Salt-Water Encroachment in Southern Nassau and Southeastern Queens Counties Long Island, New York

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GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1613-F

Prepared in cooperation with the Nassau County Department of Public Works and the New York State Water Resources Commission

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By N. J. LUSCZYNSKI *and* W. V. SWARZENSKI

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SALT-WATER ENCROACHMENT IN SOUTHERN NASSAU AND SOUTHEASTERN QUEENS COUNTIES, LONG ISLAND, NEW YORK

By N. J. Lusczynski and W. V. Swarzenski

ABSTRACT

Test drilling, extraction of water from cores, electric logging, water sampling, and water-level measurements from 1958 to 1961 provided a suitable basis for a substantial refinement in the definition of the positions, chloride concentrations, and rates of movement of salty water in the intermediate and deep deposits of southern Nassau County and southeastern Queens County.

Filter-press, centrifugal, and dilution methods were used to extract water from cores for chloride analysis at the test-drilling sites. Chloride analyses of water extracted by these methods, chloride analyses of water from wells, and the interpretation of electric logs helped to define the chloride content of the salty water. New concepts of environmental-water head and zerovels, developed during the investigation, proved useful for defining hydraulic gradients and rates of flow in ground water of variable density in a vertical direction and in horizontal and inclined planes, respectively. Hydraulic gradients in and between fresh and salty water were determined from water levels from data at individual and multiple-observation wells.

Salty ground water occurs in southern Nassau and southeastern Queens Counties as three wedgelike extensions that project landward in unconsolidated deposits from a main body of salty water that lies seaward of the barrier beaches in Nassau County and of Jamaica Bay in Queens County. Salty water occurs not only in permeable deposits but also in the shallow and deep clay deposits. The highest chloride content of the salty ground water in the main body and the wedges is about 16,000 ppm, which is about 1,000 to 2,000 ppm less than the chloride content of ocean water.

The shallow salty water in the Pleistocene and Recent deposits is connected freely with the bays, tidal estuaries, and ocean. The intermediate wedge is found only in the southwestern part of Nassau County in the upper part of the Magothy(?) Formation, in the Jameco Gravel, and in the overlying clay deposits. It extends from the seaward areas inland about 2 miles into Island Park. The deep wedge extends into southeastern Queens County and southern Nassau County principally in the deeper parts of the Magothy(?) Formation and in the underlying clay member of the Raritan Formation. The leading edge of the deep wedge is at the base of the Magothy(?) Formation. This edge is apparently at the shoreline east of Lido Beach and extends inland about 4 miles to Woodmere and about 7 miles to South Ozone Park.

Zones of diffusion as much as 6 miles wide and about 500 feet thick were delineated in the frontal part of the salty-water wedges. These thick and broad zones of diffusion were probably formed during the past 1,000 or more years in heterogeneous unconsolidated deposits by long- and short-term changes in sea level and in fresh-water outflow to the sea and by dispersion caused by the movements of the water and its salt mass. Changes in sea level and fresh-water outflow together produced appreciable advances and recessions of the salt-water front. The chemical compositions of the diffused water in all wedges are modified to some extent by base exchange and other physical and chemical processes and also by diffusion.

The intermediate wedge of salty water is moving landward at a rate of less than 20 feet a year in the vicinity of Island Park and, thus, has moved less than 1,000 feet since 1900. The leading edge of the deep wedge has advanced landward at about 300 feet a year in Woodmere in southwestern Nassau County and about 160 feet a year at South Ozone Park in southeastern Queens County, principally under the influence of local withdrawals near the toe of the wedge. Between Hewlett and Lido Beach, the deep wedge is moving inland at the rate of about 10 feet a year under the influence of regional withdrawals in inland areas. Regional encroachment of the deep wedge is apparently retarded appreciably by cyclic flow, that is, by the return seaward in the upper part of the zone of diffusion of some of the salty water moving landward in the lower part. The deep wedge has advanced landward as much as a mile locally, but less than 1,000 feet regionally since the start of withdrawals at the turn of the century.

Along and near the barrier beaches, salty water from the underside of the deep wedge in the clay member of the Raritan Formation is moving downward very slowly toward the fresh water in the Lloyd Sand Member. The downward moving salty water undoubtedly has reached the upper beds of the Lloyd in the nearby offshore areas and from there is moving landward within the cones of depression of the pumped wells along the barrier beach. The very small increases in chloride content of water pumped at Long Beach, Atlantic Beach, and Rockaway Park suggest downward intrusion and perhaps lateral intrusion from offshore areas to the supply wells in the upper beds of the Lloyd Sand Member.

The life of pumped wells near the salt-water wedges is necessarily limited. Because of the slow movement of salty water under present conditions, however, nearshore public-supply wells and most of the other wells screened in the Lloyd Sand Member, Magothy(?) Formation, and the Jameco Gravel near the wedges will not be in danger of any serious contamination by salt water during at least the next two decades.

It is estimated on the basis of present and possible future ground-water developments that by the year 2000 the leading edges of the deep wedge moving along the base of the Magothy(?) Formation may reach (a) areas about a mile inland of South Ozone Park and (b) the vicinity of Sunrise Highway at Valley Stream and Lynbrook. Elsewhere the deep wedge and the intermediate wedge of salty water may not advance more than about a mile by the year 2000. These estimates are based on the assumption that no artificial recharge, no imported water or freshened saline water, no artificially created mounds in the ground-water reservoir, or any other methods will be used to retard encroachment.

INTRODUCTION

PURPOSE AND SCOPE

This report is concerned principally with the results of a detailed investigation of salt-water encroachment in the artesian aquifers of

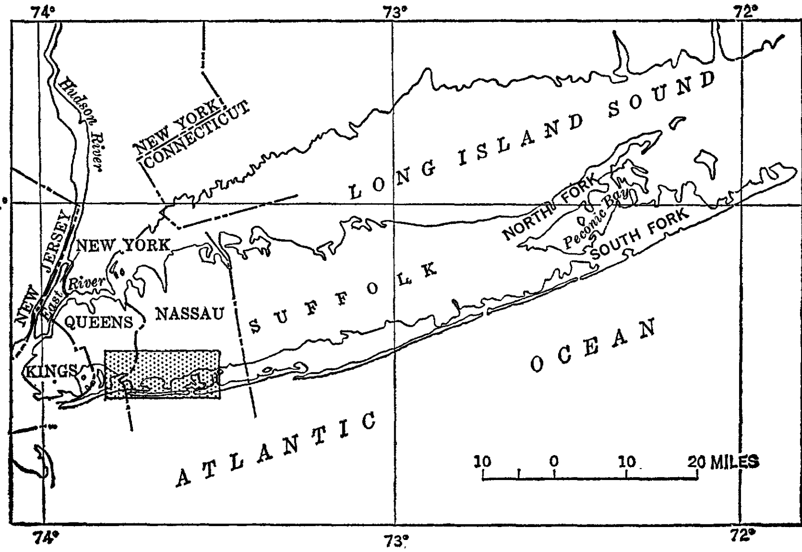

FIGURE 1.—Area of investigation.

southern Nassau and southeastern Queens Counties, Long Island, N.Y. (fig. 1). Most of the new data were collected between 1958 and 1961 by the U.S. Geological Survey in cooperation with the Nassau County Department of Public Works and the New York State Water Resources Commission. Some data obtained in 1962 were also used.

The investigation described herein is a sequel to an initial study of salt-water encroachment made from 1952 to 1956 (Perlmutter and others, 1959; Perlmutter and Geraghty, 1963). Test drilling, electric logging, core sampling, extraction of water from cores, water sampling, and monitoring of water levels provided the basis for (a) an improvement of the definition of the geologic environment, (b) the delineation of the position and the salinity of the salty-water wedges, and (c) the determination of hydraulic gradients in and the rates of movement of salty water. For this report, ground water having a chloride content of less than 40 ppm is called fresh water, that between 40 and 15,500 ppm is called diffused water, and that between 15,500 and 16,500 ppm (average of 16,000 ppm) is called salt water. Also, for the sake of convenience in some of the hydrologic sections, ground water having a chloride content of 40 to 16,500 ppm is referred to by the general term "salty water" (includes both diffused and salt water).

Five progress reports on special phases of the investigation have been published already. The results of test drilling in the Cedarhurst-Woodmere area are described by Lusczynski and Swarzenski (1960). A preliminary appraisal of findings beneath the barrier beaches in southwestern Long Island is given in a paper by Lusczynski and Swarzenski (1962). Techniques for extracting water from cores for chloride analysis are described by Swarzenski (1959) and by Lusczynski (1961a). The concepts of heads and flow in ground water of variable density that were developed during the investigation are elaborated in a paper by Lusczynski (1961b).

This investigation is part of a continuing study of the ground-water resources of Long Island by the U.S. Geological Survey in cooperation with the New York State Water Resources Commission, the Nassau County Department of Public Works, the Suffolk County Board of Supervisors, and the Suffolk County Water Authority. The investigation was made under the direction of G. C. Taylor, Jr., former district geologist. The report was prepared under the supervision of R. C. Heath, district geologist, and N. M. Perlmutter, geologist-in-charge.

LOCATION AND DESCRIPTION OF THE AREA

The report area includes most of southern Nassau County and the adjacent part of southeastern Queens County (fig. 1 and pl. 1).

The land surface in the area is a glacial outwash plain which slopes southward from an altitude of about 40 feet to sea level at shoreline. The southern half of the area consists of tidal marshes, bays, islands, and barrier beaches bordered by the Atlantic Ocean. Some low-lying marsh areas, which have been filled with sand dredged from adjacent bays and streams, were raised to levels ranging from about 2 to 10 feet above sea level,[1] and afterwards utilized for home sites. The area of bays and marshes is continuous along the south shore of Nassau County but is separated from Jamaica Bay in Queens County by Rockaway Peninsula, a northeast-trending ridge that rises 25 to 30 feet above the adjacent lowlands.

METHODS OF INVESTIGATION

DRILLING PROGRAM, 1958–61

Detailed geologic, hydrologic, and chemical data were obtained from individual test holes and multiple observation wells drilled at Woodmere and Lawrence in 1958, at Atlantic Beach and Hewlett Neck in 1959, at Lido Beach and Bay Park in 1960, and at Rockville Centre in 1961 (table 1 and pl. 1). In all, 26 wells, ranging in depth from about 6 to 1,050 feet, were installed during the period. The shallow wells were installed by driving and consisted of steel pipe terminating in screened well points. The deeper wells were installed under contract by the standard rotary drilling method; all the holes were cased and screened

[1] Altitudes of land surface, water levels, well screens, and salty-water wedges are referred to mean sea level at Sandy Hook, N.J., unless indicated otherwise; (−) indicates below mean sea level.

except the test holes N6467T, N6468T, and N6469T at Woodmere. The general procedure for installing the deep wells consisted of drilling a test hole 6 to 8 inches in diameter and coring at 5- to 20-foot intervals. Electric logs were obtained at each well and a gamma-ray log was obtained at one (table 1). Each test hole was reamed, where necessary, to a size large enough to accommodate an individual casing or several (multiple) casings and screens. (See Atlantic Beach, Hewlett Neck, and Lido Beach wells, table 1.) The screens were gravel packed, and clayey material or cement grout was pumped into the annular space in the intervals ranging from 5 to 20 feet above and below the screen. The remainder of the annular space was filled with material whose permeability corresponded to or was less than that of the natural deposits at various depths. At some places, for example Woodmere, several wells drilled individually at different times at nearby sites serve as multiple-observation wells. The finished observation wells were developed to yield at least 1 gallon per minute by a centrifugal pump.

The geologic units and lithology at each test hole were determined principally from megascopic examination of cores and on the basis of electric and drillers' logs. Water was extracted in the field from most of the cores, and the chloride content was determined by standard titration procedures.

DETERMINATION OF CHLORIDE CONTENT OF WATER FROM CORES

The centrifugal, dilution, and filter-press methods were used in the field to obtain water samples for the determination of the chloride content of the water in the cores. Techniques for the use of these methods were developed during the investigation.

Swarzenski (1959) described the centrifugal and dilution methods used during the first phase of the drilling in 1958. The centrifugal method was found to be suitable for obtaining a water sample for the determination of the chloride content of water in sand, clayey sand and silt. It involves the extraction of water by means of a centrifuge and then, titration to determine chloride content. The dilution method was devised for clay and silty clay which yield little or no water by centrifugal extraction. The laboratory procedure for this method requires a determination of moisture content from the loss in weight of a selected part of a core after this part has been dried in an oven at a temperature of 180°F for about 24 hours; the restitution of original moisture content and further dilution with distilled water; re-solution of the salts precipitated during drying; filtration; and, finally, titration to determine chloride content. The dilution method, in its present stage of development, yields only approximate results.

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The filter-press method was first used in this investigation during the test drilling at Atlantic Beach in 1959. It produced reliable results under controlled conditions, not only with samples of sand and silt but also with samples of clay and silty clay. The filter-press method and the results obtained by the filter-press, centrifugal, and dilution methods at a test well at Atlantic Beach are discussed by Lusczynski (1961a).

TABLE 1.—*Multiple observation wells in southern Nassau County at sites of test drilling in 1958–61*

Geologic unit screened: Qd, Recent deposits; Qud, upper Pleistocene deposits; Qj, Jameco Gravel; Km, Magothy(?) Formation; Krc, clay member of Raritan Formation: Krl, Lloyd Sand Member of Raritan Formation.

Remarks: C, core samples; E, electric log; G, gamma-ray log; Pn, gravel pack around screen, and material above and below the screen less permeable than that occurring naturally at the site; Pc, gravel pack around screen, and cement grout above and below screen; gpm, yield in gallons per minute.

[Altitudes, water levels, and screen settings are referred to mean sea level at Sandy Hook, N.J.]

Well	Date completed	Bottom of drilled hole (feet below sea level)	Casing diameter [1] (inches)	Screen diameter (inches)	Screen setting (feet below sea level)	Geologic unit screened	Remarks
Atlantic Beach							
N6724	Aug. 1959	6	4–1¼	1¼	[2] 3.4–5.4	Qd	Pn, 2 gpm, about 40 ft from N6701, driven well.
N6723	do	54	1¼	1¼	[3] 51.8–53.8	Qud	Pn, 15 gpm, about 40 ft from N6701, driven well.
N6705 [4]	do	285	4–1¼	1¼	[3] 135.5–145.5	Qj	Pn, 4 gpm, about 8 ft from N6701.
N6704 [4]	do	285	4	4	[2] 273–283	Km	Pn, 6 gpm, about 8 ft from N6701.
N6703 [4]	do	846	1¼	1¼	[3] 457–467	Km	Pn, 3 gpm, about 160 ft from N4405.
N6702 [4]	do	846	4	4	[3] 656–666	Km	Pn, 6 gpm, about 160 ft from N4405.
N6701 [4]	do	846	4–1¼	1¼	[3] 811–821	Krc	C, E, Pn, 3 gpm, about 160 ft from N4405.
N4405 [5]	July 1954	1,107	20–8	8	[2] 995–1,065	Krl	E, Pc, 1,400 gpm.
Bay Park							
N6241	Nov. 1949	34	1¼	1¼	[3] 32–34	Qud	3 gpm, about 10 ft from N2790, well point destroyed before 1958.
N2790	do	863	6	6	[2] 535–557	Km	C, E, Pn, 20 gpm.
N6928	July 1960	854	6–2	4	[2] 710–720	Km	C, E, Pn, 1 gpm, about 15 ft from N2790.
Hewlett Neck							
N6793	Sept. 1959	5	4	1¼	[3] 3–5	Qd	Pn, 3 gpm, 2 ft from N6706.
N6792	do	44	4–1¼	1¼	[2] 42–44	Qud	Pn, 10 gpm, 10 ft from N6706
N4026	July 1952	192	6–4	4	[2] 145–149	Qj	Pn, 20 gpm.
N6707 [4]	Sept. 1959	737	4	4	[3] 487–497	Km	Pn, 5 gpm, about 15 ft from N4026.
N6706 [4]	do	737	3–1¼	4	[3] 618–623	Km	C, E, Pn, 5 gpm, about 15 ft from N4026.

See footnotes at end of table.

TABLE 1.—*Multiple observation wells in southern Nassau County at sites of test drilling in 1958–61*—Continued

Well	Date completed	Bottom of drilled hole (feet below sea level)	Casing diameter [1] (inches)	Screen diameter (inches)	Screen setting (feet below sea level)	Geologic unit screened	Remarks
Lawrence							
N6610 [5]	Oct. 1958	222	8	----------	[2] 192–222	Qj	Pn, 600 gpm.
N6510	do	452	4–2½	----------	[3] 447–452	Km	C, E, Pn, 2 gpm, about 10 ft from N6610.
Lido Beach							
N6920	May 1960	35	4–1¼	1¼	[3] 33–35	Qd	Pn, 6 gpm, about 30 ft from N6850.
N6853 [4]	do	1,032	6–2	4	[2] 120–125	Km	Pc, 6 gpm, about 11 ft from N6850.
N6852 [4]	do	1,044	6–2	4	[3] 251–256	Km	Pc, 6 gpm, about 180 ft from N5227.
N6851 [4]	do	1,044	4–2	4	[2] 544–549	Km	Pc, 6 gpm, about 180 ft from N5227.
N6850 [4]	do	1,044	6–2	4	[3] 891–902	Km	C, E, G, Pc, 4 gpm, about 180 ft from N5227.
N6849 [4]	do	1,032	6–2	4	[3] 1,020–1,030	Krc	C, Pc, 1 gpm, about 11 ft from N6849.
N5227 [5]	June 1956	1,278	12–8	8	[2] 1,190–1,250	Krl	E, Pc, 1,260 gpm, about 403 ft from supply well N46, screened in the Lloyd Sand Member.
Rockville Centre							
N7207	Aug. 1961	90	4–2	2	[2] 87–90	Km	Pn, 1 gpm, about 10 ft from N7161.
N7161	do	690	6–4	4	[2] 654–659	Km	C, E, Pc, 20 gpm.
Woodmere							
N6246	May 1952	2	1¼	1¼	[2] 0–2	Qud	3 gpm, well point destroyed before 1958.
N1382	1941	188	8	8	[2] 168–188	Qj	Pn, 25 gpm, near former well N1379 screened at about the same depth.
N3864	May 1952	632	6	6	[2] 455–466	Km	C, E, Pn, 10 gpm.
N6581	Sept. 1958	611	8–6	6	[3] 565–575	Km	E, Pc, 25 gpm, 12 ft from N3864, 21 ft from N1382.

[1] Larger of two sizes, although extending no more than 40 ft below land surface at observation wells, extends much deeper at supply wells.
[2] Well screened in fresh water (chloride content less than 40 ppm).
[3] Well screened in salty water (chloride content more than 40 ppm).
[4] Wells installed in the same hole at different depths.
[5] Supply well; used also as observation well.

The filter-press method is simple, rapid, and convenient. It can be used to determine chloride content in the field within minutes after a core is brought to land surface. The interstitial water in a core is extracted by a commercial filter press, and the filtrate is analyzed for chloride content by titration with a standard silver nitrate solution. The filter press consists of a chamber to hold the sample, a filtering medium, a means of catching and measuring the filtrate, and provisions for a pressure source (fig. 2).

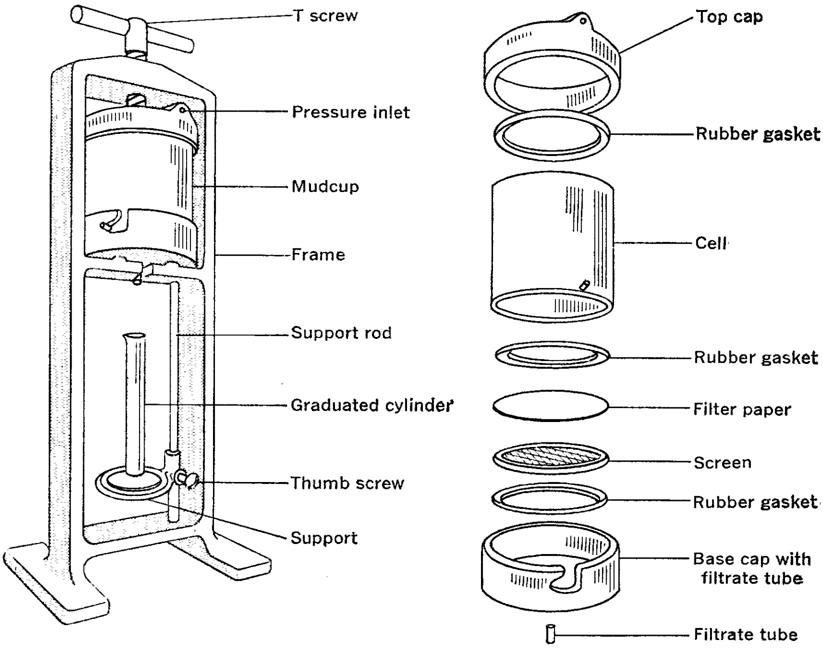


FIGURE 2.—Filter press for extracting intersitial water from cores. Courtesy of Baroid Division, National Lead Co.

The method was used for cores obtained in a split-spoon core barrel 2 inches in diameter and 18 or 24 inches long. Partial invasion of the cores by drilling fluid was unavoidable owing to the rotary method of drilling. Addition of fluorescein dye to the drilling mud gave the mud a distinctive green color, which permitted visual detection of the invaded parts of the cores. A fluoroscope was also used to assure the selection of uncontaminated material and to check the filtrate for the presence of minute amounts of drilling mud. In the filter-press method the chamber of the press is partly filled with uncontaminated material, assembled, placed in the frame, and made airtight by the T-screw. Pressure introduced through an opening in the upper cap of the chamber forces interstitial water out of the material and into the filtrate tube through a small opening in the base cap.

