that could not maintain constant flow during pumping, were omitted from this study.

Six wells were installed by standard mud-rotary drilling techniques. Well sites were chosen in Nassau County to provide an indication of movement of saltwater into the aquifer. Four wells were installed in the Magothy aquifer, and two were installed in the Lloyd aquifer. Well locations were based upon recommendations by Lusczynski and Swarzenski (1966) and an evaluation of where wells are needed to monitor encroachment in the future. Core samples were collected for filter-press analysis of chloride concentration by the method of Lusczynski (1961a) during drilling of the Lloyd aquifer wells.

Ground water was sampled at about 40 wells. Before a water sample was collected, at least three casing volumes were evacuated from the well, and consecutive measurements of pH, temperature, and specific conductance were made until the values were stable. Untreated raw samples were collected in polyethylene bottles, then packed in ice and transported to the NCDPW water-quality laboratory.

A synoptic water-level measurement was made on July 29, 1988 at 36 wells in areas affected by tides. Water levels were measured within 1 hour of high and low tide to obtain a mean value for the 6-hour period between the extremes.

POSITION OF FRESHWATER/SALT-WATER INTERFACE

Chloride concentrations were measured at 41 wells in 1988 (table 2) to delineate the extent of salty ground water in the study area (fig. 5). Data from previous reports (Lusczynski and Swarzenski, 1966; Cohen and Kimmel, 1971) were compared with recent data to identify changes and trends.

Salty-Water Wedges

Areas of salty ground water in the upper glacial, Jameco, and Magothy aquifers were delineated by Lusczynski and Swarzenski (1966). The northward and eastward extent of salty ground water differs among the aquifers. The salty water within these aquifers in eastern and central parts of the study area forms three wedges that point landward (fig. 6A)–a shallow wedge, an intermediate wedge, and a deep wedge, whose limits depend on the distribution of hydraulic head and the water-transmitting properties of the hydrologic units. The intermediate wedge and the deep wedge merge in the western part of the study area to form a single wedge through the thickness of the Jameco and Magothy aquifers (fig. 6B). In general, the chloride concentration within these wedges increases southwestward.

Shallow Wedge

The salty water in the upper glacial aquifer, which is hydraulically connected to the south-shore bays and ocean, is referred to as the shallow wedge. This aquifer is underlain by the 20-foot clay and (or) the Gardiners Clay (fig. 6). These clay units are absent locally in parts of southern Queens and southwestern Nassau Counties and probably also in offshore areas. The local absence of clay beneath the upper glacial aquifer could provide a pathway for salty ground water to enter the Jameco aquifer as well as other channel-fill deposits and upper parts of the Magothy aquifer. No data on the extent of salty ground water in the upper glacial aquifer have been obtained since the Lusczynski and Swarzenski (1966) study.

Intermediate Wedge

The intermediate wedge, which was delineated primarily from observation-well data along the barrier island in Long Beach, Lido Beach, and Atlantic Beach (fig. 7), extends into the Jameco aquifer and the upper part of the Magothy aquifer. The altitude of the landward extent of this wedge ranges from about 250 ft below sea level in the eastern part of the study area to about 150 ft below sea level in the central part. No evidence of this

Table 2. Observation-well data with 1988 water levels and chloride concentrations for 41 wells in study area, Long Island, N.Y.

[<, less than. Locations shown in fig. 5]

Well number	Screened interval (feet below sea level)		Water level (feet above or below sea level)		Mean water level[1] (feet above or below sea level)	Chloride concentration[2] (milligrams per liter)
	Top	Bottom	High tide	Low tide		
N2790	535	557	2.37	1.63	2.00	<3
N3862	287	298	2.41	2.13	2.27	1,800
N3864	455	466	-.28	-.48	-.38	100
N3865	548	558	3.33	2.99	3.16	<3
N3866	394	406	.72	.65	.69	<3
N3867	497	509	1.06	.95	1.01	5
N3932	165	169	2.54	2.05	2.30	3
N4026	144	148	2.67	2.13	2.40	<3
N4062	130	135	2.54	2.50	2.52	33
N4150	723	739	6.78	6.38	6.58	3.3
[3]N4213	125	129	1.02	.95	.99	5
N6581	566	576	-8.31	-8.47	-8.39	12,000
N6701	811	821	7.40	6.00	6.70	800
N6702	655	666	-5.26	-7.15	-6.21	15,000
N6703	458	468	1.23	-.74	.25	5,500
N6704	274	284	4.38	2.36	3.37	10
N6849	1,019	1,029	5.09	4.16	4.63	55
N6850	891	902	4.21	2.92	3.57	120
N6851	544	549	4.47	3.05	3.76	<3
N6853	120	125	3.74	2.31	3.03	<3
N6928	710	720	2.19	1.93	2.06	10
[3]N7207	87	90	3.17	1.75	2.46	13
[3]N7161	654	659	2.63	1.30	1.97	5
N8391	130	138	--	--	--	80
N10425	687	702	3.35	3.02	3.19	<3
N10430	595	600	.41	.40	.41	5
N10620	1,145	1,155	.90	-.80	.05	45
N10979	310	330	3.34	2.19	2.77	830
N11002	1,230	1,240	-.20	-3.07	-1.64	<3
N11109	775	780	-4.73	-6.20	-5.47	10,000
N10667	522	532	-.15	-.85	-.50	48
Q287	716	716	2.70	.94	1.82	150
Q566	201	220	--	--	--	[4]190
Q1071	755	820	3.04	.63	1.84	49
Q1187	134	134	6.49	6.49	6.49	10
Q1237	178	202	5.10	5.10	5.10	330
Q3109	268	288	2.51	2.11	2.31	4,700
Q3110	296	316	3.61	3.08	3.35	2,500
Q3156	215	265	--	--	--	53
Q3157	181	232	--	--	--	[5]270
Q3657	571	611	--	--	--	[6]10,000