Chloride determinations of the filtrate were made in the field by the standard titration method using a silver nitrate solution of 1 ml $AgNO_3$=1.0 mg or a solution of 1 ml Ag=0.5 mg Cl. With these silver nitrate solutions, relatively large amounts of filtrate (25 to 50 ml) are needed if fresh water is analyzed, and relatively small amounts (1 to 10 ml) if salt water or diffused water is analyzed.

For small quantities of fresh or slightly diffused water, the weaker strength solution yields more accurate results.

The filter-press method was introduced first on Long Island by C. W. Lauman & Co., Inc., well-drilling contractors of Bethpage, Long Island, N.Y., for defining chloride concentrations in sand zones during the construction of a test hole for a supply well. The results obtained, however, were only approximate, principally because the material tested was invaded by the drilling fluid.

OBSERVATION AND SAMPLING WELLS

In all, 117 wells (pl. 1 and table 1) were used as control points for water-level contour maps and for delineation of isochlors. Most of the deep and some of the shallow observation wells were equipped with water-stage recorders during part of the period 1958–61. The most complete round of measurements of water levels was obtained from recording gages or was made manually at observation, private, commercial, and supply wells in March 1961. A few later measurements were adjusted to March 1961 values for use in the preparation of the water-level contour maps. During 1958–61, water samples were taken for chloride analysis at least once at most of the wells and several times at many existing wells in the area.

Ground-water temperatures were measured in most of the finished wells. In addition, a profile of ground-water temperatures was made with an electronic thermometer in well N6701 at Atlantic Beach, in well N6706 at Hewlett Neck, and in well N6849 at Lido Beach (fig. 8).

ACKNOWLEDGMENTS

The authors acknowledge with appreciation the cooperation of various agencies, well drillers, and individuals. Special appreciation is due Mr. E. F. Gibbons, Commissioner, Mr. W. F. Welsch, former Senior Engineer, and Mr. H. L. Frauenthal, Hydraulic Engineer, of the Nassau County Department of Public Works, and to Mr. A. H. Johnson, former Associate Engineer, of the New York State Water Resources Commission for their continuous interest in and support of the investigation. The Long Island Water Corp. financed the construction of observation well N6581 in Woodmere in 1958. The village of Lawrence financed the construction of test hole N6510, drilled in 1958 at the Lawrence Golf Course. The casing and screen for the well were furnished by the Nassau County Department of Public Works. The village of Rockville Centre financed the construction of observation wells N7161 and N7201, in Rockville Centre in 1961.

The Town of Hempstead, Lee Associates, and Mr. Philip Lynne also permitted use of their property for test drilling and construction and operation of observation and sampling wells. Mr. R. Sauvage, of the Research Section of the Schlumberger Well Surveying Corp. at

Ridgefield, Conn., furnished advice and field supervision on the electric logging of the test wells at Woodmere.

The Long Island State Park Commission, the city of Long Beach, and other municipalities, water districts, water companies, commercial firms, and private individuals allowed the Geological Survey to collect water-level data and water samples at their wells. Analyses of the water samples were made by the laboratories of the Nassau County Department of Public Works and Department of Health and by the Quality-of-Water Branch of the Geological Survey.

Information on wells, pumpage, chemical quality of water, and water levels was furnished by the Long Island Water Corp., Jamaica Water Supply Co., Town of Hempstead, and other water districts and water companies in the area, as well as by the Nassau County Department of Public Works and the New York State Water Resources Commission. C. W. Lauman and Co., Inc., and Layne-New York Co., Inc., well drillers, furnished logs and well records for several supply wells.

GEOLOGIC ENVIRONMENT

The ground-water geology of southern Nassau and southeastern Queens Counties, including most of the present area of investigation, has been described in a report by Perlmutter and Geraghty (1963). The results of test drilling in Woodmere, Atlantic Beach, and Lido Beach, undertaken as part of the present investigation, have been presented in two articles by Lusczynski and Swarzenski (1960, 1962). Therefore, only a résumé of the geologic environment and its relation to the occurrence and movement of ground water is presented here. New information on the geologic environment collected since 1958 is discussed in some detail.

The distribution of the geologic units in the report area is shown on sections (pl. 2, 3) and on a map (fig. 3). Columnar plots for the test holes and some of the observation wells drilled during the investigation are shown on plate 3 and figure 6. Logs of other wells in the area are given by Perlmutter and Geraghty (1963), Leggette and others (1938), Roberts and Brashears (1946), and the New York State Water Resources Commission (1958).

Unconsolidated deposits of Late Cretaceous, Pleistocene, and Recent age, which thicken southeastward overlie crystalline bedrock. The bedrock is composed of rocks of Precambrian(?) age and slopes to the southeast from a depth of about 700 feet at the northwestern corner of the area to a depth of 1,700 feet at the southeastern corner. It is overlain by the following geologic units in ascending order: Lloyd Sand Member and clay member of the Raritan Formation of Late Cretaceous age; Magothy(?) Formation, also of Late Cretaceous age; Jameco Gravel and Gardiners Clay of Pleistocene age; upper

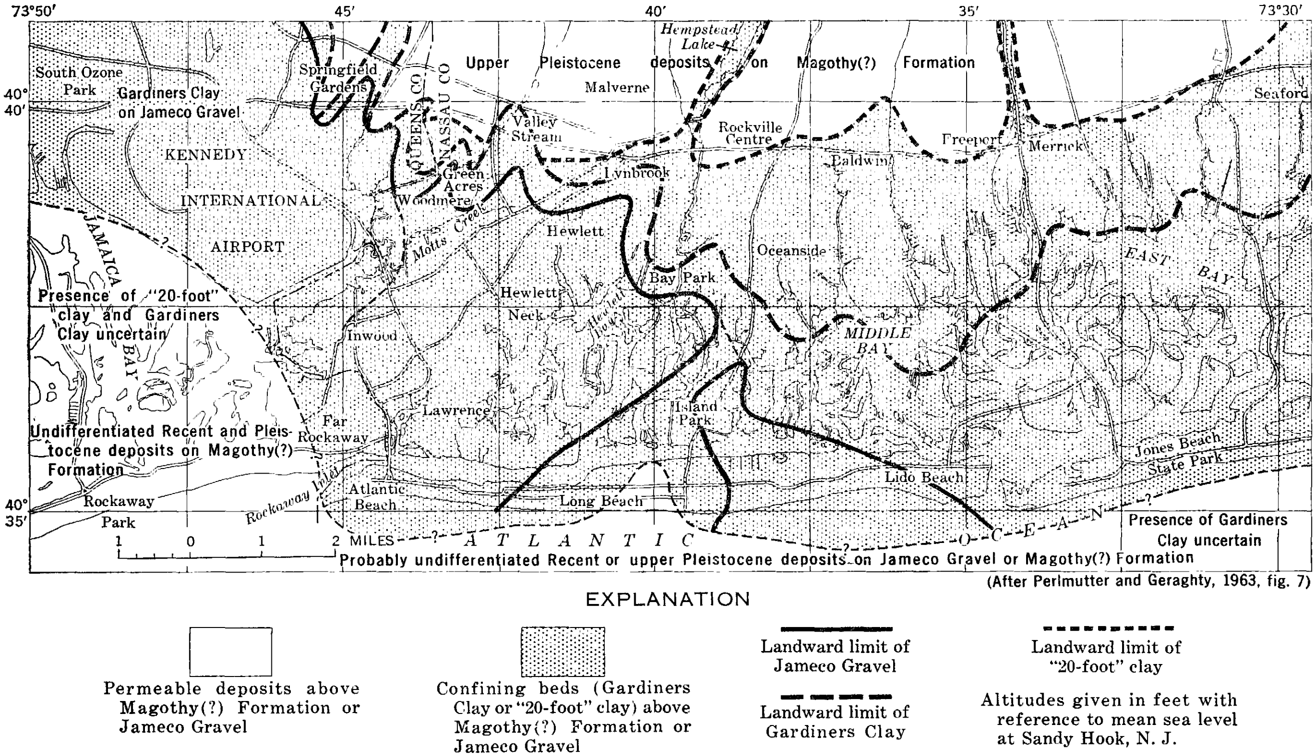


FIGURE 3.—Approximate extent of confining beds overlying the Magothy(?) Formation or Jameco Gravel.

Pleistocene deposits; undifferentiated Pleistocene and Recent deposits; and Recent deposits.

The areal extent and lithology of the unconsolidated deposits are important factors in the distribution and movement of fresh and salty ground water in the report area. Information on the occurrence and general character of geologic units is available from drillers' logs of many wells in the northern and central parts of the report area. Most of the wells, however, were not drilled deeper than the middle or lower part of the Magothy(?) Formation. Detailed stratigraphic data from examination of cores from about land surface down to and including the clay member of the Raritan Formation are available mainly in the southern part of the area at eight outpost wells drilled from 1952 to 1953 (Perlmutter and Geraghty, 1963) and at test holes and observation wells drilled during the present investigation. The deepest wells are public-supply wells in Long Beach and Lido Beach, screened in the Lloyd Sand Member of the Raritan Formation at depths of about −1,200 feet msl (mean sea level). One of these wells, N1927 in Long Beach (pl. 1, 2), penetrated bedrock at −1,458 feet.

The deepest unconsolidated unit, the Lloyd Sand Member, lies directly on the bedrock and consists of beds of fine to coarse quartzose sand and gravel, generally in a clayey matrix, and some interbedded sandy clay and clay. The thickness of the Lloyd Sand Member increases from about 200 feet in the northwestern part of the area to nearly 500 feet in the southeastern part. Electric and drillers' logs indicate that in general the upper 100 to 150 feet of the Lloyd consists of fine-textured material and is underlain by coarser and more permeable material. The Lloyd, confined by the overlying clay member of the Raritan Formation, is an artesian aquifer and contains fresh water in shoreline and inland areas. Because the overlying beds contain salty water in and landward of the shoreline areas, the Lloyd Sand Member is the only aquifer which supplies sizable quantities of fresh water along the barrier beaches in southern Nassau County (Perlmutter and Crandell, 1959, fig. 4).

The clay member of the Raritan Formation is a nonmarine deposit; it was probably deposited in fresh-water swamps and lakes and on broad floodplains of sluggish streams. The clay member is 130 to 200 feet thick and consists chiefly of clay, sandy clay, and silt and some subordinate layers of sand; disseminated lignite, pyrite, and iron oxide concretions are common. The surface of the clay member, which apparently is not eroded appreciably in most of the area, slopes at about 40 to 50 feet per mile toward the southeast from about −300 to −1,000 feet msl (pl. 5).

In general, the upper part of the clay member consists of thin, probably lenticular beds of clay, each of which is from a few feet to about 40 feet thick. The middle of the clay member consists of beds of silt and very fine to fine clayey micaceous sand, 50 to 100 feet in total thickness, and perhaps several hundred times more permeable than the beds of clay above and below. The beds in the middle of the clay member are similar in texture and appearance to the fine-grained beds of the Magothy(?) Formation. This fine-grained material seems to be characteristic of the middle of the clay member in the report area as well as in other parts of Long Island. The lower part of the clay member consists in most places of an extensive layer of clay, 20 to 40 feet thick, which apparently constitutes the principal aquiclude between the Lloyd Sand Member and the Magothy(?) Formation.

Available data in the southwestern part of the area indicate that the clay member is most permeable at Broad Channel (Q2?7), Atlantic Beach (N6701, N4405), and in the western part of Long Beach (N3448). Cores from well N6701 and the electric logs for N6701 and N4405 at Atlantic Beach show that thick clay zones are generally absent in the clay member, except for about 30 feet of clay at the base. Salty water containing 16,000 ppm of chloride occurs in the upper part of the clay member at these wells. Logs of wells in Rockaway Park and in most of Long Beach show fairly thick beds of clay within the clay member.

The clay member of the Raritan Formation is overlain by the Magothy(?) Formation, which consists of nonmarine beds of clay, silt, sand, and gravel. The Magothy(?) ranges in thickness from about 100 to 1,000 feet. The top of the formation ranges generally from about −50 feet msl at Freeport and Merrick, in the northeastern part of the area, to about −300 feet msl at Rockaway Park, in the southwestern part. The Magothy(?) surface was greatly eroded in Pleistocene and, perhaps, Tertiary time, particularly in the southwestern part of the area. Southwestward-trending channeling is indicated in the southwestern part of the area on plate 2 and plate 3 (*B–B′* and *D–D′*) of this report, and on a map of the Magothy surface prepared by Perlmutter and Geraghty (1963, fig. 5). The bottom of one channel is about −430 feet msl (pl. 3, *B–B′* and *D–D′*); here the Magothy(?) Formation has been replaced by more permeable sand and gravel, which may be wholly, or in part, correlative with the Jameco Gravel. Although the axis of this channel cannot be ascertained from existing information, it may trend toward East Rockaway Inlet near well Q1030 (pl. 1).

Most of the Magothy(?) Formation consists of clayey and silty fine to medium sand, some gravel, and thin clay layers. Thin lenses of lignite and pyrite are common throughout the formation. Beds of coarse sand and gravel form the lower part of the Magothy(?) at Cedarhurst and Atlantic Beach. Relatively permeable zones are found also in the middle and upper parts of the formation in many places. Individual strata of the Magothy(?) Formation, however, appear to be mostly lenticular and of small lateral extent. On the whole, the Magothy(?) Formation is relatively permeable at Cedarhurst and Atlantic Beach and is generally less permeable to the northeast at Woodmere and Bay Park and to the east at Lido Beach, where it contains a much larger percentage of silt and very fine clayey sand. The facies change from coarse to very fine sediments northwestward between Cedarhurst and Woodmere is illustrated in section *C–C′* (pl. 3). A similar change occurs between Atlantic Beach and Lido Beach (pl. 2, *A–A′* and figure 6). Furthermore, in Rockaway Park, Woodmere, Bay Park, Long Beach, and Lido Beach, the lower 100 feet of the Magothy(?) Formation includes beds of red and white clay and silty clay. These beds of very low permeability are as much as 40 feet thick. (See fig. 6; also, N6469T and N6581, pl. 3, *C–C′*.) They form a distinct confining unit in the lower part of the Magothy(?) Formation and may be as impermeable as parts of the clay member of the Raritan Formation.

Deposits of Pleistocene and Recent age overlie the Cretaceous deposits. They range in thickness from a few tens of feet to more than 400 feet. Although deposits of Pleistocene age occur everywhere in the report area, individual formations and units are discontinuous, and their distribution is known only approximately. The Jameco Gravel, an outwash deposit of early Pleistocene age, consists of coarse sand and gravel of heterogeneous composition; in places it is interbedded with fine sand and lignite, probably reworked from Cretaceous deposits. The surface of the Jameco Gravel is irregular and somewhat eroded.

The Jameco is restricted to the southwestern part of the report area (fig. 3), and its landward limit in this area extends southeastward from Springfield Gardens in Queens County to Lido Beach in Nassau County. The eastern limit of this gravel in the report area is apparently at Lido Beach, where it may be present in thin lenses. The Jameco probably extends west of Atlantic Beach (pl. 2), although it has not been differentiated from overlying younger outwash deposits because of scanty data. Its seaward limit is not known. The Jameco may extend offshore from Atlantic Beach and Long Beach. This gravel is a highly permeable artesian aquifer that contains salty water along the barrier beaches (pl. 2 and pl. 3, *D–D′*) and fresh water between Cedarhurst and Woodmere and also between Lawrence and

Hewlett Neck (pl. 3, *B–B′* and *C–C′*) and elsewhere. In these areas the Jameco ranges in thickness from about 30 to 100 feet.

Although the uppermost part of the Magothy(?) Formation has lenses of clay, virtually no impermeable layers of significance lie between the Magothy(?) and the overlying Jameco Gravel. These two formations are basically a single hydraulic unit, with the Magothy(?) constituting the less permeable part of the combined unit.

The Gardiners Clay, a marine interglacial deposit, overlies the Jameco Gravel and the Magothy(?) Formation. Its approximate areal extent is shown in figure 3. The top of the Gardiners is slightly eroded and is commonly found at −60 to −80 feet msl. The formation is generally 30 to 80 feet thick. Locally, it may be very thin or missing where the Cretaceous surface is relatively high, as at Long Beach (pl. 2).

The Gardiners Clay consists of greenish-gray or brown clay, silt, and sand. Locally, it may contain partly carbonized plant debris and shell fragments. It consists mostly of impermeable clay and silt in Atlantic Beach, Lido Beach, and Woodmere (pl. 3 and fig. 6). The Gardiners is moderately permeable in Cedarhurst, Lawrence, and Far Rockaway; it is not recognized with certainty west of these areas. Available data, however, suggest that the formation, or its stratigraphic equivalent, is also moderately permeable.

The Gardiners Clay and contiguous lenses of clay in the upper part of the Magothy(?) Formation in some places form a confining layer restricting the vertical movement of water. But, in other places, the Gardiners consists predominantly of quartzose or glauconitic sand, interbedded with layers of gravel, and this composition facilitates the vertical movement of ground water. Section *D–D′* (pl. 3) shows that the Gardiners Clay thins seaward between Woodmere and Atlantic Beach. This thinning and other evidence, particularly that in section *A–A′* (pl. 2), suggest that the Gardiners Clay may thin to zero offshore from the barrier beaches in Nassau County.

Upper Pleistocene deposits, as much as 100 feet thick, overlie the Gardiners Clay or the Magothy(?) Formation in most of the area. They consist chiefly of stratified sand and gravel deposited on glacial outwash. In a large part of the area, the Pleistocene deposits also include a unit called the "20-foot" clay (Perlmutter and others, 1959, p. 422), a marine deposit of greenish-gray silt and clay that is generally fossiliferous. This unit is interbedded with the outwash, generally in the lower part. It is 5 to 20 feet thick in most places, and its top is generally at about −20 feet msl. The landward limit of the "20-foot" clay (fig. 3) is approximately along Sunrise Highway, and the seaward limit may be at or north of the barrier beaches in Nassau County. The "20-foot" clay was found at Woodmere (N6467T–N6469T) (pl. 3, *C–C'*), at Lawrence (N6510) (pl. 3, *D–D'*) and Hewlett Neck (N6706) (pl. 3, *B–B'*), and at Atlantic Beach (N6701) but is apparently missing at Long Beach, Lido Beach, and Jones Beach (pl. 2). Wherever the "20-foot" clay is present (fig. 3) and is composed of relatively impermeable beds, it retards the movement of water between the underlying and overlying beds.

Undifferentiated deposits of Pleistocene and Recent age overlie the Magothy(?) Formation in the Rockaway Park-Far Rockaway area (pl. 2). It is very likely that much of the undifferentiated material, which includes glauconitic sands, is derived from the reworking of the Jameco Gravel, Gardiners Clay, and upper Pleistocene and Recent deposits.

The permeable undifferentiated deposits in all likelihood extend landward into the Jamaica Bay area. They apparently thicken southwestward along erosional valleys on the Magothy(?) surface. Undifferentiated deposits, also thickening to the southwest, may also occur offshore from the barrier beaches in the area. The basis for this hypotheses is various evidence including the alinement of the landward limit of the Jameco Gravel. It is assumed that the Jameco Gravel and overlying Pleistocene deposits at Atlantic Beach and Long Beach actually represent the thin part of the wedge of relatively permeable material thickening seaward and southwestward.

The Recent deposits consist of alluvium, dune and beach sand, muck, silt, and gravel in streambeds, tidal marshes, channels and bays, and on barrier beaches. They are generally too thin or data were not available to differentiate them from the Pleistocene deposits on the geologic sections, except on plate 2 and in figure 6.

In summary, the "20-foot" clay and Gardiners Clay are the only relatively impermeable deposits of any consequence between the land surface and the clay member of the Raritan Formation. Where these deposits are missing or are permeable, the Magothy(?) Formation and the overlying deposits constitute a single hydraulic unit consisting of moderately permeable material from land surface to the top of the clay member of the Raritan Formation. Such permeable units occur in the northern, southwestern, and presumably offshore parts of the study area (fig. 3). In most of Nassau County north of Sunrise Highway, the upper Pleistocene deposits and the Magothy(?) Formation constitute a single hydraulic unit, although the Magothy(?)

on the average is probably about half as permeable as the overlying glacial outwash deposits.

PERMEABILITY OF GEOLOGIC UNITS

The coefficient of permeability is a measure of the capacity of material to transmit water. This coefficient (generally referred to only as permeability) was expressed by Meinzer (Wenzel and Fishel, 1942) as the rate of flow of water in gallons per day through a cross-sectional area of 1 square foot under a hydraulic gradient of 1 foot per foot at a temperature of 60°F. In field practice the adjustment to the standard temperature of 60°F is commonly ignored, and permeability is then understood to be the field coefficient at the prevailing water temperature. Theis (1935) introduced the term "coefficient of transmissibility," which is expressed at the rate of flow of water at the prevailing water temperature, in gallons per day, through a vertical strip of aquifer 1 foot wide extending the height of the aquifer tested under a hydraulic gradient of 100 percent. The coefficient of permeability is the coefficient of transmissibility divided by the thickness of aquifer tested.

Permeabilities of unconsolidated deposits are used in subsequent parts of this report to calculate the approximate rates of movement of salty water. The permeability is greatest along a plane parallel to the bedding, although it probably is not the same in all directions along this plane. The permeability is lowest perpendicular to the bedding, that is, chiefly in the vertical direction, inasmuch as the beds are nearly horizontal.