[1] Mean water levels are the average of high and low water levels measured through a tidal cycle in July of 1987. The range of water levels in wells caused by tides is greatest near the Atlantic Ocean. Wells on Long Beach with screen zones in the Magothy and Lloyd aquifers have a tidal range between 1.4 and 2.. This range generally decreases landward of the ocean.

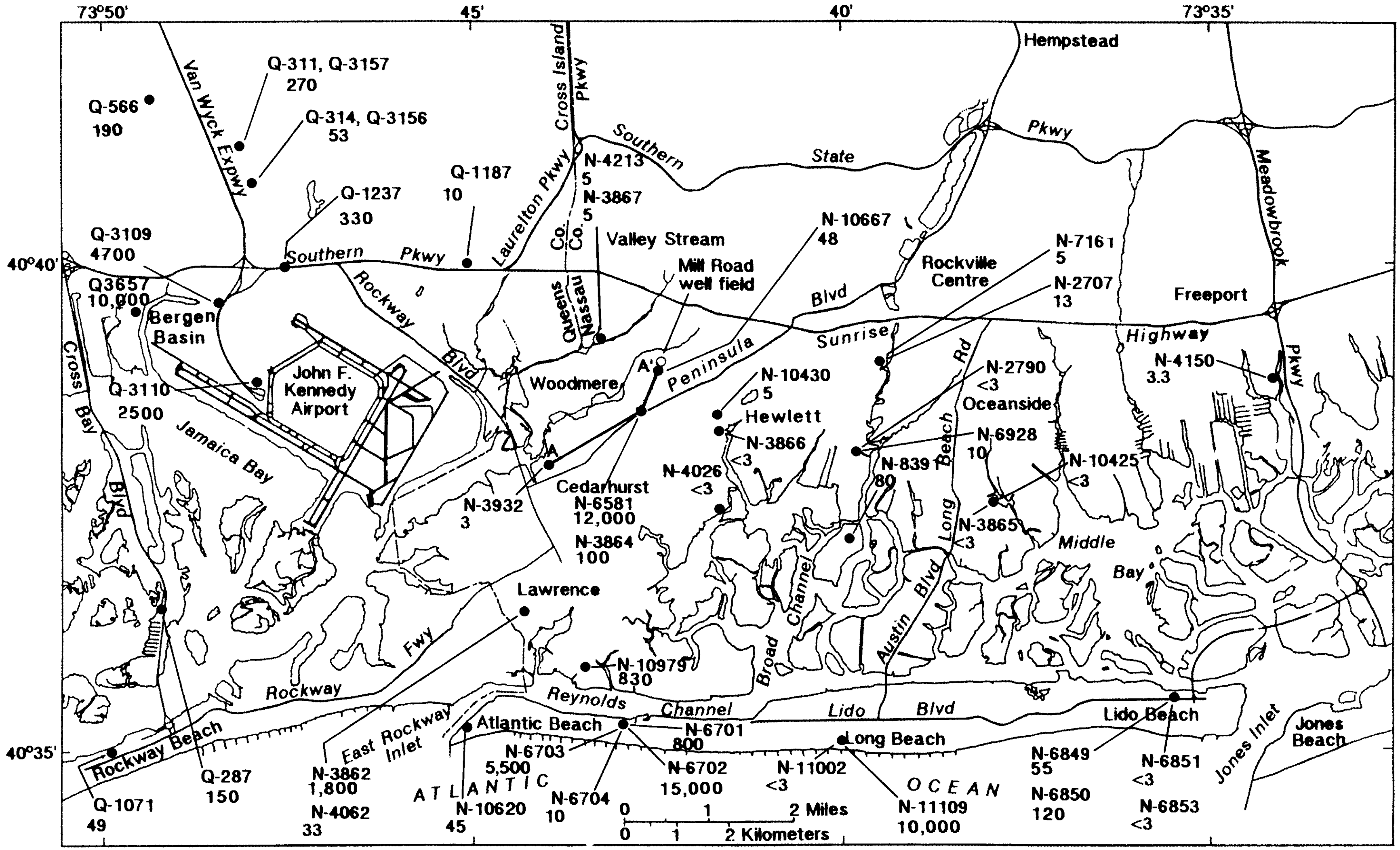
[2] As reported by Nassau County Department of Public Works, 1988.

[3] Water levels in these wells are known to be affected by local pumpage.

[4] As reported by Jamaica Water Supply Company, 1983.

[5] As reported by Jamaica Water Supply Company, 1987.

[6] Sampled 8/23/89.



Base from New York State Department of Transportation planimetric maps; 1975, 1981; 1:24,000 quadrangles

EXPLANATION

● N-6702 400 — Well location and state identification number. Lower number is chloride concentration in milligrams per liter

○ — Well field

A———A' — Trace of hydrogeologic section

Figure 5. Locations of wells from which 1988 chloride-concentration data were used to monitor saltwater intrusion in study area, Long Island, N.Y. (Location is shown in fig. 1.)

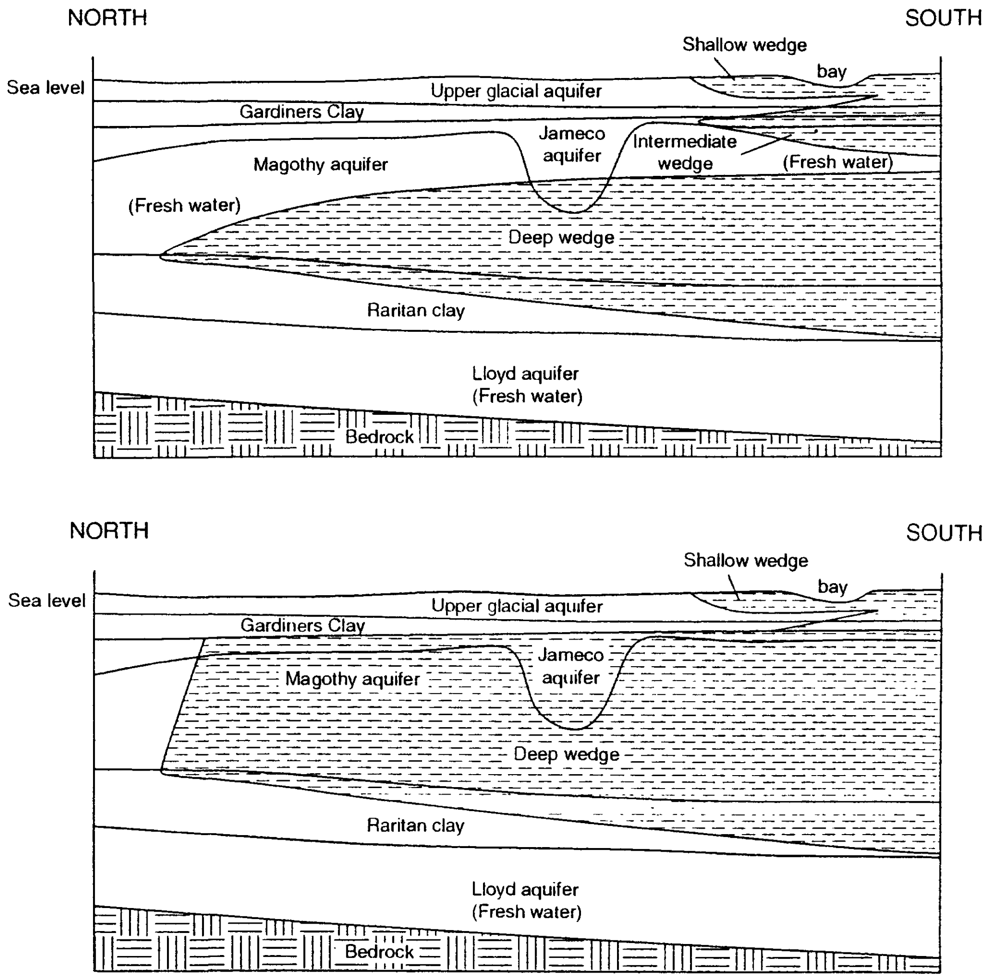


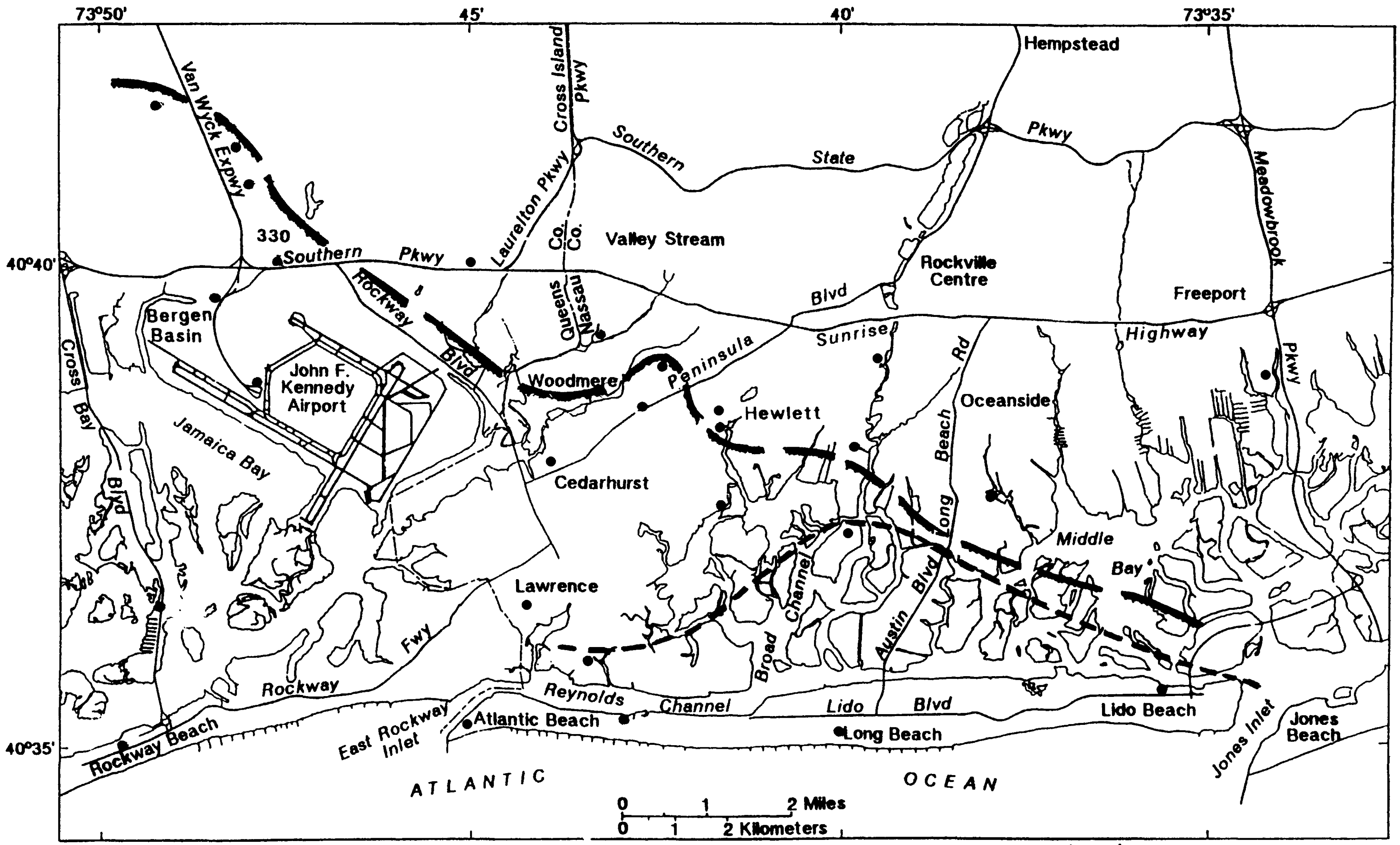
Figure 6. Extent of salty ground water in southwestern Nassau County, N.Y. (top) and southeastern Queens County, N.Y. (bottom). (Modified from Lusczynski and Swarzenski, 1966, pl. 3.)

wedge was detected in the western part of the study area; its presence in the eastern and central parts could be related to the discontinuous nature of the 20-foot clay and (or) Gardiners Clay. The salty ground water in this wedge lies above freshwater in the Jameco and Magothy aquifers; this anomaly has been attributed to density-dependent ground-water flow (Lusczynski and Swarzenski, 1966) and local differences in the hydraulic properties of the Jameco and Magothy aquifers. Pore-water chloride data from the filter pressing of cores collected in this study during the drilling of well N11109 in Long Beach confirm the presence of the intermediate wedge in that area. The lower surface of the intermediate wedge at this site is about 450 ft below sea level.