On the whole, if a judgment is made on the basis of the character of material constituting the aquifers in the study area, the horizontal permeabilities of the upper Pleistocene deposits and Jameco Gravel are greatest, those of the Magothy(?) Formation are lowest, and those of the Lloyd Sand Member are intermediate.

The horizontal permeability of the outwash in the upper Pleistocene deposits at the Bookhaven National Laboratory was 1,350 gpd per sq ft (M. A. Warren and N. J. Lusczynski, 1958, written commun.). Because outwash in the report area is lithologically similar to the deposits at Brookhaven, permeabilities of about 1,000 to 1,500 gpd per sq ft (gallons per day per square foot) probably apply to most of the outwash.

An average horizontal permeability of about 1,700 gpd per sq ft was computed for the Jameco Gravel near well N1401 at the pumping station in Woodmere by private consultants (R. M. Leggette and M. L. Brashears, written commun., 1955).

The horizontal permeability of selected permeable zones in the

Magothy(?) Formation, given in the table below, were computed by N. J. Lusczynski from aquifer tests made in 1952 and 1958.

Permeabilities of selected zones in the Magothy(?) Formation

Well	Locality	Estimated thickness of beds tested (feet)	Coefficient of permeability (gpd per sq ft)	Description
N3861	Cedarhurst	115	1,000	Medium to coarse sand and zones of fine sand.
N3862	Lawrence	110	800	Fine to coarse sand.
N3865	Oceanside	60	200	Fine to medium clayey sand and zones of medium to coarse sand.
N3867	Green Acres	60	1,100	Medium to very coarse sand and zones of coarse to very coarse gravel.
N6581	Woodmere	60	500	Coarse sand and gravel and fine to medium clayey sand.

The wells listed are screened in fresh or salty water near the interface of the deep salty-water wedge, in the area where the rate of encroachment is to be determined. Each well is equipped with a 10-foot screen placed in what appeared to be the most permeable zone in the lower part of the Magothy(?); one well (N3862) was screened in the upper part of the formation. Each well was pumped at nearly a constant rate, which ranged from 80 to 130 gpm (gallons per minute) at different wells, for 1 to 26 hours. Water-level measurements were made in the pumped wells only as no observation wells were available.

The coefficient of transmissibility was first computed from drawdown readings using the modified Theis nonequilibrium formula (Jacob, 1944). The coefficient of permeability was calculated by dividing the transmissibility by the thickness of the beds tested. Because of the lenticularity of the beds of the Magothy(?) Formation, the thickness of the beds tested could not be determined precisely. The thickness tested at all wells was probably only a small percentage of the entire Magothy(?) because of the short length of each well screen.

The table of coefficients of permeability gives a range of 200 to 1,100 gpd per sq ft for 60 to 115 feet of moderately to highly permeable beds in the Magothy(?) Formation. Individual layers or zones of coarse sand and gravel may have coefficients as high as 2,000 gpd per sq ft. Also, other individual layers or zones of silt and clay have coefficients much less than 200 gpd per sq ft. On the basis of the above-mentioned coefficients, a permeability of 1,000 gpd per sq ft is used in a later section of the report to calculate the probable maximum rate of lateral encroachment of salty water in the Magothy(?) Formation. This figure is not in any way to be interpreted as an average value of permeability of the entire Magothy(?) Formation, which may be about 500 gpd per sq ft.

A horizontal permeability of about 900 gpd per sq ft for the Lloyd Sand Member was determined by Jacob (1941, p. 784) from an aquifer test at well Q1030 at Rockaway Park. A reanalysis of the test data by Lusczynski using the leaky aquifer formula (Jacob, 1946) indicates a permeability of about 500 gpd per sq ft. The results of an aquifer test made in 1960 also show that the permeability of the Lloyd Sand Member is about 500 gpd per sq ft at well N5227 at Lido Beach. The average permeability of the Lloyd Sand Member in the report area may range from about 500 to 1,000 gpd per sq ft.

Ratios of horizontal to vertical coefficients were determined for the outwash in the upper Pleistocene deposits at the Brookhaven National Laboratory in Suffolk County (M. A. Warren and N. J. Lusczynski, written commun., 1958). These ratios showed that vertical permeabilities of the sand and gravel beds of the Jameco Gravel, Magothy(?) Formation, and Lloyd Sand Member may be at least 4 to 18 times smaller than the horizontal permeabilities cited above.

A test by a private laboratory on a core sample of the "20-foot" clay from a test boring near Oceanside gave a coefficient of permeability (presumably in a vertical direction) of about 0.007 gpd per sq ft. A vertical permeability of about 0.3 gpd per sq ft was estimated for beds of sandy clay that constitute the Gardiners Clay at the Brookhaven National Laboratory area (M. A. Warren and N. J. Lusczynski, written commun., 1958). The estimate was based on downward leakage from the upper Pleistocene deposits through the Gardiners Clay to the Magothy(?) Formation. On the basis of these two coefficients, it is estimated that the average vertical permeability may be as low as 0.01 to 0.001 gpd per sq ft for clay and about 0.1 to 1.0 gpd per sq ft for sandy clay in the "20-foot" clay, the Gardiners Clay, and the clay member of the Raritan Formation.

FRESH AND SALTY GROUND WATER

GENERAL DESCRIPTION

Precipitation is the source of natural fresh water, and the ocean water is the source of salty water in the unconsolidated deposits in Long Island. Fresh ground water in Long Island contains about 10 ppm (parts per million) or less of chloride content. In inland areas a chloride content of about 10 to 40 ppm generally signifies contamination of ground water by manmade wastes. In shoreline areas it may signify mixing of fresh water and some salty water. In this report a chloride concentration of more than 40 ppm in shoreline areas is assumed to indicate contamination by salty water.

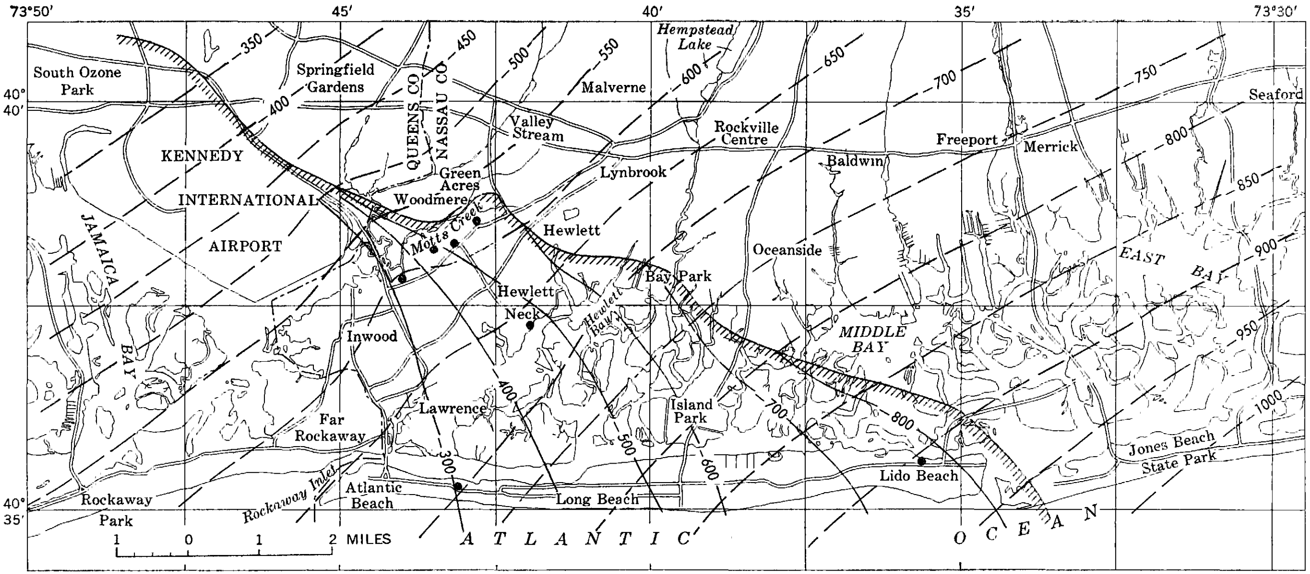
Ocean water has a chloride content of about 18,000 ppm. The Atlantic Ocean at the shoreline (Group C, pl. 4) had a chloride content of about 17,300 ppm. Chloride concentrations of more than 16,500 ppm, however, have not been found in the ground water in the unconsolidated deposits at and north of the barrier beaches in the project area.

The distribution of fresh and salty ground water in the report area was delineated from analyses of the chloride content of water extracted from cores, from water samples at observation and supply wells, and from interpretation of electric logs. Fresh water under water-table and artesian conditions is found in all the deposits in the northern and eastern parts of the area. Both fresh and salty ground water occur in the southwestern part of the area (pls. 2, 3, 5 and figs. 4, 5).

The main body of salty ground water is connected with the open bodies of salty water south of Jamaica Bay in southeastern Queens County and with the ocean south of the barrier beaches in Queens and Nassau Counties. Shallow, intermediate, and deep extensions (called wedges) from the main body are found in the southwestern part of the project area. The shallow wedge is connected freely with the salt water in the open bays, tidal estuaries, and the ocean. The intermediate wedge occurs at about −100 to −400 feet msl in southwestern Nassau County. The deep wedge occurs at depths of about −150 to −1,000 feet msl in southeastern Queens and southern Nassau Counties. The landward limit of the intermediate and deep wedges is shown in figure 5.

The approximate landward limit of the salty water in the Lloyd Sand Member near the barrier beaches in southern Queens and Nassau Counties is shown in figure 9. Its position is determined principally from the chloride content of water in screened wells and from electric logs in test holes.

The deep salty-water wedge is the largest, thickest, and most significant with respect to potential contamination of existing supply wells. It occurs principally in the Magothy(?) Formation and clay member of the Raritan Formation. The toe of the wedge is at or near the base of the Magothy(?) Formation and trends southeastward along an irregular line from South Ozone Park, Queens County, about 7 miles north of the shoreline, to a point about a mile or two east of Lido Beach, Nassau County, from where it continues south of the shoreline (pl. 5). It is probably offshore within 2 miles of Jones Beach in the southeastern corner of the area. The leading edge of the deep wedge increases in depth from about −300 feet msl



EXPLANATION

● Control well

— 400 — Salty-water contour
Drawn on upper surface of deep salty-water wedge, in feet

— — 700 — — Structure contour
Drawn on surface of clay member of Raritan Formation, in feet

Approximate landward limit of deep salty-water wedge on surface of clay member of Raritan Formation

Altitudes given in feet with reference to mean sea level at Sandy Hook, N. J.

FIGURE 4.—Map showing contours on upper surface of deep salty-water wedge in the Magothy(?) Formation.

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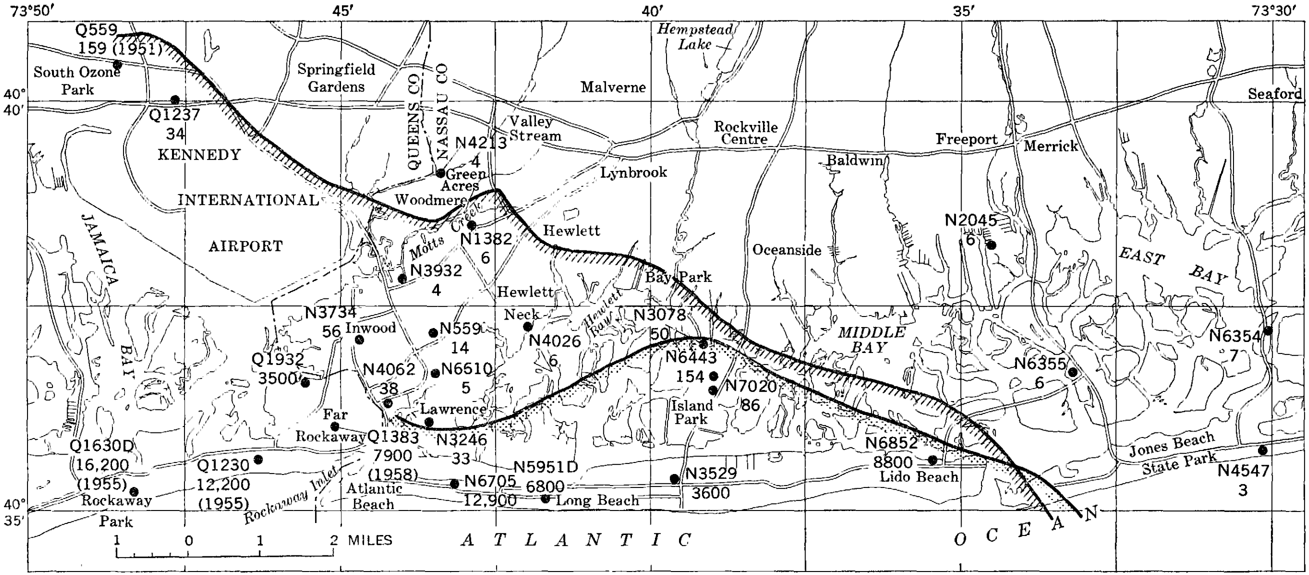

EXPLANATION

N3529
3600
Well

Upper number is well number; lower number is chloride content in parts per million in 1960-61, unless otherwise indicated. All wells screened in depth interval 100-300 feet below mean sea level (Sandy Hook, N. J., datum)

Approximate landward limit of deep salty-water wedge on surface of clay member of Raritan Formation

Approximate landward limit of intermediate salty-water wedge

FIGURE 5.—Approximate landward limit of intermediate wedge, and deep wedge of salty water at the base of the Magothy(?) Formation.

in South Ozone Park to about −950 feet msl east of Lido Beach. The upper surface of the deep wedge slopes landward or northeastward at about 100 to 300 feet per mile from about −150 feet msl to more than −800 feet msl (fig. 4). Its upper surface is shaped differently in each of the four sections on plates 2 and 3; this difference in shape is attributable to effects of geologic and hydraulic environments, also local pumping, and locales of natural discharge areas. Comparison of contours on the upper surface of the deep salty-water wedge with contours on the surface of the clay member of the Raritan Formation (pl. 5 and fig. 4) shows that the wedge in the Magothy(?) Formation decreases in thickness from about 400 feet at Atlantic Beach to zero at the leading edge.

The bottom surface of the deep wedge dips seaward in the clay member of the Raritan Formation. Its thickness in the clay member increases from zero at the leading edge (pl. 3, *B–B′*) to about 180 feet at the barrier beaches (pl. 2). Because the salty water has nearly reached the bottom of the clay member at the barrier beaches, it must be in the upper beds of the Lloyd Sand Member in nearby areas offshore and undoubtedly occupies the entire thickness of the Lloyd offshore.

Significant also to salt-water encroachment is the intermediate wedge of salty water extending from offshore areas into southwestern Nassau County. Along the barrier beaches it occurs from about a mile west of Atlantic Beach to perhaps no more than 2 miles east of Lido Beach, and is found as far inland as Island Park, about 2 miles from the shoreline (fig. 5). It is predominantly in the upper part of the Magothy(?) Formation, in the Jameco Gravel, and in the Gardiners Clay at about −100 to −400 feet msl. The intermediate wedge, which contains as much as 12,900 ppm chloride at Atlantic Beach, is underlain and overlain by fresh water (pls. 2, 3 and fig. 6) in places; in other places along the barrier beach (pl. 2), it probably is connected with shallow salty water.

Shallow salty water is found generally at depths of less than 100 feet in the Gardiners Clay, upper Pleistocene deposits, and Pleistocene and Recent undifferentiated deposits beneath and near embayments, lagoons, and estuaries. The areal extent and landward limit of the shallow salty water is not known in any detail. It probably extends several hundred feet into marshes that border the estuaries and bays. Most of the sites where shallow salty water was found are indicated on plates 2 and 3 and in figure 6. A detailed discussion of the shallow salty water is beyond the scope of this report.

The distribution of the chloride content of ground water, which is described in some detail in the following sections, shows wedges of salty ground water 6 miles wide and as much as 500 feet thick.

The occurrence and distribution of fresh and salty water in the area is influenced not only by geologic environment but also by the heads and patterns of flow in the fresh and salty water.

The thick and broad zone of diffusion in the deep wedge (pl. 2*A*) is undoubtedly a result of the heterogeneous geologic environment and changes in sea level and ground-water levels during the past 1,000 or more years. The diffused zones are produced principally by long and short term changes in sea level and in the fresh-water outflow to the sea, which result in advances and recessions of the salt-water fronts. Ionic diffusion and dispersion may also play minor roles in the formation of zones of diffusion. The seaward thickening of the upper zone of diffusion in the deep wedge (pls. 2*A* and 3) is probably in part the result of seaward return of some of the salty water that moved landward after it was mixed with some of the fresh water moving seaward.

The vertical distribution of the chloride content was used to compute the average density of ground water between sea level and the screen of each observation well. The densities so obtained were used to calculate the vertical components of the hydraulic gradients in fresh and salty water. The data on vertical and horizontal distribution of chlorides in the salty-water wedges will be useful for future studies on dispersion and definition of flow patterns in the zone of diffusion.

DELINEATION ALONG PROFILES

ROCKAWAY PARK TO JONES BEACH

The general distribution of fresh and salty ground water beneath the barrier beaches from Rockaway Park to Jones Beach is shown by isochlors in section *A–A′* (pl. 2*A*). Detailed information on the lithology and chloride concentration of water at test well N6701 at Atlantic Beach and at well N6850 at Lido Beach (fig. 6) helped to define the isochlors elsewhere in the section. A detailed report on section *A–A′* was published in 1962 (Lusczynski and Swarzenski).

The relationship of apparent resistivities shown by electric logs to lithology and salinity at Atlantic Beach and Lido Beach proved useful in interpreting electric logs for definition of salinity at other wells in the section. Isochlors were extended, thus, with a fair degree of confidence into areas where no chloride data were available. The isochlors also are based on chloride analyses of water from public-supply, commercial, and observation wells.

In section *A–A′* the main body of salty water is found between Rockaway Park and Atlantic Beach. It extends beneath the barrier beaches from about sea level into the clay member, penetrating at least its upper half and perhaps its entire thickness at and in the

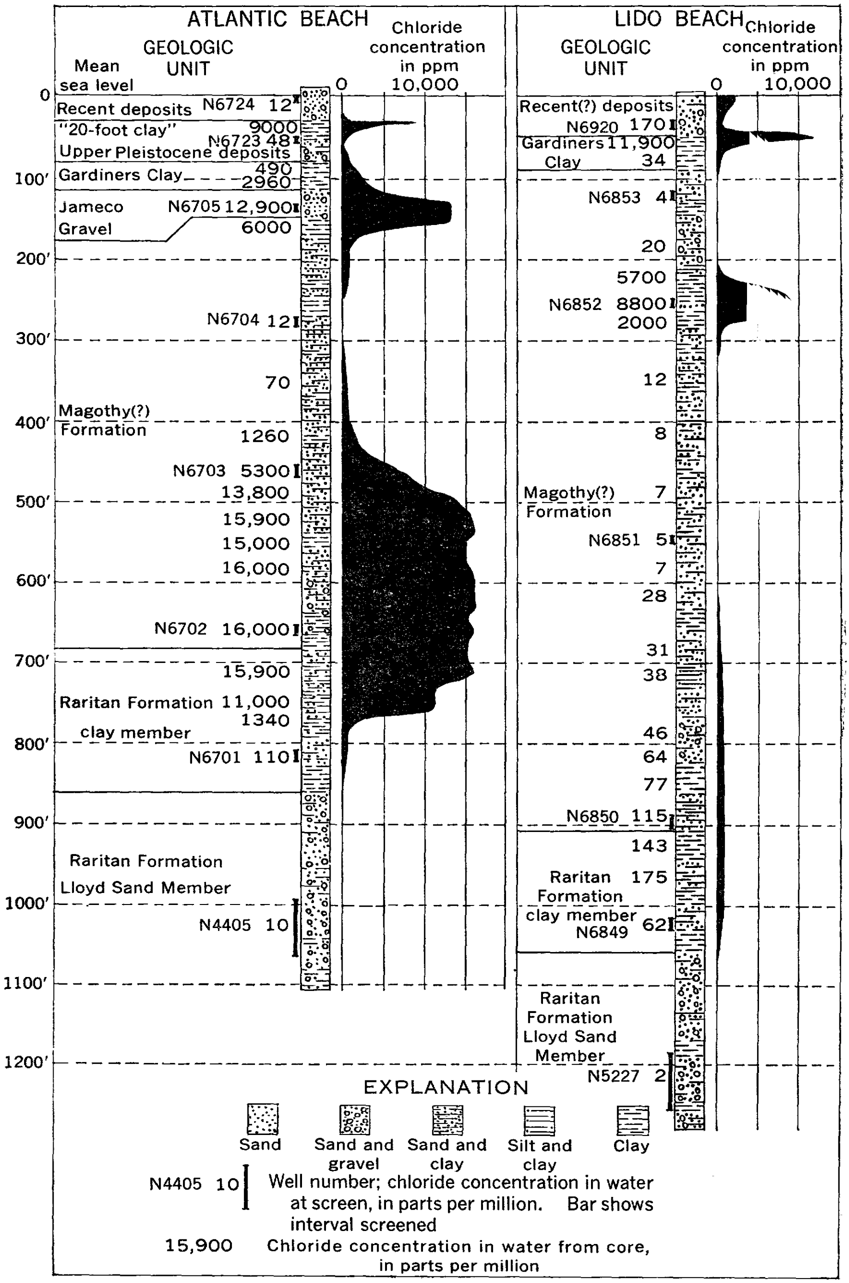

FIGURE 6.—Columnar sections and chloride distribution curves at Atlantic Beach and Lido Beach, N.Y.

vicinity of well Q1030 at Rockaway Park. The shallow, intermediate, and deep salty-water wedges in section *A–A′* occur east of Atlantic Beach (pl. 2*A* and fig. 6) in the unconsolidated deposits overlying the Lloyd Sand Member.