Deep Wedge

The deep wedge is present in Queens and Nassau Counties (fig. 7). Its landward extent is along the surface of the Raritan clay. The altitude of the landward extent in the eastern part of the study area is about 900 ft below sea level; in the western part, it is about 350 ft below sea level.

Four new observation wells (N10425, N10430, N11109, and N10667) were installed at the base of the Magothy aquifer in the study area to monitor the shape and position of the deep wedge (table 2). Well N10425 in Oceanside and N10430 in Hewlett (fig. 5) were screened in freshwater at the base of the Magothy aquifer below the screens of older wells at these locations to detect landward movement of saltwater in the deep wedge in these areas.



Base from New York State Department of Transportation planimetric maps; 1975, 1981; 1:24,000 quadrangles

EXPLANATION

APPROXIMATE LANDWARD LIMIT OF DEEP WEDGE

APPROXIMATE LANDWARD LIMIT OF INTERMEDIATE WEDGE

Figure 7. Landward limit of deep and intermediate saltwater wedges, Long Island, N.Y. (Modified from Lusczynski and Swarzenski, 1966, p. 3.)

Well N11109, in Long Beach, was screened in the Magothy aquifer at an altitude of 775 to 780 ft below sea level. Pore-water chloride data from the filter pressing of cores (Lusczynski, 1961a) collected during the drilling of this well indicate that the upper surface of the deep wedge at this site is 650 ft below sea level. Chloride concentrations in water samples from this well exceeded 10,000 mg/L.

Observation well N10667, at the southern end of the Mill Road well field (fig. 6), was screened in the Magothy at an altitude of 522 to 532 ft below sea level. This well was intended to monitor landward movement of the deep saltwater wedge beneath the well field; chloride concentrations at this well in 1988 were about 50 mg/L. Well N6581, which is about 2,640 ft south of well N10667, was screened at an altitude of 566 to 576 ft below sea level. Chloride concentrations exceeding 12,000 mg/L in water samples from this well in 1988 indicate that the deep wedge is near the well field (fig. 7).

Lloyd Aquifer

The Lloyd aquifer generally contains freshwater in the study area. Chloride concentrations in the Lloyd aquifer along the barrier islands increase westward from less than 5 mg/L at Lido Beach to about 50 mg/L at Rockaway Beach. Chloride concentrations in 1988 at two new observation wells screened in the Lloyd aquifer on the barrier island, N11002 in the city of Long Beach and N10620 in Atlantic Beach, were 45 mg/L and less than 3 mg/L, respectively. Pore-water chloride concentrations in samples from these wells indicate the presence of salty ground water in the Raritan clay (40 ft below the Raritan surface at Long Beach and 80 ft below it at Atlantic Beach). The Raritan clay is about 200 ft thick in both areas.

Possible evidence of salty ground water was found at two wells during the study. Water samples from one recently installed private well (Q3657) west of John F. Kennedy Airport (JFK), near Bergen Basin in Queens (fig. 5), had chloride concentrations of 10,000 mg/L in 1989; this value is consistent with the concentration of 8,700 mg/L at another private well (K3426) that taps the Lloyd aquifer 3 mi west of Q3657 in Kings County, just beyond the study area. These concentrations are much higher than those at wells to the south along the barrier islands and at public-supply wells north of JFK. Samples from public-supply wells north of JFK have had chloride concentrations less than 5 mg/L. The source of the anomalously high chloride concentrations is a matter of conjecture but is a concern to water suppliers. More data would be needed for an assessment, however.

Well N6701, in Atlantic Beach on the barrier island, is screened above the Lloyd aquifer in the Raritan confining unit at an altitude of 811 to 821 ft below sea level. Chloride concentrations in well N6701 increased from 2,000 mg/L in 1960 to 8,110 mg/L in 1969. In 1988, chloride concentrations were less than 1,000 mg/L. The reason for this variation in chloride concentration is unknown.

Movement of Freshwater/Saltwater Interface at Selected Sites

The position of the freshwater/saltwater interface has changed little since the 1960's. Of the 23 wells sampled in the current study and by Cohen and Kimmel (1971), only four showed change in chloride concentration (N6701, N3864, N6581, and Q1237); of these four, the latter three also had shown increases during 1960-69. The position of the interface has changed in some areas, as evidenced by increases in chloride concentrations. The rate of increase is dependent on many factors, including the position of the well screen with respect to the transition zone, the uniformity of chloride concentrations within the transition zone, and the direction and rate of movement of the salty ground water by advection and dispersion.

Movement of the freshwater/saltwater interface near the Mill Road well field is indicated by an increase in chloride concentrations in well N3864 (fig. 8) and in well N6581. Both wells are about 0.5 mi south of the well field. Well N6581 is screened at the base of the Magothy aquifer in the deep wedge, and well N3864 is screened 100 ft higher. Electric-log data indicated that the upper boundary of the deep wedge moved upward 21 ft during 1952-58. Lusczynski and Swarzenski (1960) used this increase in thickness of the deep wedge at this site to calculate a saltwater-encroachment rate of nearly 300 ft/yr. The chloride concentration at well N3864 was not higher than 5 mg/L before 1969 but increased from 18 mg/L in 1985 to 133 mg/L in 1988 (fig. 8A); this increase is indicated in figure 9. The chloride concentration at the other well (N6581) increased from 11,000 mg/L in 1969 to about 12,000 mg/L in 1988. The position of the 40-mg/L concentration contour, as inferred from the increase in chloride concentration at well N3864,

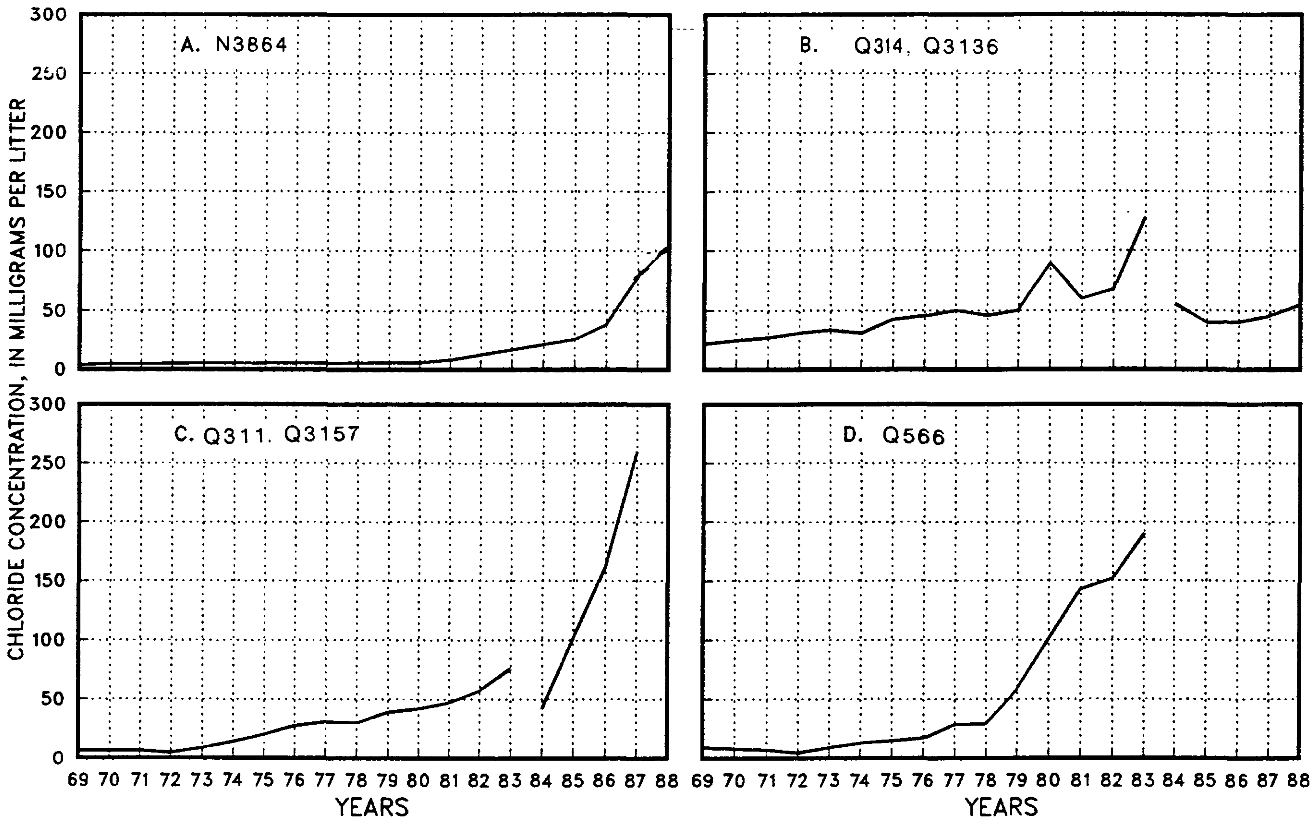


Figure 8. Partial chloride-breakthrough curves for selected wells, Queens and Nassau Counties, N.Y.: A. N3864. B. Q314 and its replacement (Q3156). C. Q311 and its replacement (Q3157). D. Q566. (Well locations are shown in fig. 5.)

indicates that the deep wedge in this area increased in thickness by about 75 ft during 1958-88 and has moved landward at an average rate of 100 ft/yr. The movement of the chloride front corresponds to the migration of salty ground water along the surface of the clay lens near the bottom of the Magothy Formation in Woodmere.