The deep wedge occupies most of the Magothy(?) Formation and the clay member of the Raritan Formation at Atlantic Beach, where it is in material that is relatively more permeable than the material in most places shown on the section (fig. 6). Maximum chloride concentrations of about 16,000 ppm occur in the lower part of the Magothy(?) Formation and also in the upper part of the clay member of the Raritan Formation. The upper part of the deep wedge is characterized by a zone of diffusion as much as 250 feet thick at Atlantic Beach. The zone of diffusion in the lower part is only about 100 feet thick, principally because it is mainly in fine sand and clayey silt. Decreases in chloride content of the water at Atlantic Beach in material of low permeability are evident in the distribution curve (fig. 6), even for minor lithologic variations. The chloride concentration decreased to about 110 ppm at the base of a sandy zone near the bottom of the clay member. This zone is separated from fresh water in the underlying Lloyd Sand Member by 29 feet of clay of very low permeability (fig. 6).

The deep wedge extends eastward from Atlantic Beach to about 1 or 2 miles east of Lido Beach. It is about 550 feet thick at Atlantic Beach and nearly 300 feet thick at Lido Beach. The chloride content of the salty water at the base of the Magothy(?) Formation in western Long Beach is estimated to be at least 5,000 ppm and may be as much as 10,000 ppm, as suggested by the apparent resistivity curves of the electric logs for wells N2597 and N6450 (pl. 2*A*). The lower value was used to plot the isochlors. Because of the relatively high apparent resistivities indicated by the electric logs for wells N5308, N5768, and N6850 at Lido Beach, the water in the lower Magothy(?) and in most of the clay member in eastern Long Beach and in Lido Beach probably has a chloride content of less than 1,000 ppm, under conditions similar to those illustrated for well N6850 (fig. 6).

The deep wedge at Lido Beach is found mainly in the lower part of the Magothy(?) and throughout most of the clay member of the Raritan Formation. As shown on plate 2*A* and in figure 6, chloride concentrations of 10 to 40 ppm occur between −600 and −765 feet, marking a transition zone from fresh water above (normally less than 10 ppm) to saltier water in the Magothy(?) below. Chloride concentrations, however, are as much as 115 ppm in the basal Magothy(?) and reach a maximum of about 175 ppm in the clay member. A chloride concentration of 62 ppm was found in water from well N6849 screened in a sandy zone near the bottom of the clay member. This zone is separated from fresh water in the underlying Lloyd Sand Member by about 30 feet of clay.

The distribution of the chloride content in the underside of the deep wedge in the clay member of the Raritan Formation is defined accurately only at the test wells at Atlantic Beach and Lido Beach; the distribution elsewhere is estimated. The bottom of the salt-water wedge, defined by the 40-ppm isochlor is probably within the lowermost clay in the clay member; however, at well N41 in Long Beach, it may have penetrated the upper part of the Lloyd Sand Member.

Salty ground water from about sea level to about −400 feet (pl. 2*A*) between Atlantic Beach and Lido Beach includes the intermediate and shallow wedges. These two wedges are separated by zones of fresh water at Atlantic Beach and Lido Beach (pl. 3, *D–D'* and fig. 6). They are probably also separated similarly in other places between Atlantic Beach and Lido Beach. Exact localities, however, are not known, in part because of the scanty data on the position and character of the discontinuous Pleistocene clays and other deposits at depths of less than −200 feet.

The intermediate wedge between Atlantic Beach and Lido Beach is in the lower part of the Pleistocene deposits and in the upper part of the Magothy(?) Formation, and it extends along the barrier beach from about 1 mile west of Atlantic Beach to no more than 2 miles east of Lido Beach. The chloride concentrations in the intermediate wedge are as high as 12,900 ppm in the permeable Jameco Gravel at Atlantic Beach and 8,800 ppm in fine clayey sand and clay at Lido Beach. The pronglike extension of the intermediate wedge at Lido Beach is in relatively tight material that is overlain by sand and gravel and underlain by fine to medium sand that contains fresh water. If salty water were in the more permeable material above and below the prong, it has probably been flushed out.

Shallow salty water is found in the upper Pleistocene and Recent deposits and in the upper part of the Gardiners Clay between Rockaway Park and Jones Beach. The upper limit of the shallow salty water is probably near sea level. Its lower limit is also not known precisely. Because of scanty data no attempt was made to show isochlors in the uppermost 100 feet of the salty water on plate 2*A*. At Atlantic Beach the shallow zone of salty water is mainly in the "20-foot" clay, where it has a maximum concentration of 9,000 ppm in the uppermost 5 feet of a silt and clay unit (fig. 6). At Lido Beach the shallow zone of salt water contains about 150 to 1,800 ppm of chloride in the Recent deposits and as much as 11,900 ppm in the upper 5 feet of the Gardiners Clay. The shape of chloride distribution at the shallow depths (fig. 6) suggests that the salty water in the shallow marine clays at Atlantic Beach and Lido Beach is being flushed out by fresh water. This replacement of salty water by fresh water may have been true in the past, but hydraulic gradients suggest no predominant direction of flow of the salt water between 1959 and 1961 at Atlantic Beach and a predominantly downward flow in 1960 and 1961 at Lido Beach.

Two principal bodies of fresh water, one in the Lloyd Sand Member and the other in the Magothy(?) Formation, occur beneath the barrier beaches in section *A–A′* (pl. 2*A*). Abundant reserves of fresh water are available under artesian conditions between Rockaway Park and Jones Beach where the Lloyd Sand Member is 250 to 500 feet thick. The chloride content of the fresh water in the Lloyd increased from 2 ppm at Lido Beach to 26 ppm at Rockaway Park in 1960–61.

There are, however, indications that the upper beds of the Lloyd beneath and seaward of the barrier beaches may contain some salty water. Water from well Q1030 at Rockaway Park contained 40 to 200 ppm chloride in 1939, and the chloride content of water from several other deep wells in the vicinity of Rockaway Park also showed several hundred parts per million during periods of pumping. Pumping from the Lloyd Sand Member was stopped in the Rockaway Park area in about 1940, and as indicated by the chloride content of 26 ppm at well Q1030 in March 1961, the chloride has returned to a lower concentration. The temporary increase in 1939 of chloride content of water in the Lloyd Sand Member at Rockaway Park may have been due to the downward movement of salty water from the overlying clay member, or perhaps more likely to a lateral movement of salty water in the upper beds of the Lloyd Sand Member from nearby areas, because of pumping for commercial use prior to 1940. At well N4405 in Atlantic Beach, analyses by the Long Island Water Corp. showed that the chloride content of water increased from 10 ppm in 1954 to 14 ppm in 1960, and to nearly 16 ppm in 1962. The increase of 6 ppm, although small, may indicate the presence of brackish water in the Lloyd near the pumped well.

At Long Beach, chloride concentrations in water from well N41, screened in the upper part of the Lloyd Sand Member, were as high as 80 ppm in 1960 and in previous years, whereas deeper wells in the same area show concentrations of less than 10 ppm (pl. 2*A*). The higher concentrations at well N41 may be due to a leaky casing or leakage along the annular space between the casing and the clay member. Hydraulic gradients, however, created by heavy withdrawals in the locality show that salty water could have moved downward into the upper part of the Lloyd Sand Member from the overlying clay member at and near well N41 or that salty water could have moved laterally along the upper beds of the Lloyd Sand Member from nearby areas offshore.

The increase in the chloride content of the water in the Lloyd Sand Member westward and the chloride data at Rockaway Park, Atlantic Beach, and Long Beach were considered in estimating the landward limit of the salty water in the Lloyd Sand Member (fig. 9). The leading edge or front of the salty water is apparently everywhere at or near the barrier beaches along the south shore in Long Island. Its position, about 2 miles offshore from Jones Beach, is interpolated from available data.

The position of the leading edge of the salty water in the Lloyd is mainly a natural occurrence except at Rockaway Park and Long Beach, where average withdrawals of 3 to 5 mgd (million gallons per day) during the past 20 years may have resulted in contamination at one well.

Salty ground water having the salinity of sea water may be as much as 3 miles seaward of the leading edge or front of the salty water in the Lloyd. This conclusion is based on the thickness of the Lloyd and on the width of the zone of diffusion in the Magothy(?) Formation along the barrier beach between Atlantic Beach and Lido Beach (pl. 2).

A significant and sizeable wedge of fresh water extends in the Magothy(?) Formation from Jones Beach to about half a mile west of Atlantic Beach between the shallow or intermediate wedges of salty water and the deep wedge of salty water. This wedge of fresh water may be as much as 900 feet thick at Jones Beach, but it decreases in thickness westward to about 65 feet at Atlantic Beach and apparently thins to zero just west of Atlantic Beach.

At Jones Beach, fresh water occurs in the Magothy(?) Formation between −100 and −400 feet msl and between −700 and −1,000 feet msl. The relatively low resistivities, however, shown at Jones Beach by the electric log of well N5129 between about −400 and −700 feet, in the middle of the Magothy(?), suggest the presence of slightly salty water containing more than 40 ppm but perhaps less than 100 ppm chloride; no analyses are available to verify this suggestion. The low resistivities at about −400 to −700 feet msl may reflect only differences in lithology or perhaps a difference in the chemical composition of the fresh water in the lower part of the Magothy(?) from that in the middle part of the formation. At least some of the water at Jones Beach in the lower part of the Magothy(?) is derived from the Lloyd Sand Member, whereas that in the middle part of the Magothy(?) is from inland areas.

The fresh-water wedge in the Magothy(?) Formation between Lido Beach and Atlantic Beach had a chloride concentration of 4 to 12 ppm at observation and commercial wells in 1960–61. The chloride content of the water at well N5768 at Lido Beach increased from less than 10

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ppm to 16 ppm during the period of seasonal pumping in 1959; this fact may indicate the presence of slightly brackish water near the well screens. Also, the water in the middle of the Magothy(?) Formation near former well N319 at Long Beach may be slightly salty because even in 1903 it had a chloride content of 29 ppm. Water in the Magothy(?) Formation at and near well N3448 may have a chloride content of about 40 ppm.

In addition to the lenses of fresh water between the shallow and intermediate salty-water wedges, mentioned previously, there are also lenses of unconfined fresh water in the uppermost deposits at Atlantic Beach and undoubtedly in other places between Rockaway Park and Jones Beach. These lenses of shallow unconfined fresh water grade laterally into salty water near the shoreline; they are missing wherever the barrier beaches are of insufficient width and altitude to store fresh water derived from precipitation.

FAR ROCKAWAY TO BAY PARK

Section *B–B′* (pl. 3*A*) shows the distribution of fresh and salty water in the upper Pleistocene deposits, Magothy(?) Formation,and clay member of the Raritan Formation between Far Rockaway and Bay Park.

The isochlors in the upper zone of diffusion at wells N6510 at Lawrence and N6706 at Hewlett Neck are based on the chloride content of the water extracted from cores. Those at the site of well N3862 at Lawrence are based on (a) water samples at wells N3862, N4062, and N7000, (b) the resistivity curve of the electric log for well N3862, and (c) the position of isochlors at wells N6510 and N6706 in this section and at well N6701 at Atlantic Beach in section *A–A′* (pl. 2*A*). The isochlors in the underside of the deep wedge in the clay member are best defined at well N6706 at Hewlett Neck from analyses of water extracted from cores; those at well N3862 are based on interpretation of the resistivity curve of the electric log. The isochlors in Far Rockaway and near Bay Park are based on analyses of water samples from observation and supply wells. Those near Bay Park are also based on chloride content from cores.

Along section *B–B′*, the main salty-water body occurs in the unconsolidated deposits from about sea level down to and including the clay member of the Raritan Formation, at and seaward of Far Rockaway. The deep wedge in the Magothy(?) and the clay member extends more than 4 miles northeastward from the main body. It decreases in thickness in this distance from about 700 feet northeast of Far Rockaway to zero at the base of the Magothy(?) Formation near Bay Park. The deep wedge occurs in relatively tight material at well N3862 at Lawrence, in relatively coarse material at well N6510 at Lawrence, and also at well N6706 at Hewlett Neck, and below a tight clay near the bottom of the Magothy(?) at Bay Park.

The upper surface of the deep wedge is S-shaped; actually no two of the upper surfaces on plates 2 and 3 are alike, and the variation of the surface indicates the local effects of lithology, heads, and flow patterns. The lower surface of the wedge has penetrated the clay member about 100 feet at Lawrence (N3862) and about 60 feet at Hewlett Neck (N6706). This increase seaward of the depth of penetration of the salty water suggests that the 40-ppm isochlor is at least in the middle beds at Far Rockaway and undoubtedly in the lower beds of the clay member seaward of Far Rockaway (pl. 3).

The toe of the deep wedge is probably near well N6928, which is screened in the basal Magothy(?) at Bay Park. The water at the screen of well N6928 had a chloride content of 14 ppm in August 1960, when the well was completed, and 18 ppm in September 1961; this difference in chloride concentration may suggest a slight contamination by nearby salty water. The contamination is verified to some degree by the fact that the chloride content of the fresh water is only 4 ppm at well N2790 (screened about 170 feet higher than well N6928) and less than 10 ppm at other wells screened in the lower part of the Magothy(?) Formation landward of the toe of the deep wedge (pl. 2).

The isochlors on plate 3*A*, *B–B′*, define the characteristic increase in the thickness of the upper zone of diffusion seaward (see also pl. 3*A*, *C–C′* and *D–D′*). In section *B–B′*, the thickness of the diffused zone increases seaward from about 130 feet at Hewlett Neck to about 250 feet at Lawrence. The diffused zone along the base of the Magothy(?) Formation is nearly 2 miles wide between Hewlett Neck and Bay Park.

Shallow salty water is found locally in and near the "20-foot" clay along the shoreline between Hewlett Neck and Bay Park.

CEDARHURST TO WOODMERE

Section *C–C′* (pl. 3*A*) shows the deep wedge extending from seaward areas northeastward from Cedarhurst to Woodmere. This section was discussed in detail in a progress report by Lusczynski and Swarzenski (1960).

Isochlors in section *C–C′* are best defined at test holes N6467T and N6469T, where determinations of the chloride content were made on water samples obtained by the centrifugal method; a few determinations were made by the dilution method. The isochlors at well N3861 and at well N6581 are based on electric logs, chloride concentrations at well screens, and determinations in 1958 by the dilution method of cores taken in 1952 near the lower 20 feet of the hole. Isochlors in the upper zone of diffusion at well N3861 were estimated principally from electric logs and the chloride distribution in the upper zone of diffusion at well N6467T in Woodmere, at well N6510 in Lawrence, at well N6701 in Atlantic Beach, and at well N6706 in Hewlett Neck.

The deep wedge occurs principally in the Magothy(?) Formation. It decreases in thickness from about 300 feet at well N3861 at Cedarhurst to about 41 feet at well N6581 at Woodmere, about 1¼ miles to the northeast. The wedge apparently thins to zero about 400 feet beneath the supply wells at the Mill Road pumping station, immediately inland from well N6581. The elongated character and the slope of the upper surface of the deep wedge is due to the heavy localized withdrawals at the pumping station.

The part of the wedge in the Magothy(?) Formation occurs in relatively coarse material at well N3861, in relatively tight material at test hole N6469T, and in relatively coarse material at well N6581. The toe of the wedge is beneath tight beds of red and white clay in the lower part of the Magothy(?) Formation between test hole N6469T and well N6581. The extent of this clay landward from well N6581 is not known, but a knowledge of this extent, especially at a site below the supply wells at the pumping station, is important for predicting upward flow of salty water in the deep wedge.

The lower surface of the wedge penetrated the uppermost part of the underlying clay member of the Raritan Formation, consisting of a tight clay. By 1958, salty water had reached a depth of 28 feet below the top of the clay member at well N3861; 17 feet below, at test hole N6467T; 3 feet below, at test hole N6469T; and 4 feet below, at well N6581. The downward movement of the salt mass is retarded by the upward flow of fresh water at Woodmere.

The chloride content of the salty water in Woodmere is highest about 50 feet above rather than along the top of the clay member (pl. 3*A*, *C–C′*). It decreased landward from 16,000 ppm at N6467T to about 8,000 ppm at N6581 in beds 10 to 50 feet above the clay member, and from about 8,000 ppm at N6467T to about 1,000 ppm at N6581 along the top of the clay member. This situation is probably caused in part because the salty water moving landward is diluted by the fresh water moving upward from the Lloyd Sand Member.

The isochlors on plate 3*A*, *C–C′*, indicate the characteristic increase in the thickness of the upper zone of diffusion seaward. The diffused zone shown in section *C–C′* increased in thickness from a few tens of feet at test hole N6467T in Woodmere to about 150 feet at well N3861 in Cedarhurst. The zone is at least a mile wide at the base of the Magothy(?) Formation.

Shallow salty water was found locally above the "20-foot" clay at well N6242 at Cedarhurst and also at test hole N6467T in the vicinity of the tidal reaches of Mott Creek.

WOODMERE TO ATLANTIC BEACH

The interfingering of fresh water with the shallow, intermediate, and deep salty-water wedges between Woodmere and Atlantic Beach is illustrated in section *D–D′* (pl. 3*A*).

The deep wedge in the Magothy(?) Formation and the clay member of the Raritan Formation extends about 4 miles north of Atlantic Beach. Its thickness decreases in this distance from about 550 feet at Atlantic Beach to zero between test holes N6467T and N6468T at Woodmere. The isochlors in the deep salty-water wedge are accurately defined at each well or test hole; only those below the bottom of well N6510 at Lawrence are estimated.

The diffused zone of the deep wedge in the clay member increases in thickness seaward from about 20 feet at Woodmere to nearly the entire thickness of 180 feet of the clay member at Atlantic Beach. On the basis of this increase, the bottom surface of the deep wedge should be in the upper beds of the Lloyd Sand Member immediately offshore from Atlantic Beach. Salty water is probably offshore farther from Atlantic Beach in the lower beds of the Lloyd than in the upper beds. This situation would require heads in the upper beds to be lower than those in the lower beds. Such an occurrence is possible where salty water is moving downward into the Lloyd at and seaward of the shoreline, as at Atlantic Beach. The fresh water in the Lloyd, therefore, cannot discharge in offshore areas but instead moves upward from the deeper beds near and landward of the toe of the fresh-water wedge offshore in the Lloyd.

The position of salty water offshore in the Lloyd along section *D–D′* is a matter of speculation, because actually the offshore geologic environment is not known. However, because of the thickness and continuity of the clay member and the Lloyd Sand Member along and north of the barrier beach and also because the bedrock for several miles offshore has about the same slope as in inland areas (Oliver and Drake, 1951), the Lloyd Sand Member and the clay member in all likelihood extend several miles seaward. The Lloyd may be less permeable in offshore areas.

The intermediate wedge of salty water (pl. 3*A*, *D–D′*) is at about −50 to −250 feet msl at Atlantic Beach (N6701) and extends inland about a mile to the vicinity of well N3246 at Lawrence. It becomes part of the shallow and deep wedges along or seaward of the shoreline.

The landward limit of the shallow salty water is approximately at the limit of the tidal marshes north of the south shore bays. Shallow salty water also occurs locally in the lowlying areas near Mott Creek in Woodmere at test holes N6467T and N6468T (pl. 3*A*, *D–D′*).

CHEMICAL QUALITY

Chemical analyses of fresh, diffused, and salt water in the ground-water reservoir in southern Nassau and southeastern Queens Counties are listed in table 2. For purposes of this report, fresh ground water is defined as water having a chloride content of less than 40 ppm and generally less than 100 ppm total dissolved solids. Diffused ground water is water having a chloride content of 40 to about 15,500 ppm and a total dissolved solids content of about 100 to 28,000 ppm. Salt ground water has a chloride content of about 15,500 to 16,500 ppm and a total dissolved solids content of about 28,000 to 31,000 ppm. Ocean water at Atlantic Beach has a chloride content of about 17,300 ppm and a total dissolved solids content of about 31,000 ppm. Ocean water farther offshore has a chloride content of about 18,000 ppm and a total dissolved solids content of more than 31,000 ppm.

Bar graphs (Hem, 1959, p. 178) showing the percentage equivalents per million cations (Ca, Mg, and Na+K) and anions (HCO_3, SO_4, and $Cl+F+NO_3$) are used in this report for illustrating the relative proportions of dissolved material in water. An equivalent per million is the concentration in parts per million divided by the combining weight of the ion. The percentage of the equivalents per million of each cation or anion is its relative proportion to the total equivalent of all cations or anions.

Bar graphs (pl. 4) of the chemical analyses of fresh water, diffused water, and salt water are arranged in six groups. Group A includes wells screened in fresh water in the Magothy(?) Formation and Jameco Gravel, and includes one well screened in the upper Pleistocene deposits. Group B includes wells screened in fresh water in the Lloyd Sand Member. Group C includes wells in diffused and salt water, arranged in order of decreasing mineral content. Groups D, E, and F include wells in fresh, diffused, and salt water generally along sections *A–A′*, *B–B′*, and *C–C′*. (See pls. 2 and 3.)