Observation well Q1237 (fig. 5) has been used to monitor saltwater encroachment in the upper part of the deep wedge in the Jameco aquifer. The chloride concentration at this well increased from 112 mg/L in 1969 to greater than 300 mg/L in 1988. Chloride concentrations in production wells north and west of Q1237 indicate landward movement of saltwater in the lower part of the deep wedge in the Jameco aquifer; these wells include Q314, which was replaced by Q3156 in 1983; Q311, which was replaced by Q3157 in 1983; and Q566. The replacement wells were drilled to similar depths and are near the original wells. Data from annual sampling of these wells, usually during the summer, were provided by the Jamaica Water Supply Company. Reported chloride concentrations at well Q314 (fig. 8B) were about 20 mg/L during 1961-69 but increased to 128 mg/L in 1983. This well was replaced with well Q3156, from which chloride concentrations of about 50 mg/L have been reported since 1984. This apparent decrease is unexplained but could reflect local differences in the hydraulic properties of the Jameco between the two wells within the 50-ft screen interval. Samples from well Q311, its replacement (Q3157), and Q566 all indicate increases in chloride concentration since the early 1970's (figs. 8C, 8D). Chloride concentrations increased significantly at well Q311 (fig. 5) and its replacement (Q3157), from less than 50 mg/L in 1984 to more than 250 mg/L in 1987 (fig. 8C). Concentrations at well Q566 (fig. 5) increased from about 25 mg/L in 1978 to nearly 200 mg/L in 1983 (fig. 8D).

Water Levels in Observation Wells

Spatial variations in fluid density within each of the saltwater wedges can complicate predictions of ground-water flow direction and magnitude from measured hydraulic head. A common practice in hydraulic studies in areas where fluid-density varia-

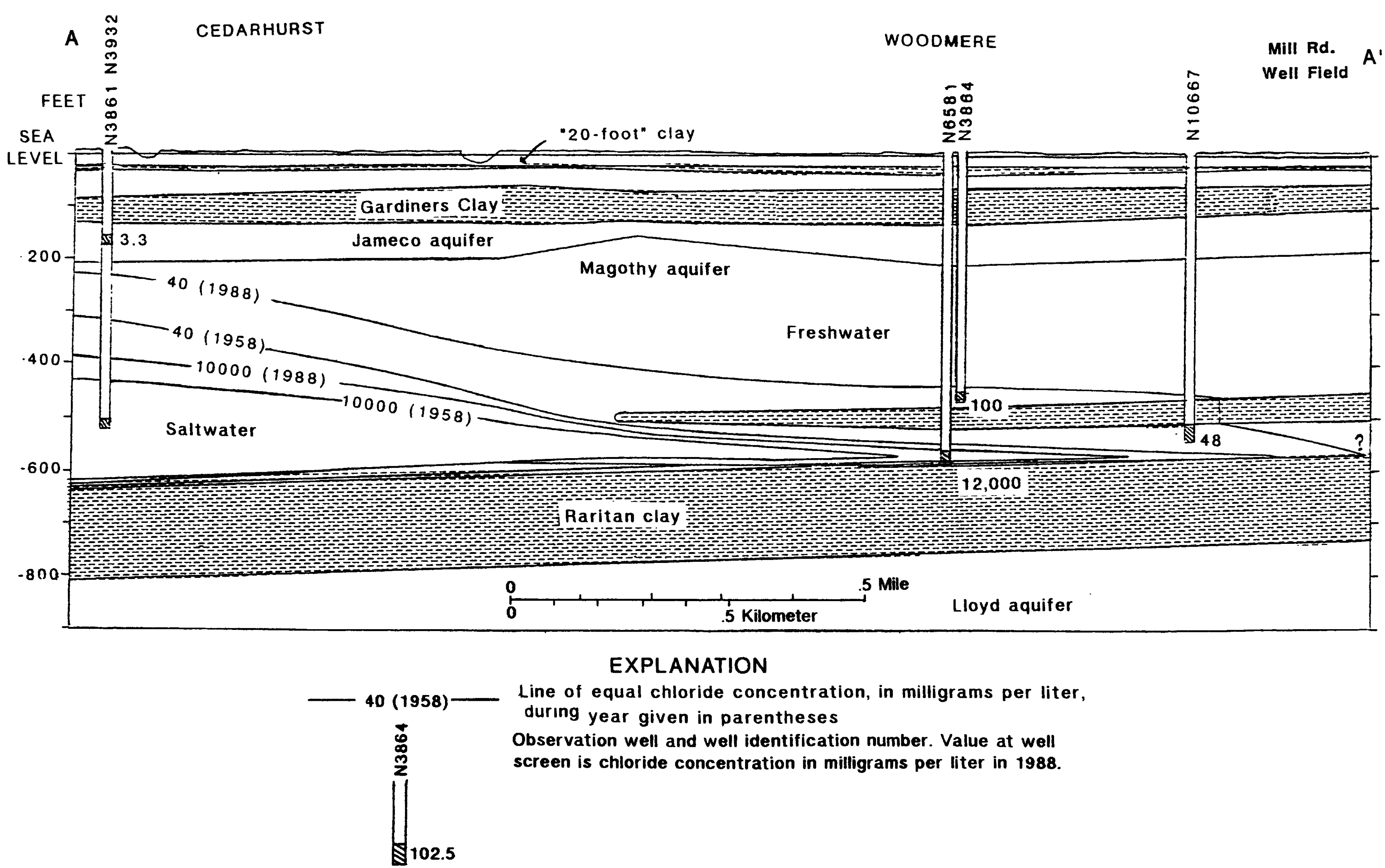


Figure 9. Hydrologic section A-A′, Nassau County, N.Y., showing position of 40- and 10,000-milligram per liter salt fronts in 1958 and 1988, (Modified from Lusczynski and Swarzenski, 1960, pl. 3. Trace of section is shown in fig. 5.)

tions are present is to normalize measured hydraulic heads by calculating the equivalent-freshwater head defined (at a point) as the water level in a well filled with freshwater from a point to a level high enough to balance the existing pressure at the point (Lusczynski 1961b). The normalized head data are commonly contoured to define a surface where flow is assumed to be orthogonal to the contours. As discussed by various authors (Lusczynski, 1961b); Reilly and Goodman, 1985), accurate determination of ground-water flow direction and magnitude requires consideration of both pressure and density-related gravity-force components. The equivalent-freshwater head accounts for the pressure component only; the effect of gravity that results from the variable density of the fluid is ignored. One approach to defining the flow field in a variable-density-fluid environment is to develop a numerical flow model that incorporates the effects of density (as discussed by Reilly and Goodman, 1985 and Essaid, 1990). Such an approach was beyond the scope of this study, but the head and chloride-concentration data needed for estimation of density are given in table 2.

Future Monitoring of Freshwater/Saltwater Interface

About 25 percent of the wells reported on by Cohen and Kimmel (1971) were not sampled because the screens were clogged, or the well casing was obstructed. The loss of these observation wells and other similar wells on Long Island is of concern to the water-management community, not only because data and sampling capability are lost, but because the cost of replacement continues to increase.

Use of plastic well casing wherever feasible for the purpose of monitoring the movement of salty ground water would facilitate induction logging, which measures the electrical conductivity of the formation. This technique has proved useful because it provides a continuous record of formation conductivity along the entire well length. The electrical conductivity of the formation is affected by the pore-fluid conductivity, which reflects the salinity (chloride concentration). This type of geophysical logging is insensitive to the conductivity of fluid in the well and therefore can maintain the monitoring capability of a well whose screen becomes clogged or whose casing fails, as long as the well remains open.

SUMMARY AND CONCLUSIONS

The landward movement of salty ground water in a 150-mi^2 south-shore area of southeastern Queens and southwestern Nassau Counties that includes the barrier beach is evidenced by an increase in chloride concentration at some production wells and observation wells since the 1960's. Movement of salty ground water in the vicinity of these wells is attributed to ground-water pumping at or near the wells, and the rate of movement is likely to be accelerated by increased pumping. The positions of two saltwater wedges in the Jameco and Magothy aquifers the study area have been updated. Of the 23 wells sampled in the current study and by earlier investigators, only four showed any change in chloride concentration; three of these also showed increases during 1960-69.

The increase in chloride concentration at a well in Woodmere by 1988, and the position of the 40-mg/L chloride front in 1958, indicate the rate of movement of the deep wedge near the Mill Road well field to be about 100 ft/yr. Graphs of chloride concentration at production wells in southeastern Queens County through time indicate that the interface is moving toward at least three pumping centers.

Most of the observation wells used to monitor movement of salty ground water have not shown any significant change in chloride concentration since their installation. This is probably because: (1) the rate of landward movement is relatively slow (about 100 ft/yr in Woodmere), and (2) the wells are not close enough to the saltwater interface to detect increases.

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