Only qualitative interpretations have been made of the bar graphs on plate 4 because of the relatively small number of complete analyses available. Also, the percentage equivalents may be subject to errors attributable in part to the limitations in determining the ionic concentrations by standard laboratory techniques.

Group A is divided into four sets of wells (a–d), most of which show changes in the composition of ground water between the landward and seaward sides of the toe of the deep salty-water wedge. Wells in sets (a–d) are arranged approximately along lines of flow in the early 1900's before the start of withdrawal. This arrangement was chosen because ground water moves very slowly and has moved only a relatively short distance since 1900. Any changes, therefore, in chemical composition of the water must have occurred along the lines of flow before the start of withdrawal.

Significant differences in the relative proportion of Ca+Mg and HCO_3 ions (set a) are indicated along the flow line in the Magothy(?) Formation between Seaford (N180) and Jones Beach (N129). The differences are due in part to the fact that water moving laterally seaward mixes with that leaking upward from the Lloyd Sand Member. The Ca+Mg cations increased in the Magothy(?) Formation along another flow line (set b) from about 20 to 30 percent at Merrick (N4149) and Freeport (N4150) to about 50 to 70 percent at Lido Beach (N6851, N6853, N5768); this change is accompanied by an increase in HCO_3 ions. Fresh water moved westward from Lido Beach (N6851) toward Atlantic Beach (N6704) even before the start of withdrawal and along this flow line only a decrease of the Ca+Mg ions and a corresponding increase in Na+K ions is noted.

The proportion of Ca+Mg ions increased along a third flow line in the Magothy(?) Formation (set c) from about 35 percent at Rockville Centre (N7161) to about 50 percent at Lawrence (N6610) and then to about 70 percent at Lawrence (N7000); the proportion of HCO_3 ions changed slightly between Rockville Centre (N7161) and Lawrence (N6610) and increased appreciably between wells N6610 and N7000 in Lawrence. Apparently no large changes occurred in the composition of fresh water in the lower part of the Magothy(?) between wells N3867 and N3864 (set d), nor in the Jameco Gravel between wells N1379 and N3932 along a former line of flow in the Green Acres-Cedarhurst area; this fact is attributable in part to the short distance between the wells.

Before the start of withdrawal from the Lloyd Sand Member, fresh water moved generally south to southwestward from Sunrise Highway to nearshore and offshore areas in the southeastern part of the study area, where it changed course and moved generally westward along the shore and the offshore areas toward and beyond the Jamaica Bay area, approximately parallel to the leading edge of the salty water (fig. 9). Group B shows some variation in the percentage of Mg and, thus, also in the percentage of Na+K; there is also a significant increase in the Cl ion accompanied by a corresponding decrease in the SO_4 ion along the line of flow from Lido Beach (N5227, N5308) to Rockaway Park (Q1030). The increase in chloride content along the flow line is additional evidence that the frontal area of the salty water in the Lloyd Sand Member is farther offshore from Lido Beach than from Long Beach, Atlantic Beach, and Rockaway Park (fig. 9).

TABLE 2.—*Chemical analyses of ground water in*

Water-yielding unit: Qg, Gardiners Clay; Qj, Jameco Gravel; Qj(?), possibly Jameco Gravel; Krl, Lloyd tion; Qud, upper Pleistocene

[Analyses by the

Well	Depth of screen below sea level (feet)	Water-yielding unit	Date of collection	Temperature (° F)	Density at 68° F (gm/ml)	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)
										Atlantic
-------	-------	-------	Apr. 13, 1956	-------	1.019	1.2	1.3	0.00	351	1,190
										Nassau
N67	(?)-1,031	Krl	Aug. 2, 1962	61.2	-------	8.2	3.2	0.05	0.9	0.8
N129	879-889 902-941	Km	Nov. 10, 1953	-------	-------	7.6	.24	-------	.5	.2
N180	(?)-745	Km	Aug. 2, 1962	54.6	-------	8.4	1.1	.02	.9	.0
N2790	535-557	Km	Aug. 1, 1962	59.2	-------	7.4	.18	.01	.4	.7
N3448	1,187-1,227	Krl	July 1962	-------	-------	9.0	.00	.11	1.8	2.7
N3687	1,190-1,240	Krl	July 16, 1962	-------	-------	8.8	.52	.06	1.6	1.9
N3861	515-526	Km	Apr. 17, 1956	59	1.016	10	78	1.3	365	1,090
			Aug. 6, 1959	-------	1.020	-------	-------	-------	-------	-------
N3862	289-299	Km	Apr. 17, 1956	57	.999	19	146	1.8	230	174
N3932	165-169	Qj	Aug. 17, 1959	-------	.998	-------	-------	-------	-------	-------
N4026	144-148	Km	Apr. 16, 1956	55	-------	12	1.4	.10	7.0	2.9
			July 11, 1960	56.0	.9982	9.2	4.7	.06	3.2	1.9
N4062	130-135	Qg	Aug. 12, 1959	-------	.999	-------	-------	-------	-------	-------
			Aug. 1, 1962	62.5	-------	20	2.5	.31	10	4.0
N4405	995-1,065	Krl	Sept. 15, 1954	-------	-------	8.2	7.9	-------	2.0	.7
			July 16, 1962	-------	-------	9.1	.21	.08	2.0	1.9
N5227	1,190-1,250	Krl	Nov. 14, 1961	-------	-------	9.3	1.5	-------	.9	.5
N5308	1,150-1,210	Krl	July 16, 1962	-------	-------	10	.43	.07	1.5	1.1
N5768	438-459 501-523	Km	-----do-------	-------	-------	10	.09	.01	6.4	2.7
N6510	447-452	Km	July 21, 1958	60.9	1.017	12	129	2.5	374	949
			Aug. 6, 1959	-------	1.01775	-------	-------	-------	-------	-------
			Jan. 5, 1961	56.0	1.0178	13	158	2.3	362	958
N6581	565-575	Km	Oct. 6, 1958	60.5	1.008	9.9	158	4.2	308	546
			Aug. 18, 1959	-------	1.009	-------	-------	-------	-------	-------
			Jan. 5, 1961	56.0	1.0097	12	174	3.5	307	624
N6610	192-222	Qj(?)	Sept. 11, 1958	56	-------	13	.48	.09	2.5	.8
N6702	656-666	Km	July 19, 1960	60.6	1.0197	7.2	45	1.8	353	1,060
N6703	457-467	Km	July 21, 1960	61.9	1.0048	10	65	3.1	239	418
N6704	273-283	Km	July 19, 1960	59.6	.9982	7.9	1.7	.08	2.5	.5
N6705	135.5-145.5	Qj	-----do-------	60.4	1.0153	19	97	1.6	326	827
N6706	618-623	Km	July 11, 1960	62.3	1.0187	7.5	77	2.4	346	1,040
N6707	487-497	Km	-----do-------	59.8	1.0000	9.3	39	.98	82	76
N6723	51.8-53.8	Qud	July 29, 1959	58	.9979	-------	-------	-------	-------	-------
N6724	3.4-5.4	Qd	Aug. 7, 1959	-------	.999	-------	-------	-------	-------	-------
N6792	42-44	Qud	July 11, 1960	58	.9991	17	2.9	.35	87	26
N6849	1,020-1,030	Krc	July 6, 1960	62	.9985	11	2.2	.12	1.8	1.7
N6850	891-902	Km	July 5, 1960	61	.9986	7.9	.93	.00	7.8	2.0
N6851	544-549	Km	July 6, 1960	59	.9982	7.3	.41	.00	7.6	1.5
N6852	251-256	Km	July 8, 1960	57	1.0109	7.9	175	7.3	514	633
N6853	120-125	Km	-----do-------	56	.9982	8.1	.97	.18	13	1.0
N6928	710-720	Qd	Aug. 26, 1960	-------	-------	6.3	.38	.01	9.0	2.6
N7000	93-103	Qud	Aug. 1, 1962	-------	-------	27	2.8	.15	12	2.5
N7161	654-659	Km	-----do-------	59.1	-------	7.3	2.5	.02	1.6	.5
										Queens
Q1030	724-789	Krl	Aug. 3, 1962	60.8	-------	5.3	3.1	0.33	4.8	2.0
Q1929	964-1,014	Krl	-----do-------	67	-------	8.9	3.0	.06	3.2	1.8

[1] Includes hardness of all polyvalent cations reported.

southern Nassau and southeastern Queens Counties

Sand Member of Raritan Formation; Krc, clay member of Raritan Formation; Km, Magothy(?) Forma-
deposits; Qd, Recent deposits.

U.S. Geological Survey]

Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (residue at 180° C)	Hardness as $CaCO_3$	Specific conductance (micromhos at 25° C)	pH
Ocean										
9,520	373	129	2,290	17,200	0.0	1.1	31,000	5,770	47,100	7.6
County										
3.2	0.4	2	6.5	4.2	0.0	0.0	28	6	39	5.1
25	5.6	37	29	4.7	.0	.3	96	2	137	6.2
2.9	.4	3	5.7	3.4	.0	.0	24	2	30	5.3
3.6	.7	6	4.5	3.5	.0	.0	24	4	30	5.5
8.9	1.2	0	20	8.2	.1	.0	53	16	96	4.5
7.8	1.0	7	17	4.0	.1	.0	51	12	72	5.5
8,670	295	16	2,010	15,800	.0	2.1	28,300	5,510	43,000	5.2
				15,500			29,600		38,800	3.50
580	15		139	1,890	.0	2.8	3,170	1,600	5,930	3.45
				4.5			34		41	5.8
20	1.5	15	18	32	.0	.1	106	30	191	6.1
5.7	.7	16	8.0	5.8	.1	.0	43	16	63	6.2
				49			160		266	6.7
18	2.8	50	3.7	29	.1	.1	117	42	187	6.6
13	.4	6.4	15	10	.1	.1	53	8	90.6	6.8
13	1.1	9	13	12	.1	.0	62	13	98	5.8
6.2	.5	4	14	2	.1	.1	36	4	50	5.3
6.4	.7	3	16	1.8	.2	.0	42	8	58	5.0
11	3.3	36	14	10	.1	.0	76	27	121	6.5
7,670	236	0	1,970	14,000	.4	2.7	27,200	4,840	36,300	3.6
				14,000				26,600	36,300	3.70
7,760	207	13	1,850	14,300	.3	.0	26,400	4,850	36,900	5.1
3,670	50	0	1,080	7,390	.2	0	14,200	3,020	20,100	4.3
				8,030			14,900		22,200	3.40
4,100	57	8	1,080	8,340	.2	.4	15,300	3,340	23,100	5.3
4.1	1.2	14	4.3	5.4	0	0	38	10	48	6.1
8,630	275	42	1,950	15,800	.4	5.9	30,600	5,240	41,100	5.4
2,390	50	0	458	4,830	.2	.8	9,350	2,320	14,500	3.6
8.4	2.0	19	8.0	5.4	.0	.1	49	8	76	6.4
6,800	181	0	1,710	12,200	.2	4.5	24,100	4,220	33,200	3.40
8,130	221	41	1,850	15,000	.3	5.9	28,700	5,150	39,400	5.3
520	8.0	0	76	1,150	.1	.4	2,180	518	3,760	4.35
				48			274		395	7.8
				17			451		648	6.9
212	11	355	96	296	.2	6.2	940	324	1,620	7.0
106	3.2	92	82	61	.3	.4	318	12	540	7.2
148	7.5	109	100	114	.2	.2	449	28	783	7.0
5.0	2.6	28	13	3.6	.1	.0	59	20	92	6.5
3,910	85	0	1,140	8,180	.2	4.4	15,500	3,890	23,900	4.2
6.2	2.6	51	8.2	4.2	.0	.3	73	37	124	8.2
23	2.6	64	16	13	.2	0	107	33	181	6.9
6.3	2.0	64	.2	6.0	.1	.3	100	41	123	6.8
5.2	.6	10	4.5	4.0	.0	.0	28	6	40	5.8
County										
20	4.7	41	0.8	25	0.2	0.0	84	20	154	6.6
13	1.4	5	16	16	.1	.0	65	16	107	5.3

The fresh water in the Lloyd Sand Member at well N67 (Group B), screened in the Lloyd at Freeport, has nearly the same chemical characteristics as that in the lower part of the Magothy(?) Formation at well N4149 in Merrick and at well N4150 in Freeport (Group A, set b). This similarity might be expected because of the upward leakage of fresh water from the Lloyd Sand Member to the Magothy(?) Formation (fig. 9). The similarity suggests that the composition of the fresh water was changed little in its movement through the clay member of the Raritan Formation.

Salt water and diffused water in the deep and intermediate wedges (Group C) have a total dissolved solids content exceeding 24,000 ppm and resemble ocean water at Atlantic Beach very closely, and diffused water containing a total dissolved solids content of about 2,000 to 16,000 ppm in Group C generally resembles that of ocean water. Apparently small increases in the Ca+Mg and HCO_3 proportions occurred as the salty water moved landward from seaward sources. These increases are evident from the comparison of the bar graphs along lines of flow of salty water in the deep wedge between the source salty water and (a) Cedarhurst (N3861) to Woodmere (N6581), as shown in Groups C and D, (b) Lawrence (N6510) to Hewlett Neck (N6706, N6707), as shown in Groups C and E, and (c) Atlantic Beach (N6702, N6703), as shown in Groups C and F. Also, very small increases (Group C) occurred as salty water moved landward in the intermediate wedge from seaward areas to Atlantic Beach (N6705) and to Lido Beach (N6852). A significant increase in the Ca+Mg proportions, however, occurred between the source of the salty water and the Lawrence area (N3862) (Group C and E).

The bar graph of diffused water in the clay member at well N6849 in Lido Beach (Group F) is similar to that for diffused water at the base of the Magothy(?) Formation at well N6850. It resembles fresh water in the Lloyd Sand Member at the supply well N5227 at Lido Beach much more than it does the fresh water in the middle of the Magothy(?) Formation at well N6851 at the same site. This similarity is not surprising in view of the upward leakage of fresh water from the Lloyd; it also suggests that the composition of water changed little in its passage upward through the clay member of the Raritan Formation. The dissimilarity between the diffused water near the toe of the deep wedge at Lido Beach (N6850) and that in the overlying fresh water in the middle of the Magothy(?) Formation (N6851) at the same site is a verification of the virtually separate and distinct flow lines in the diffused water at the base of the Magothy(?) Formation and in the overlying fresh water.

The percentage composition of the diffused water at the base of the Magothy(?) Formation at Lido Beach (N6850) is approximately the same as that of the fresh water at the base of the Magothy(?) Formation at Jones Beach (N129). This fact suggests that water moving upward from the Lloyd has not changed appreciably in its passage through the clay member of the Raritan Formation.

The bar graphs in Groups D, E, and F (pl. 4) suggest that the diffused water in the report area is not a theoretical mixture of the source fresh and salty water; trilinear plots verify this conclusion (Perlmutter and Geraghty, 1963, p. 46–47). Modifications from a theoretical mixture are caused in the ground-water reservoir by chemical and physical reactions between the different kinds of water moving in the reservoir. Changes are also caused by reactions between (a) the rocks and minerals in the unconsolidated deposits and (b) the water and its constituents.

Dispersion is another influence that alters the composition of diffused water from that expected of a theoretical mixture of fresh and salty water. Dispersion in porous media consists of two separate mechanisms (Bosworth, 1949): (a) convection, the mechanical transfer of water and its salt mass, and (b) ionic diffusion, the chemical transfer of salt mass from one region to another. Except at very slow velocities, dispersion due to convection is much more rapid than that due to ionic diffusion (Cooper, 1959, and others). Dispersion is associated with the interrelated movements of fresh, diffused, and salt water; these movements vary with changes in the quantities of fresh water moving seaward and also with oceanic tides. In different regions the two mechanisms of dispersion also cause the individual ions in the salt mass to move at different rates.

The rates of dispersion attributable to tidal effects in alternating beds of high and low permeability such as those found in the Magothy(?) Formation, are considerably larger than those in homogeneous beds (Cooper, 1959). This fact accounts in part for the wide zone of diffusion between Atlantic Beach and Lido Beach.

Fresh ground water and ocean water generally contain relatively little or no iron and manganese and have a pH of about 5 to 8. The salt and diffused ground water, however, in the study area have appreciable concentrations of iron and manganese and a relatively low pH (table 2). Salty water, having a total dissolved solids content of more than 2,000 ppm, also contains as much as 175 ppm iron and 7.3 ppm manganese, and the pH ranges from about 3.4 to 7.8.

DIRECTION AND RATE OF FLOW OF FRESH AND SALTY GROUND WATER

GENERAL PRINCIPLES

The movement of fresh and salt water has been studied by many investigators including Muskat (1946), Hubbert (1940, 1953), Cooper

(1959), Kohout (1960, 1961), Henry (1959, 1960), and Perlmutter and Geraghty (1963). The principal concern in this section of the report is the definition of the direction and rate of movement of water in the zone of diffusion and in the main salt-water body under the natural and artificial conditions existing in March 1961.

The direction of flow is defined by normals to water-level contours. The velocity for steady-state conditions is computed by Darcy's law expressed as $V=PI/\theta$, where V is the velocity, P is the permeability, I is the hydraulic gradient, and θ is the effective porosity.

Water moves from points of higher head to lower head. The hydraulic gradient in fresh and salty ground water is the difference in head per unit distance along a flow line; in any other direction the difference in head per unit distance is a component of the gradient. Because the density of water in the zone of diffusion varies from place to place, heads observed in pairs of nearby wells in the zone of diffusion cannot be used directly to determine velocities except in special circumstances. In the following sections, new concepts of head relations are introduced; these concepts permit computation of the directions and rates of movement of water of variable density.

FLOW OF WATER OF VARIABLE DENSITY

HEADS AND GRADIENTS

The head at a point in ground water of variable density varies with the datum and the density of the water in terms of which the head is measured. In this report, water at any point is called point water; point water may be fresh, diffused, or salt (fig. 7).

Point-water head at a point in ground water of variable density is defined as the elevation, referred to mean sea level, of the top of a column of point water balancing the existing pressure at the point (for example, the head in a well filled with point water, fig. 7*A*). From this definition

$$\rho_i H_{ip}=Z_i\rho_i+(p_i/g), \tag{1}$$

where

i=a point in ground water of variable density,
ρ_i=density of water at i,
H_{ip}=point-water head at i,
Z_i=elevation of i, measured positively upward,
p_i=pressure at i, and
g=gravitational acceleration.

The first subscript in H_{ip} refers to the point in question, and the second subscript signifies that the water in the well is the same as that at the point.

Fresh-water head at a point in ground water of variable density is defined as the elevation of the top of a column of fresh water balancing the existing pressure at the point (for example, the head in a well filled with fresh water, fig. 7*B*). From the equality of pressures (fig. 7*A* and *B*), fresh-water head may be expressed in terms of point-water head by the relation

$$\rho_f H_{if} = \rho_i H_{ip} - Z_i(\rho_i - \rho_f), \tag{2}$$

where

ρ_f=density of fresh water, and
H_{if}=fresh-water head at i.

Water having a constant density need not be used in the well for measurement of the pressure and head. In fact, using environmental water (defined below) for determining velocities in the vertical direction in ground water of variable density is advantageous.

Environmental water is defined as water of variable or constant density that exists in the aquifer along a vertical line between the point in question and the top of the zone of saturation (fig. 7*C*). Environmental-water head at a point in ground water of variable density is defined (Lusczynski, 1961b; Lusczynski and Swarzenski, 1962) as the head consisting of (a) a column of environmental water from the point to the top of the zone of saturation and (b) a positive or negative head of fresh water, which, when added to the column of environmental water, will balance the existing pressure at the point. (See fig. 7*C*.)

Environmental-water head must be computed because it cannot be determined in the field. From the equality of pressure (figs. 7*b*, *c*; 7*a*, c), one can write:

$$\rho_f H_{in} = \rho_f H_{if} - (\rho_f - \rho_a)(Z_i - Z_r) \tag{3}$$

$$\rho_f H_{in} = \rho_i H_{ip} - Z_i(\rho_i - \rho_a) - Z_r(\rho_a - \rho_f) \tag{4}$$

where

ρ_a=average density of water between elevations of Z_r and i,
H_{in}=environmental-water head at i, and
Z_r=elevation of reference point from which the average density of water to i is determined and above which the water is fresh.

The relation between environmental-water head and fresh-water head is expressed in equation 3. The relation between environmental-water head and point-water head is expressed in equation 4.

As stated, ρ_a is the average density of water between a selected reference point and the point in question. The reference point must

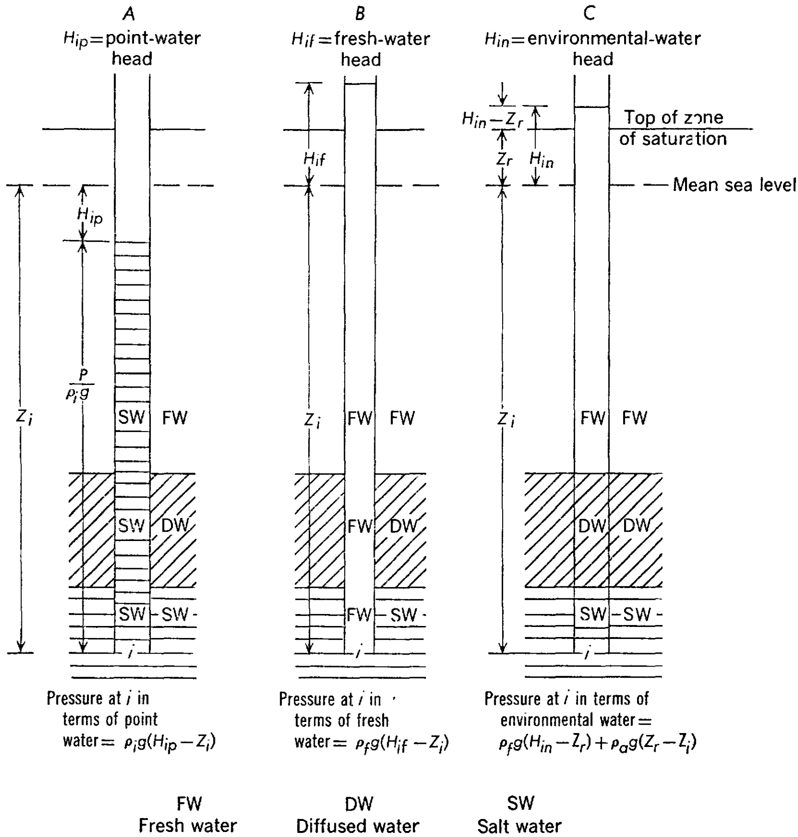

FIGURE 7.—Heads in ground water of variable density.

be the top of the zone of saturation if the uppermost water body is not fresh. If the uppermost body is fresh, the reference point may be anywhere within the interval of fresh water. If the water is fresh above mean sea level, it is convenient to make the reference point coincident with mean sea level, in which case $Z_r=0$, and equations 3 and 4 reduce to

$$\rho_f H_{in}=\rho_f H_{if}-Z_i(\rho_f-\rho_a) \tag{3a}$$

and

$$\rho_f H_{in}=\rho_i H_{ip}-Z_i(\rho_i-\rho_a) \tag{4a}$$

In these equations, ρ_a is then the average density of water between mean sea level and point i.

In this report a fresh-water head is computed from a point-water head using equation 2. An environmental-water head is computed from a fresh-water or point-water head using equations 3a and 4a. The densities ρ_f and ρ_i were determined principally from samples of

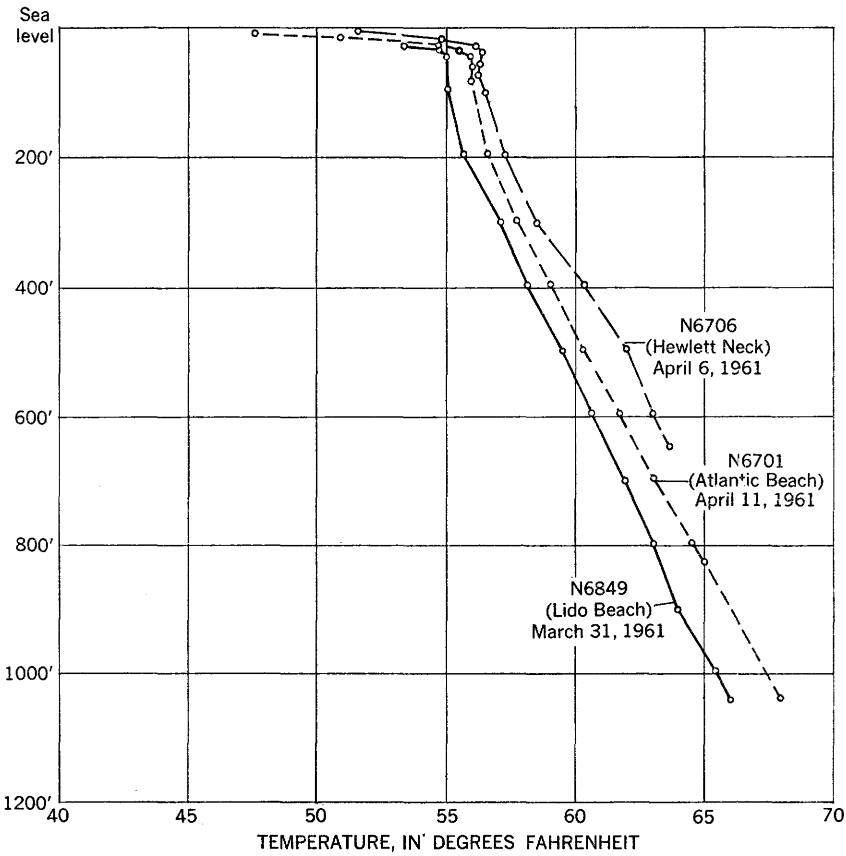

FIGURE 8.—Ground-water temperatures at Atlantic Beach, Lido Beach, and Hewlett Neck.

fresh water and salt water obtained in 1959–62. Also, the difference in densities ($\rho_i-\rho_f$) was determined at several sites in the field by observing the change in heads produced by the replacement of the salty water in a well with fresh water. The average density (ρ_a) was computed from the average chloride content of environmental water and the known relationship between the chloride content and density at the particular site.

All the densities used in the computations are those at field temperatures of the water, which were determined from temperature profiles in wells at Atlantic Beach, Hewlett Neck, and Lido Beach (fig. 8) and from the temperature of water at the screens of selected wells.

Ground-water temperatures at corresponding depths were found to be 1° to 2° cooler (difference increases with depth) at Lido Beach than at Atlantic Beach, about 7 miles to the west. The temperatures at corresponding depths also were found to be about 1° to 2° cooler at Atlantic Beach than at Hewlett Neck, about 2 miles landward of

Atlantic Beach. These indications of increases in temperatures westward and landward are substantiated by ground-water temperatures at public supply, observation, and other wells in areas south of Sunrise Highway in southwestern Nassau County.

VELOCITY

HORIZONTAL AND VERTICAL COMPONENTS

Lusczynski (1961b, p. 4250) gave equations for computing the horizontal and vertical components of velocity in ground water of variable density. The equations, which are based on a generalized form of the Darcy equation, define these components when the axes of the principal directional permeabilities coincide with the x and y coordinates axes in a horizontal plane and with the z axis in a vertical direction. In simplified form, these equations written to express the actual component velocities are:

$$v_x=\frac{P_xI_x}{\theta};\ v_y=\frac{P_yI_y}{\theta};\ v_z=\frac{P_zI_z}{\theta}, \tag{5}$$

where v_x, v_y, v_z are the actual velocities, P_x, P_y, P_z are the principal directional permeability coefficients and I_x, I_y, I_z are the hydraulic gradients in the x, y, and z directions, and θ is the effective porosity. I_x and I_y are computed from fresh-water heads and I_z from environmental-water heads. The permeability coefficient, $P=\frac{k\rho g}{\mu}$, includes the property of the medium, k; the density of the water, ρ; the gravitational acceleration, g; and the viscosity, μ, of the water. The velocity of the ground water is the vector sum of the components determined from 5.

In this report, P_x, P_y, and permeabilities in other directions parallel to the bedding planes, which are virtually horizontal, are assumed to be the same, although they may differ by at least a small amount. Only the difference between horizontal and vertical permeability is considered to be significant. Generally, the horizontal permeability is appreciably higher than the vertical. M. A. Warren and N. J. Lusczynski (written commun., 1958) determined that the horizontal permeability of the Pleistocene sand and gravel in central Suffolk County, Long Island, is 4 to 18 times the vertical permeability.

The velocity, in feet per year, for an assumed effective porosity of 0.25, can be expressed by the equation:

$$V=0.037PI, \tag{6}$$

where P is the permeability in gallons per day per square foot, and I is the hydraulic gradient in feet per mile. Equation 6 is used in a later section of the report to compute rates of salt-water encroachment.

FLOW ON AN INCLINED PLANE

Equations for determining the direction and rate of flow in ground water of variable density on an impermeable inclined surface are given in this section. The case of two-dimensional steady flow in isotropic material is considered first.

The differential form of the Darcy equation for flow at a point i in ground water of variable density, when expressed in terms of fresh-water heads, is (Lusczynski, 1961b, p. 4249–4250):

$$\vec{q}_i = -\frac{P}{\theta}\,[\nabla H_{if} + d_i \vec{k}], \qquad (7)$$

where

$\vec{q}_i$=vector pore velocity,
P=permeability,
θ=effective porosity,
∇H_{if}=gradient of fresh-water heads,
d_i=density-difference ratio, $(\rho_i - \rho_f)/\rho_f$, and
$\vec{k}$=unit vector directed upward along a vertical.

For any two nearby points, 1 and 2, along a flow line,

$$\bar{v} \cong -\frac{P}{\theta L}\left[(H_{1f} - H_{2f}) + \int_2^1 d_i dz\right],$$

$$\bar{v} \cong -\frac{P}{\theta L}\,[(H_{1f} - H_{2f}) + \bar{d}(Z_1 - Z_2)], \qquad (8)$$

where $\bar{v}$ is the average pore velocity and $\bar{d}$ is the average density-difference ratio between points 1 and 2, a distance L apart.

The velocity is zero along a normal to the flow line and thus from equation 7

$$(H_{3f} - H_{4f}) = \int_3^4 d_i dz \cong \bar{d}(Z_4 - Z_3), \qquad (9)$$

where $\bar{d}$ is the average density-difference ratio between any pair of points 3 and 4, on the normal to the flow line.

Equation 9 shows that in ground water of variable density normals to flow lines are lines along which the difference in fresh-water heads between two nearby points is equal to an integral which, in turn, is approximately equal to the difference in elevation multiplied by the average density-difference ratio between the two points on an inclined surface. Inasmuch as the velocity components along such normals are zero, lines along which equation 9 applies are herein named zero-vels (lines of zero velocity).

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As suggested by equations 7 and 9, zerovels can be determined conveniently by comparison of two maps (not included in the report) showing (a) lines of equal fresh-water heads along an inclined plane and (b) lines of equal density-difference ratios along the same plane. A zerovel depicts the direction along which the left-hand side of equation 9, determined from (a), equals the right-hand side of equation 9, determined from (b).

The direction of flow at any point in ground water of variable density is normal to a zerovel. Velocity along the line of flow can be computed by using equation 8, the above-mentioned contour maps, or the method explained in the following paragraph.

For flow along a horizontal line on an inclined surface, the second term in the brackets in equation 8 is zero. The velocity, therefore, becomes

$$v=-\frac{P}{\theta}\left[\frac{H_{1f}-H_{2f}}{L}\right], \tag{10}$$

which is the ratio of permeability to porosity multiplied by the hydraulic gradient defined by fresh-water heads. If the flow is not along a horizontal line, equation 10 defines only the horizontal component of the velocity.

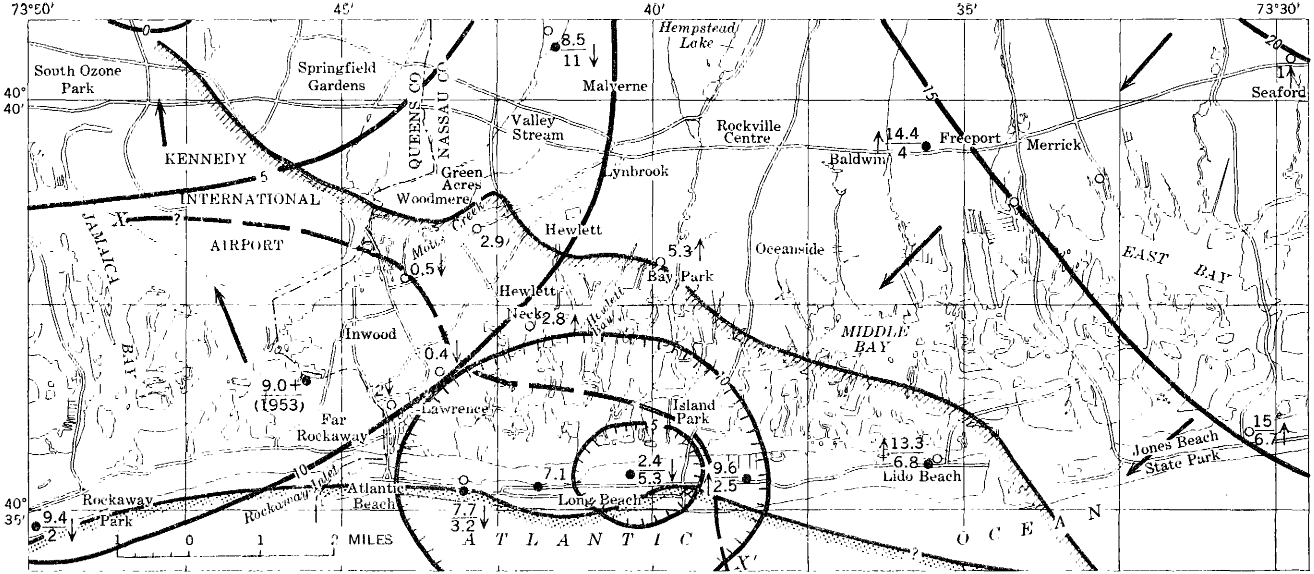
In this report, zerovels in the zone of diffusion are defined by equation 9, the direction of flow is found from the normals to the zerovels, and the velocity along the direction of flow is computed by the method described in the preceding paragraph.

MOVEMENT OF WATER IN THE GEOLOGIC UNITS

LLOYD SAND MEMBER AND CLAY MEMBER OF RARITAN FORMATION

Fresh-water isopotentials in the Lloyd Sand Member, based in part on heads observed during March 1961 and in part on isopotential maps for 1947 and 1950 (Lusczynski, 1950; Lusczynski and Roberts, 1952) are shown in figure 9. The heads in the study area ranged from about 0 to about 20 feet above sea level in March 1961; they are several feet lower during the period of heavy withdrawls in the summer. Heads in the cone of depression created by withdrawals from public-supply wells at Long Beach were 2.4 feet at well N44 in March 1961; these heads may have been lower at other supply wells at Long Beach. During the past 15 to 20 years, heads in the Lloyd have been below sea level in central Queens, northwest of the report area, where a sizeable cone of depression has been created by withdrawals of about 4 to 6 mgd from public-supply wells (fig. 11, graph k).

Before the start of withdrawals from the Lloyd in the early 1900's, fresh water moved generally southward in the northern half of the area of investigation, southwestward in the southeastern part, and



9.4 / 2 ↑ (solid dot)
Well screened in Lloyd Sand Member

Upper figure is fresh-water head, in feet; lower figure and arrow are difference in environmental-water head, in feet, and direction of flow across the clay member of the Raritan Formation

2 ↓ (open circle)
Well screened in Magothy(?) Formation

Figure and arrow are difference in environmental-water head, in feet, and direction of flow across the clay member of Raritan Formation

——10——
Fresh-water isopotential, in Lloyd Sand Member, in feet

←——
Direction of flow in Lloyd Sand Member

Approximate landward limit of deep salty-water wedge on surface of clay member of Raritan Formation

X— — — —X'
Approximate line delineating areas where flow across clay member is upward on landward side and downward on seaward side

Approximate landward limit of salty water in the Lloyd Sand Member of Raritan Formation

Heads and altitudes given in feet with reference to mean sea level at Sandy Hook, N. J.

FIGURE 9.—**Fresh-water isopotentials in Lloyd Sand Member of Raritan Formation, March 1961.**

westward along the shore in the southwestern part, to discharge areas south of Queens and Kings Counties (fig. 1). Along its course to the discharge areas, much of the fresh water from the Lloyd leaked upward to shallower aquifers.

Lateral discharge of fresh water from the Lloyd in offshore areas is prevented by fresh-water heads in salty ground water offshore in the Lloyd; these heads are higher than those in the fresh ground water at comparable depths beneath the barrier beaches, as shown in the following table:

Fresh-water heads in the Lloyd Sand Member in 1961

Location	Depth (ft below msl)	Estimated fresh-water head in salt water [1] (ft above msl)	Observed fresh-water head in fresh water [2] (ft above msl)
South of Rockaway Park	800	17	9
South of Jones Beach	1,300	27	14

[1] Assuming a head of zero in salt water having a density of 1.021 g per ml (grams per milliliter).
[2] Estimated from plate 2*B* and figure 9.

The heads in fresh water in the table are for 1961; probably they were not more than a foot or two higher before the start of withdrawals from the Lloyd.

Normals to the isopotentials (fig. 9) indicate that under present (1961) conditions, fresh water in the Lloyd moves southwest from Jones Beach toward and along the salt-water front in the aquifer in the offshore areas and then landward toward Long Beach, Rockaway Park, and central Queens County. This change in direction from the natural flow pattern is caused principally by withdrawals from the Lloyd Sand Member.

Landward gradients created by withdrawals at Long Beach since about 1920, at Lido Beach since 1937, and at Atlantic Beach since 1954, cause encroachment of salt water from offshore areas toward the supply wells. As stated before, nearby salty water may already have moved in laterally in places along the upper beds in the Lloyd at Long Beach and perhaps along the middle beds at Atlantic Beach.

The direction of flow of fresh and salty water across the clay member overlying the Lloyd Sand Member was determined at selected sites (fig. 9) from differences in environmental-water heads at the base of the Magothy(?) Formation and in the Lloyd Sand Member (pl. 2*B* and 3). The differences in heads indicate that generally salty water is moving downward from the Magothy(?) toward the Lloyd Sand Member in areas seaward of line *X–X′* (fig. 9) and that fresh water is moving upward from the Lloyd in most places between line

X–X′ and Sunrise Highway to the north. Line *X–X′* shifts landward 1 or 2 miles during the summer when withdrawals from the Lloyd Sand Member are the heaviest.

Salty water has already reached the lower part of the clay member between Rockaway Park and Lido Beach (pl. 2*B*). Hydraulic gradients favor continuous downward movement of salty water along the barrier beach between Rockaway Park and Long Beach. At Lido Beach, however, the flow is upward most of the year, except during the summer when wells N46 and N5227 are pumped nearly continuously. The rate of downward penetration of salty water in the clay member at Atlantic Beach, Long Beach, and Lido Beach is probably not more than a foot a year, owing to the generally low permeability of the clay member, even at times of heaviest withdrawals from supply wells (Lusczynski and Swarzenski, 1962, p. 192). It may, however, be faster in some places where the clay member is more permeable, but such places have not been identified. Lateral movement of the salty water toward the supply wells is doubtless much faster than the downward movement of this water through the clay member; however, the distance salty water must travel laterally may be several tens to thousands of times more than the distance through the clay member.

With the flow directions defined, it is possible to offer an explanation for the unusual pattern of isochlors at Lido Beach as shown on plate 2*A*. As discussed previously, the chloride content of about 175 ppm in the clay member (fig. 6) exceeds that of about 115 ppm at the base of the Magothy(?). A hypothesis explaining this anomaly and the thick zone of diffusion at Lido Beach is as follows: (a) Originally a relatively thin wedge of salt water arrived at the site of well N6850 at Lido Beach while the deep wedge moved eastward in the lower part of the Magothy(?) Formation, (b) some of the salty water moved downward into the clay member by diffusion, and (c) the remainder of the salty water in the lower part of the Magothy(?) Formation was redistributed by dispersion over a thicker zone. These processes could have taken place during a long period of time, even in the presence of an upward hydraulic gradient across the clay member (fig. 9), provided that the rate of movement of fresh water upward did not exceed the rate of downward movement of salt by diffusion. The diffusion of salt water is very slow, but even so it might have been faster than the movement of fresh water through the relatively impermeable clay member at Lido Beach.

MAGOTHY(?) FORMATION

Fresh, diffused, and salt water are moving in the basal part of the Magothy(?) Formation on the relatively impermeable clay member of the Raritan Formation. Locally, the flow is virtually two dimensional and parallel to the inclined surface of the clay member. The rates and directions of the flow of salty water can be computed approximately.

Isopotentials in fresh and salt water and zerovels in the zone of diffusion are shown for the base of the Magothy(?) Formation as of March 1961 (pl. 5). The isopotentials and zerovels are based on point-water heads measured in wells screened in or near the lower part of the Magothy(?) or are extrapolated from heads in wells screened in the middle and upper part of the Magothy(?) Formation.

The zerovels on plate 5 were determined by the method described previously (p. F46). They were chosen arbitrarily to pass through the fresh-water heads of 7.5 and 7.0 feet at Long Beach, 6.5 feet at Lido Beach, and 6.7 and 5.8 feet at Hewlett Neck. The fresh-water heads that are shown at the intersection of contours on the surface of the clay member of the Raritan Formation with the zerovels and salt-water isopotentials were determined from a contour map of fresh-water heads.

If the permeability of the lower beds of the Magothy(?) Formation is the same in all directions parallel to the surface of the clay member, the flows in fresh water and in salt water are normal, respectively, to the fresh-water and salt-water isopotentials, and the flow in diffused water is normal to the zerovels.

Normals to salt-water isopotentials indicate that the main body of salt water is moving northeastward in areas southwest of Cedarhurst and eastward at Lawrence and Atlantic Beach. The salt-water isopotentials show that the hydraulic gradients are about 2 feet per mile, and the coefficient of permeability of the beds through which the salt water is moving is probably no more than 1,000 gpd per sq ft. Substitution of these values in equation 6 gives a rate of movement for the salt water of not more than 75 feet a year, in March 1961, southwest of Cedarhurst and west of Atlantic Beach.

Normals to the zerovels indicate that in March 1961 the diffused water in southwestern Nassau County was moving generally northeastward. Hydraulic gradients in the zone of diffusion decrease from an average of about 1.5 feet per mile on the salt-water side to about 0.3 feet per mile on the fresh-water side of the diffused zone. The permeability of the beds through which the diffused water is moving probably does not exceed 1,000 gpd per sq ft. Using these values in equation 6 gives a rate of movement of the diffused water at the base of the Magothy(?) of not more than about 55 feet per year on the salt-water side and not more than about 10 feet per year on the fresh-water side of the zone of diffusion.

The gradients in salt water on the seaward side of the diffused zone between Lawrence and Hewlett Neck during the period of heavy pumping in July 1954 and August 1960 were about 30 percent higher than those in March 1961, whereas the gradients in the diffused water between Hewlett Neck and Bay Park were practically the same during these three periods. Therefore, the higher regional rates of encroachment along the base of the Magothy(?) Formation probably did not exceed 100 feet a year in salt water and 10 feet a year in the diffused water near the toe of the deep wedge.

The decrease in the rate of movement between the salt-water and fresh-water side of the zone of diffusion suggests that only some of the salty water moves to the toe of the deep wedge from the salt-water side to the fresh-water side of the diffused zone. As indicated previously, some salty water moves downward into the clay member, although the amount is small owing to the low permeability of the member. Also, some salty water moves to the upper part of the zone of diffusion, as suggested by the upward components of the hydraulic gradients in the upper part of the deep wedge at Atlantic Beach and Lido Beach (pl. 2*B*), at Lawrence (pl. 3*B*, *B–B′*), and at Cedarhurst (pl. 3*B*, *C–C′*).

Local encroachment in Woodmere is caused by withdrawals at the Mill Road pumping station (pl. 3*B*, *C–C′*). Here the leading edge of the deep wedge has advanced about three-quarters of a mile farther inland than in nearby areas. The total advance since 1900 has been about a mile. The toe of the salty-water wedge in the lower part of the Magothy(?) is already beneath the pumping center, owing to continuous withdrawals for many years from the Jameco Gravel and upper Pleistocene deposits at the pumping station. A landward hydraulic gradient in the diffused water of about 15 feet per mile in March 1961 was determined from the fresh-water head at well N6581 and the head estimated at the toe of the wedge (pl. 3*B*, *C–C′*). A permeability of about 500 gpd per sq ft for the sand and gravel at the base of the Magothy(?) was computed from an aquifer test at well N6581. From these values the rate of movement of salty water at the toe of the deep wedge between well N6581 and the pumping center was computed to be about 280 feet per year in March 1961.

The gradient between well N6581 and the pumping center was about 25 feet per mile at the end of August 1960 when withdrawals were large and about 30 feet per mile in July 1954 during another period of very large withdrawals. At these times the rates of encroachment were estimated at about 460 and 550 feet a year, but such rates apply only for relatively short periods of time. The average yearly rate of encroachment of the toe of the deep wedge between well N6581 and the pumping center is about 300 feet a year. This rate is verified by the comparison of the electric logs of well N3864 drilled in

1952 and those of nearby well N6581 drilled in 1958. Resistivity curves show an increase in the thickness of the diffused water from 20 to 41 feet between 1952 and 1958 (Lusczynski and Swarzenski, 1960, p. 1747). These data imply an encroachment rate of nearly 300 feet a year. Encroachment is also confirmed by the increase from 7,500 to 8,800 ppm in the chloride content of water sampled at well N6581 from 1958 to 1961.

The rate of local encroachment of the deep wedge in southeastern Queens in response to nearby pumping can be estimated from the change of chloride content of water at two supply wells screened in the Jameco Gravel in South Ozone Park in southeastern Queens. The chloride content of water from well Q559 increased from 5 ppm in 1935 to 20 ppm in 1938 and was as high as 159 ppm in 1951 at the time the well was abandoned. The chloride content increased from about 5 ppm in 1940 to about 20 ppm in 1960 at well Q314, about 3,500 feet northeast of Q559. On the basis of the reported chloride content of 20 ppm in 1938 at well Q559 and in 1960 at well Q314, it is estimated that the salty water moved inland a distance of about 3,500 feet in 22 years, at an average rate of about 160 feet a year.

The deep wedge may have advanced as much as a mile locally but not more than 1,000 feet regionally since the start of heavy withdrawals in the early 1900's.

It is estimated that by the year 2000, considering the present and the probable future withdrawals and losses through sewers, the toe of the deep wedge (pl. 5) moving at or near the base of the Magothy(?) Formation may reach more than a mile north of well Q314 and also the vicinity of Sunrise Highway between Valley Stream and Lynbrook. Elsewhere the regional advance will be much less than a mile. Of course, any reduction or elimination of withdrawals in and near these areas will slow down the rate of encroachment. These estimates are based on the assumption that there will be no artificial recharge, importation of water, artificially created water barriers, or other methods intended to reduce or prevent encroachment.

Isopotentials in the fresh water moving at the bottom of the Magothy(?) Formation in the northern part of the area and above the deep wedge in the southern part are shown on plate 5. They are based mainly on heads at wells screened in or near the bottom of the fresh water, but a few were estimated from heads in wells screened at shallower depths in the Magothy(?) and in the Jameco Gravel. For the isopotentials at Woodmere, heads at the top of a fairly thick clay zone near the bottom of the Magothy(?) Formation (pl. 3*B*, *C–C'*) were used.

Isopotentials on plate 5 define a sizeable cone of depression created by the large withdrawals at the Mill Road pumping station in Woodmere, where the flow of fresh water is toward the pumping center. Actually not only the fresh water but also the salty water is moving landward toward the pumping center from Cedarhurst (pl. 3*B*, *C–C′*, and pl. 5). Normals to the isopotentials elsewhere in Nassau County indicate a distinct change in direction of flow of fresh water from generally southward in the northern part to westward in the southern part. This pattern of movement suggests that fresh water moving seaward from inland areas along the lower part of the Magothy(?) Formation does not discharge offshore but instead moves between the intermediate and deep wedges of salty water (pl. 2*B*) along the barrier beach toward discharge areas in and west of Jamaica Bay (fig. 3). There is undoubtedly a mutual influence on directions and rates of flow in the deep salty-water wedge and in the overlying fresh water.

The decrease in the rate of landward movement of salty water at the base of the Magothy(?) Formation (pl. 5), upward gradients in the upper part of the zone of diffusion (pls. 2*B* and 3), and the movement of fresh water over the deep wedge (pl. 5) to discharge areas suggest a sweepback or cyclic flow of the diffused water in the upper part of the deep wedge. This sweepback apparently takes place in a zone as much as 100 feet thick, approximately between the 40-ppm and the 5,000-ppm isochlors. The sweepback is suggested by the following examples.

A decrease in head of about 0.4 foot from point A to point B in Lawrence (pl. 3*B*, *B–B′*) is computed from the bracketed term in equation 8. The decrease indicates a southwestward sweepback in the upper part of the zone of diffusion. Such flow is generally in the same direction as that of the overlying fresh water (pl. 5) but opposite to that of the salty water at the base of the Magothy(?) Formation (pl. 5).

A decrease in head of about 0.8 foot is also determined from points A and B in the upper part of the zone of diffusion in section *A–A′* (pl. 2*B*). This decrease indicates that the flow in the upper part of the zone of diffusion has a westward component. In all likelihood, the sweepback is northwestward, perhaps in about the same direction as the flow of the overlying fresh water (pl. 5), which contrasts with the eastward flow of the deep salty water at the base of the Magothy(?) Formation (pl. 5).

The concept of cyclic flow in the Long Island area was suggested diagrammatically by Spear (1912, sheet 17). The concept of this type of flow was discussed theoretically by Lusczynski in December 1956 in a talk on general concepts and principles of salt-water encroachment given at a meeting of the American Association for the Advancement of Science in New York. Cyclic flow as a consequence of dispersion was suggested by Cooper (1959) and investigated in southeastern Florida by Kohout (1960, 1961). According to Todd (1960), several earlier investigators have mentioned cyclic flow.

The return, or sweepback, of salty water to the sea by the seaward movement of the overlying fresh water necessarily retards the encroachment of the salty-water wedge along the base of the Magothy(?). The reduction in rate of encroachment is indicated by the decrease in the regional rate of movement along the surface of the clay member of the Raritan Formation from not more than 100 feet a year on the salt-water side of the diffused zone to not more than 10 feet a year at the toe of the deep wedge.

MAGOTHY(?) FORMATION AND JAMECO GRAVEL (−150 FT MEAN SEA LEVEL)

Fresh-water isopotentials in fresh and salty water at −150 feet msl in March 1961 are shown on plate 5. The selected plane intersects the upper part of the deep wedge in southeastern Queens County and the upper part of the intermediate wedge of salty water in southwestern Nassau County. The isopotentials are for heads at −150 feet, which occur either in the Jameco Gravel or in the upper part of the Magothy(?) Formation (pls. 2*B* and 3); in both formations the water is confined by the Gardiners Clay or the "20-foot" clay in much of the area south of Sunrise Highway. In the extreme southeastern part of Queens County and in offshore areas, the confining clays are known or believed to be missing (fig. 3), and the salty water at −150 feet is probably in the undifferentiated Recent and Pleistocene deposits. In these areas, isochlors are not shown because of lack of data. The isopotentials in fresh water are based on observed fresh-water heads. Those in salty water are based on fresh-water heads computed by use of equation 2 from observed or estimated salty-water heads.

The configuration of the fresh-water isopotentials reflect the geologic environment and also the hydraulic relations. The cone of depression in the Cedarhurst-Woodmere area is caused by large withdrawals from the Jameco Gravel and the upper Pleistocene deposits at the Mill Road pumping station in Woodmere. The shape of the 4-foot contour in fresh water southeast of the cone of depression reflects in part downward leakage of fresh water from the upper Pleistocene deposits northeast of the Rockaway Peninsula where the water-table mound is known to be as high as 10 feet above sea level. Contours in the south-central part of the area reflect the landward projection of the intermediate wedge of salty water.

Horizontal components of flow at −150 feet are indicated by arrows drawn normal to the isopotentials. They show that fresh water moves south to southwestward in most of the area but radially toward the pumping center in Woodmere. Landward advance of the intermediate wedge is suggested by the increase in chloride content of water at several commercial wells in Island Park (pl. 5). At well N6643 in Island Park (pl. 1), the chloride content increased from 60 to 154 ppm from 1959 to 1961, and at nearby well N7020, it increased slightly fom 78 to 86 ppm between April and August 1961. The increases may be attributable to pumping at these wells and also at public-supply and commercial wells screened in fresh water between the salt-water front and Sunrise Highway. On the basis of a hydraulic gradient of about 1 foot per mile and an estimated maximum permeability of 1,000 gpd per sq ft for the deposits, the rate of movement of the intermediate wedge is estimated to be not more than 40 feet a year between Long Beach (N3529) and Island Park (N7020). The rate was probably not more than 10 to 20 feet a year between Island Park (N7020) and Oceanside (N3078) in the frontal regions of the intermediate wedge in 1961.

At this rate the toe of the intermediate wedge has advanced regionally less than 1,000 feet since 1900. It is estimated on the basis of the present rate of encroachment and on the basis of the present and probable future development of ground water that the intermediate wedge will not advance more than a mile by year 2000.

The reduction in the rate of landward movement of salty water from not more than 40 feet a year in the Long Beach-Island Park area to less than 20 feet a year in the Island Park-Oceanside area is due in part to the upward leakage of salty water between the barrier beach and the toe of the intermediate wedge. Heads in the intermediate wedge of salty water (pl. 2*B*) are high enough to cause upward leakage of salty water into the upper Pleistocene deposits in places along and also north of the barrier beach.

At about −130 feet in Lawrence, the chloride content of water at well N4062 in the upper part of the deep wedge decreased from 68 ppm in 1959 to 38 ppm in 1961. At the same site, at a depth of −300 feet, the chloride content of the water at well N3862 remained virtually unchanged at about 2,000 ppm from 1952 to 1961. These two wells near the shoreline are several miles from the pumping centers; therefore, the chloride content of the water doubtless reflects only local conditions.

Well N3734 in Inwood is within the cone of influence created by the pumping at the Mill Road station at Woodmere when heavy withdrawals are made during the summer. At such times, gradients in both the fresh water and salt water are landward from well N3734 to the pumping center at Woodmere. Landward movement of salty water at Inwood is suggested also by the increase in chloride content from 21 to 56 ppm at well N3734 from 1951 to 1961. During periods of below average withdrawal, however, as in March 1961 (pl. 5), or during average withdrawal, the cone of depression extends seaward only as far as Cedarhurst. At such times, fresh water moves seaward from Cedarhurst to Inwood (pl. 5) and in effect helps to retard the landward movement of salt water in the vicinity of Inwood.

A slight amount of encroachment of salty water in the upper part of the deep wedge at about −200 feet at well Q1237 in South Ozone Park is suggested by the net increase in chloride content from 20 ppm in 1953 to 34 ppm in 1960. Northwest of Q1237 the rate of movement between wells Q559 and Q314 (pl. 5) is probably about 160 feet a year. The rate of encroachment of salty water is undoubtedly much slower at −200 feet than at greater depths along the base of the Magothy (?) Formation.

Heads are about 4 to 10 feet in the fresh water in deposits underlying the "20-foot" clay and Gardiners Clay in most of southern Nassau County south of Sunrise Highway. These heads are sufficient to cause upward leakage of sizeable quantities of fresh water through the overlying clays into the salty water in the upper Pleistocene and Recent deposits and into the bays.

GEOLOGIC AND HYDRAULIC CONTROLS

As indicated in the previous sections, the movement of salty ground water is relatively slow, almost stationary in most places. Also, the period of about 60 years since man made his first significant withdrawals from the artesian formation in southern Queens and Nassau Counties is relatively short. The present (1961) occurrence, position, alignment, and even the sizeable thickness and width of the zone of diffusion of the deep wedge of salt water as well as the intermediate wedge, therefore, are phenomena attributable mainly to natural conditions that prevailed long before the start of ground-water development in the report area. The deep wedge in the Magothy(?) Formation could have been in existence long before the deposition of Pleistocene deposits and thus long before the formation of the intermediate wedge, part of which is in Pleistocene deposits.

Encroachment, however, resulting from man's present and probable future development of ground water will be much more rapid in the next 50 to 100 years than in the past. There is no practical need for speculating too much on past events. The concern is principally with the definition of present occurrences and rates of encroachment of salt water so that the rates and occurrences can be used as a suitable basis for predicting future situations.

The permeable upper Pleistocene and Recent deposits constitute the uppermost beds in the ground-water reservoir. The upper Pleistocene deposits, found everywhere in Long Island, are the principal intake areas of recharge from precipitation, which is the only natural source of fresh ground water. Most of the water reaching these deposits eventually discharges into streams and bays. Some of the fresh water, however, in these deposits seeps down into the deeper formations in central Nassau County (fig. 3), if the downward-moving fresh water is not retarded by clay layers of any significant thickness or extent between the land surface and the base of the Magothy(?) Formation. Only the thick and extensive clay member of the Raritan Formation underlying the Magothy(?) Formation offers significant resistance to the fresh water leaking downward to the Lloyd Sand Member in the central part of Nassau County and upward from it in the southern part of the county. Bedrock underlying the Lloyd Sand Member is practically impermeable and, hence, serves only as the base for the groundwater reservoir.

Under natural conditions, fresh water in the Lloyd Sand Member and in the middle and lower part of the Magothy(?) Formation moved from inland areas to near or offshore areas and then changed its direction at the salt-water front and moved to discharge areas at and west of Jamaica Bay. The change in direction occurred because the heads in the salty ground water offshore, which are higher than those in the fresh water, prevented discharge in the offshore areas. Under present conditions, fresh water in the offshore part of the Lloyd Sand Member moves landward toward pumping centers in the Atlantic Beach-Lido Beach area and in central Queens County (fig. 9). Most of the fresh water in the middle and lower part of the Magothy(?) Formation moves toward a discharge area in Jamaica Bay (pl. 5), and some moves toward the pumping center in Woodmere. Fresh water in the upper part of the Magothy(?) Formation beneath the "20-foot" clay and Gardiners Clay discharges into the south shore bays and into the Atlantic Ocean (pls. 2*B*, 5).

The ocean and the bays are the sources of the salty ground water. The fact that the main body of salty ground water is less saline than the ocean water offshore may indicate that the bays and nearshore areas were the source of the salty water. Jamaica Bay and the Atlantic Ocean, immediately offshore from Rockaway Park eastward (fig. 3), are probably the present source or intake of the main salt-water body and the deep wedge. The salty water from these areas moves through the undifferentiated Recent and Pleistocene deposits and the Magothy(?) Formation. Salty water moves landward along the clay member of the Raritan Formation in a north and northeastward direction (pls. 2*B*, 5); some of it moves into the upper part of the zone of diffusion and is then swept back by the overlying fresh water into the Jamaica Bay area and the Atlantic Ocean.

The toe of the deep salty wedge at the base of the Magothy(?) Formation acts somewhat like a line sink. There is movement toward it of both the fresh and salty water. The head loss in salty water along a flow line from the intake area of salty water to the toe of the deep wedge east of Hewlett is about 8 feet—about 7 feet in salt water from Jamaica Bay to east of Hewlett Neck (pl. 5) and about 1 foot (from equation 8) in diffused water from Hewlett Neck to east of Hewlett. The head loss in salty water between the intake area and the toe at Lido Beach is about 10 feet. Such losses are considered to be natural occurrences and may be due mainly to the circulatory movement of the salty water; actually heads in fresh water at the toe between Hewlett and Lido Beach have been lowered only slightly, if any, by the withdrawals in the past 60 years.

The Ghyben-Herzberg equation neglects head losses in salt water and, partly for this reason, cannot give the correct depth to salty water. There is now enough evidence in this report and in papers by Cooper (1959), Henry (1959), Kohout (1960), and Perlmutter and Geraghty (1963) to substantiate the occurrence of head losses in salty water under dynamic conditions of fresh-water outflow to the sea.

The virtual line sink at the toe of the deep salty-water wedge is an essential feature of the mechanism producing cyclic flow of salt water from seaward areas along the bottom of the Magothy(?) Formation toward the toe of the wedge and to the bay and ocean in the upper part of the wedge.

The clay member of the Raritan Formation appreciably retards movement of the deep salty-water wedge downward to the underlying Lloyd Sand Member; this retardation accounts for the occurrence of fresh water in the Lloyd in shoreline and offshore areas. Enough time had elapsed, however, even before the start of pumping, for the salty water from the Magothy(?) Formation to reach the lower beds of the clay member along the barrier beach between Rockaway Park and Long Beach and undoubtedly also the upper beds of the Lloyd Sand Member in immediate offshore areas and the lower beds in more offshore areas. Withdrawals from the Lloyd Sand Member in the last half century at Long Beach have increased the rate of downward encroachment into and perhaps through the clay member, and they, of course, have simultaneously increased lateral encroachment in the Lloyd from offshore areas.

Undifferentiated Recent and Pleistocene deposits, as well as the Magothy(?) Formation offshore from Atlantic Beach and Long Beach, probably constitute the principal conduits for the movement of the intermediate salty-water wedge (figs. 3, 5). Ocean water apparently moved into rather permeable material offshore to intermediate depths below which further penetration was prevented by higher heads in the underlying fresh water (pl. 2*B*). The movement landward of the intermediate wedge of salty water may be facilitated by the westward-northwestward movement of the underlying fresh water and to some extent by the withdrawals of fresh water near the wedge and in inland areas.

Under present conditions, downward movement of the salty water from the embayed areas and shallow deposits in southern Nassau County is prevented generally by the higher heads in the deposits below the "20-foot" clay and Gardiners Clay; these heads cause upward leakage of fresh water. Downward movement of shallow salty water through the "20-foot" clay and the Gardiners Clay occurs along the barrier beaches, where replenishment from precipitation maintains heads in the shallow deposits greater than those in the underlying "20-foot" clay or Gardiners Clay (pl. 2*B*) part of the time.

EFFECT OF REDUCTION IN SEAWARD FLOW OF FRESH WATER

In coastal areas, water in the ground-water reservoir drains to streams, bays, and eventually to the ocean. A salty-water wedge stabilizes within a ground-water reservoir at some position near the shoreline or offshore consistent with the quantity of fresh water flowing seaward at and near the wedge and also consistent with the ocean level. The rate of fresh-water outflow depends in part on the amount and rate of precipitation falling on the land areas. The requirements for a completely stabilized wedge are a constant flow of fresh water into the ocean and a constant ocean level (except for tides).

Movement of the salt-water wedge results from a change in the seaward flow of fresh water or by a change in sea level. According to Marmer (1949), mean sea level in the Long Island area rose approximately half a foot since the early 1900's. Some encroachment, therefore, is taking place because of this small rise in mean sea level.

During a period of constant sea level, a decrease of seaward flow of fresh water along any part of a stabilized front causes changes in heads, gradients, and flows, and results in the gradual encroachment of the salty-water wedge to a new landward position. Withdrawals of fresh water from anywhere in the Long Island ground-water reservoir ultimately reduce seaward flow and cause salt-water encroachment if accompanied by loss of some of the water by consumptive use or through discharge to the ocean. If such withdrawals are made at considerable distances landward from the wedge, they will have a regional effect on the position of the front over a relatively wide area. As shown in figure 10*A*, a reduction in seaward flow to a lower, constant rate because of inland withdrawls will cause the salty-water wedge to move landward, after a certain time, to a new stabilized position. This position is that expected under present conditions in

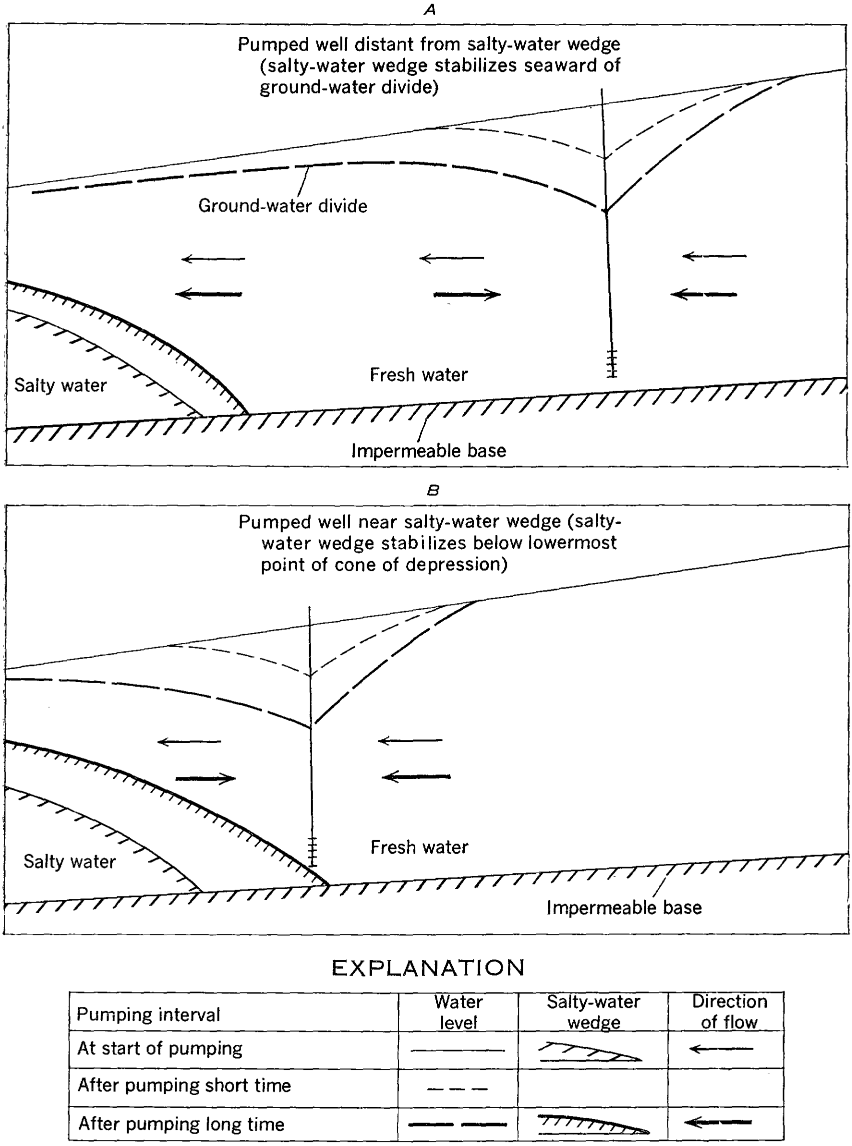


FIGURE 10.—Theoretical movement of salt-water wedge in response to distant and nearby withdrawal.

parts of the study area where regional encroachment of the deep wedge has been indicated.

Withdrawals near the salt-water front can have an immediate influence in starting and maintaining the movement of the saline wedge landward toward a pumped well, as indicated in figure 10*B*. The wedge will eventually arrive at the pumped well. This occurrence is typical of existing conditions in the Cedarhurst-Woodmere area (pl. 3*A*, *C–C′*). Encroachment typified in figures 10*A*, and 10*B* would be accelerated by a general rise in sea level.

Elimination of seaward flow in the entire hydraulic unit would cause continued encroachment on a regional basis and eventual encroachment of salty water to positions at or about sea level in inland areas.

The hydrologic system of Long Island trends toward an equilibrium wherein seaward flow of fresh water equals the recharge minus the net withdrawal, except as modified by changes in the amount of ground water in storage. The principal concern in this report is the amount of fresh-water flow needed to control encroachment in the confined beds beneath the Gardiners Clay and the "20-foot" clay. The change of storage is relatively small in these confined beds. Thus, recharge and net withdrawal are the only factors significant to the determination of seaward flow of fresh water.

In the following paragraphs, encroachment is appraised on the basis of changes in seaward flow that can be expected from known or assumed changes in recharge and net withdrawal. First, the encroachment of salty water in the Lloyd Sand Member is considered; then the encroachment of the deep wedge in the Magothy(?) Formation in three areas—southeastern Nassau, southwestern Nassau, and southeastern Queens; and finally, the encroachment of the intermediate wedge in the upper part of the Magothy(?) Formation, Jameco Gravel, and overlying deposits in southwestern Nassau.

Salty water in the Lloyd Sand Member apparently is in the upper or middle beds of the Lloyd Sand Member at or near Rockaway Park, Atlantic Beach, and Long Beach (fig. 9). Salty water may be in the lower beds of the Lloyd perhaps as much as 3 miles offshore from the leading edge.

The Lloyd Sand Member is recharged in inland areas north of Sunrise Highway by water moving downward from the Magothy(?) Formation. This replenishment has probably decreased appreciably with the increase in withdrawal from the Magothy(?) Formation between 1945 and 1960 (fig. 11, graphs A–d). Withdrawals from the Lloyd Sand Member were virtually constant during this period because increases along the barrier beaches in southern Nassau County were balanced by decreases in central Queens County (fig. 11, graphs h–i). Withdrawals from the Lloyd Sand Member created a cone of depression in central Queens County and in the Long Beach area and caused landward gradients in the fresh water in the Lloyd Sand Member in part of the study area (fig. 9).

Withdrawals from the Lloyd caused a drop in water levels of 3 to 4 feet from 1945 to 1960 at well N7 in Valley Stream and at well N67 at Freeport. Withdrawals from wells on the barrier beach, especially

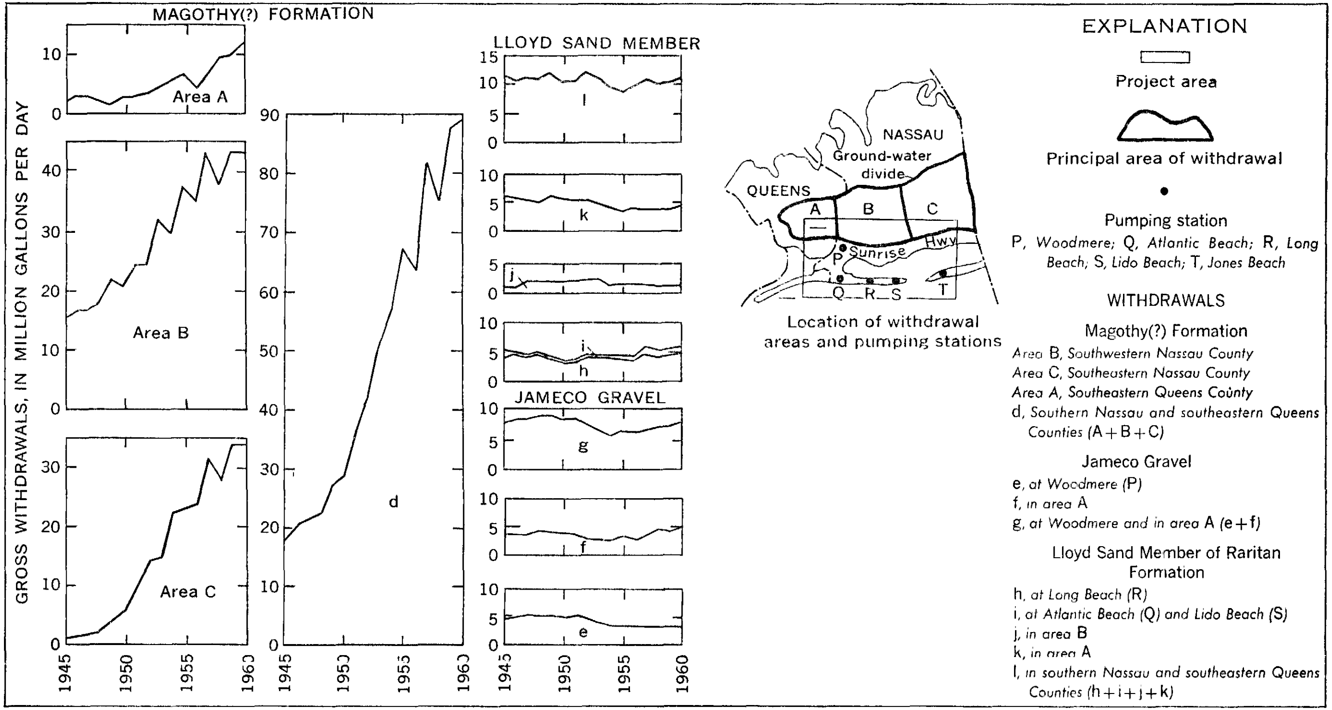


FIGURE 11.—Ground-water withdrawals for public supply in southern Nassau and southeastern Queens Counties, 1945–60.

those at Long Beach, which were about 5 mgd in 1960, have lowered water levels at least 10 feet at Long Beach; this decline in water levels caused an increase in hydraulic gradients vertically and laterally along the barrier beach. As a result, the rate of downward movement of salty water through the clay member of the Raritan Formation and the rate of lateral movement of the salty water from offshore areas in the Lloyd Sand Member were increased, causing local encroachment of the type illustrated in figure 10*B*. Present evidence points to the fact that salty water will continue to move downward in the barrier-beach areas and landward from offshore areas because of local and regional withdrawals from the formation.

In southeastern Nassau, the toe of the deep salty-water wedge is in the Magothy(?) Formation north and east of Lido Beach and probably no more than 2 miles offshore from Jones Beach. Recharge to the ground-water reservoir south of the main ground-water divide in area C (fig. 11) has been reduced only slightly since World War II by pavements, streets, and buildings, if the 2 percent increase in direct runoff (and thus a corresponding decrease in recharge to the ground-water reservoir) in east-central Nassau County (Sawyer, 1961) applies to the entire area.

Gross withdrawal for public supply from the Magothy(?) Formation increased between 1945 and 1960 from 1 to nearly 34 mgd in area C in southeastern Nassau County (fig. 11, graph C). The withdrawals were made entirely north of Sunrise Highway, except for about 0.2 mgd at Jones Beach. Most of the withdrawals in area C are returned to the upper Pleistocene deposits through septic tanks and leaching basins near the point of use. Because of the downward movement of some of the water from the shallow aquifer to the Magothy(?) Formation north of Sunrise Highway, the used water returned to the shallow aquifer replaced at least some, if not most, of the water pumped from the Magothy(?). The remainder is lost by discharge from the shallow aquifer to streams and bays. The actual net withdrawals from the Magothy(?) Formation cannot be determined. They are probably relatively small. The water level declined about 1½ feet between 1945 and 1960 in well N180, screened near the bottom of the Magothy(?) Formation at Seaford. The lowering of the water levels reflects principally the increase in pumping locally and regionally, which caused a decrease in seaward flow in the Magothy(?) Formation. At Jones Beach, water levels have changed very little since 1933. This fact indicates that the net withdrawals in inland areas have not yet reduced the fresh-water outflow at Jones Beach significantly. The salty water in southeastern Nassau will begin its movement landward, as typified in figure 10*A*, but only after the reduction is felt at the salt-water front. Needless to say, this reduction in flow will take place sooner and the resulting encroachment will reach farther inland, if all the used water (about 34 mgd) presently returned to the ground-water reservoir near points of withdrawal is piped to treatment plants and then is wasted to the sea.

A head of about 11 feet above sea level in 1903 at the former well N319 screened in the middle of the Magothy(?) at Long Beach was reported by Veatch and others (1906); it was based on an estimated altitude of land surface. The water level at the site of this well was about 6 feet above mean sea level in 1961 (pl. 5). There is no plausible reason, on the basis of data available now, for the level in Long Beach to have been as high as 11 feet in 1903 or at any time since then nor for there to have been an apparent decline in levels in the Magothy(?) Formation. Levels are believed to be nearly unchanged at the site of former well N319 at Long Beach, much the same as they are virtually unchanged at Jones Beach.

The toe of the deep salty-water wedge is in the Woodmere-Bay Park area in southwestern Nassau County. Natural recharge to the ground-water reservoir has been reduced since World War II by various works of man that have made the land surface impermeable or less permeable in southwestern Nassau County in area B (fig. 11). Reduction in recharge is known principally by construction of additional storm sewers to carry storm runoff to the streams and bays and also by the continued increase of yearly peak flows in streams gaged in the area (R. M. Sawyer, oral commun., 1961). As a result, there probably has been some reduction in recharge to the Magothy(?) Formation in recent years owing to the increase in storm runoff; the amount of reduction is not known definitely.

Gross withdrawals for public supply in the Magothy(?) Formation in area B (fig. 11) in southwestern Nassau County have increased from about 15 to 44 mgd between 1945 and 1960. Those gross withdrawals made in the Jameco Gravel at the Mill Road pumping station in Woodmere decreased from about 5 mgd between 1945 and 1952 to about 3 mgd between 1954 and 1960 (graph e). Most of the water pumped from the Magothy(?) Formation and the Jameco Gravel in southwestern Nassau was previously returned after use to the ground-water reservoir via cesspools, leaching basins, or in other ways. Since 1953, however, the used water has been piped to sewage plants for treatment and disposal at sea. Underflow was thus reduced nearly 44 mgd by 1960 in the inland areas.

Water levels have dropped about 6 feet since 1945 at well N1613 in Valley Stream north of Sunrise Highway and about half a foot since 1951 at well N2790 in Bay Park south of Sunrise Highway, near the toe of the deep salty-water wedge. Decreased replenishment, increased net withdrawals, reduced underflow, decline of water levels, and landward gradients in the deep salty-water body foretell continued regional encroachment of salty water in the Magothy(?) Formation in southwestern Nassau County. In Woodmere, the regional encroachment is superimposed on the local encroachment caused by heavy withdrawals in the immediate vicinity of the deep wedge.

The toe of the deep wedge is at or near the base of the Magothy(?) Formation north of Sunrise Highway in southeastern Queens County in area A (fig. 11). Here the Jameco Gravel and the Magothy(?) Formation constitute one hydraulic unit. Replenishment to the ground-water reservoir by precipitation has been reduced significantly in this area as a result of loss of water through sewers. Withdrawals for public supply from this hydraulic unit have increased appreciably (fig. 11, graphs c and f). Also, ground water pumped for public supply is piped after use to treatment plants and is disposed to tidal water. The combined effect of decreased replenishment and increased withdrawal in this hydraulic unit is expressed by lowered water levels of about 4 to 7 feet from 1895 to 1955 in the Magothy(?) Formation and the Jameco Gravel (Perlmutter and Geraghty, 1963, fig. 7). This situation was favorable to the continuous movement landward of the deep wedge in this unit, inasmuch as water levels are being lowered continuously in the southeastern part of Queens County.

The intermediate wedge of salty water extends landward to Oceanside in south-central Nassau County. The net withdrawals for commercial and private uses at numerous sites between Sunrise Highway and the frontal areas were estimated to be at least 1 mgd in 1960. Withdrawals in the vicinity of the intermediate wedge of salty water resulted in the local encroachment illustrated in figure 10*B*. Reduction of seaward flow of fresh water by withdrawals for public supply in the Magothy(?) Formation principally at Rockville Centre, Baldwin, and Freeport contributes also to regional encroachment of the intermediate wedge of salty water. Actually, the entire combination of withdrawals in inland areas, which favor the further encroachment of the deep wedge, also contributes to the encroachment of the intermediate wedge.

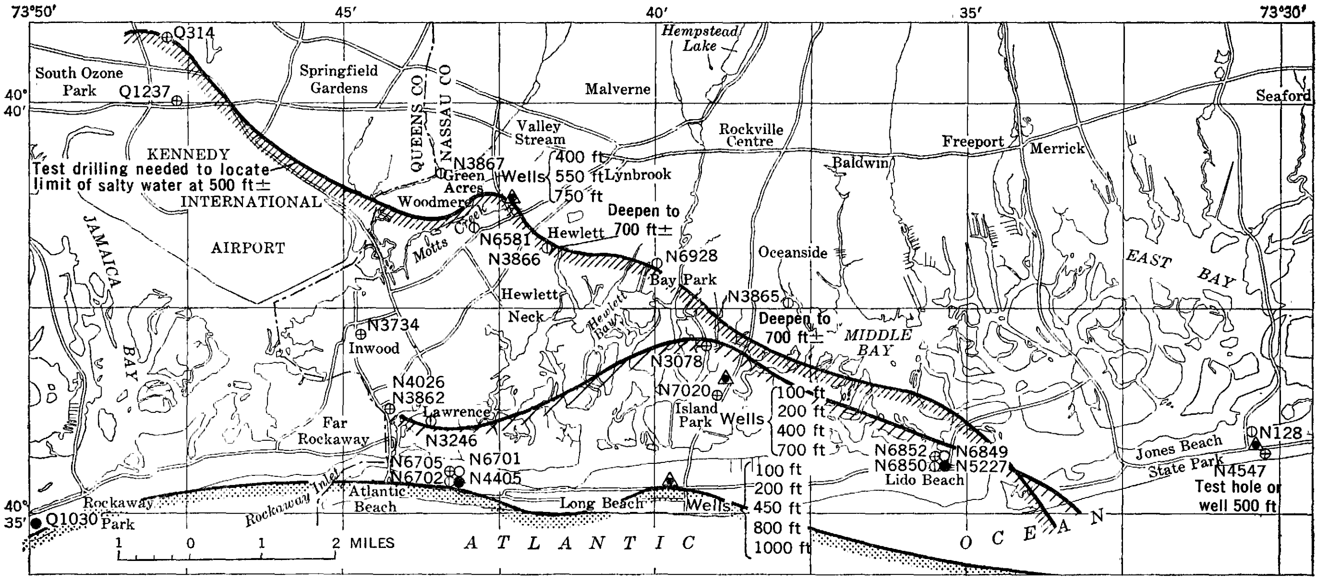
The positions of the salt-water wedges in the Lloyd Sand Member, the Magothy(?) Formation, and the Jameco Gravel are actually seaward of their ultimate stabilized positions consistent with present net withdrawals. Under conditions of regional encroachment, there is necessarily a time lag between the start of increased net withdrawal in inland areas and the ultimate arrival of a salt-water wedge at its new stablized position, especially in a large hydraulic system. Many years wlll be required, under regional encroachment, first for the increased withdrawal inland to fully effect a reduction in flow at the wedge and then for the wedge to actually move to the new position of stabilization inland. The lag effect is evident from studies of flow-line patterns by Jacob (1950), Brown (1959), and others. To determine the time lag and the new positions of stability of the salt water is not easy because of the size and extent of the ground-water reservoir and the complexity of the hydraulic interconnections between the formations. As stated previously, however, if present and probable future ground-water developments are considered, it is estimated that by year 2000 the deep and intermediate wedges will not advance much more than a mile locally and less than a mile regionally in the study area. The encroachment, however, will be less if remedial steps such as artificial recharge, use of imported water and desalinized water, or construction of artificial water mounds are undertaken.

MONITORING SALT-WATER ENCROACHMENT

Data on water levels and the chloride content of the water in monitoring wells at strategic locations in the contiguous fresh- and salty-water bodies are invaluable for determining the effect of reduction in seaward flow of fresh water and for predicting future positions of the salty-water wedges in the study area. Encroachment will be revealed by the increase in chloride concentrations of water in wells, by the lowering of water levels in contiguous fresh-water and salty-water bodies, and by the increase in the landward hydraulic gradients in the salty water. The network of existing observation wells (fig. 12), including those drilled between 1952 and 1961, and also existing public supply, commercial, and private wells in shoreline areas (pl. 1) needs to be supplemented to monitor salt-water encroachment more effectively.

Test drilling, recommended in the following paragraphs, includes the construction of additional wells at Woodmere, Island Park, Long Beach and Jones Beach and deepening of individual wells at Hewlett and Oceanside in Nassau County. It also includes construction of wells near the northeastern boundary of the New York International Airport (fig. 12) in Queens County.

The toe of the deep wedge has already reached supply well Q314 in South Ozone Park, Queens County. The slight contamination of water in this well will increase at a faster rate as the salty water continues to move inland under the influence of local and regional pumping. This well may be considered as an outpost well for the more landward supply wells; it will serve as a monitoring well for the lower part of the Jameco Gravel much the same as well Q1237 monitors the encroachment in the upper part of the Jameco Gravel in South Ozone Park.



EXPLANATION

EXISTING MONITOR WELLS

N4547

Well number

⊕ Well tapping upper part of Magothy(?) Formation or Jameco Gravel

○ Well tapping clay member of Raritan Formation

Ⓘ Well tapping lower part of Magothy(?) Formation

● Well tapping Lloyd Sand Member of Raritan Formation

▲ Site of proposed monitor well(s)

Proposed depths for well screens are given in feet below land surface

Approximate landward limit of intermediate salty-water wedge

Approximate landward limit of deep salty-water wedge on surface of clay member of Raritan Formation

Approximate landward limit of salty water in the Lloyd Sand Member

FIGURE 12.—Network of existing and proposed monitoring wells.

The position of the deep wedge between South Ozone Park and Woodmere is known only approximately. Test drilling and observation wells at several sites near Rockaway Boulevard, northeast of the New York International Airport, would provide more precise definition of the position and rate of encroachment of the deep salty wedge in this part of Queens County.

An increase in the chloride content of the water in observation well N6851 in Woodmere will indicate the extent of local encroachment of the thin wedge of salty water which is moving landward along the base of the Magothy(?) nearly 400 feet below the supply wells at the Mill Road pumping station. The thin wedge may be confined beneath a thick clay in the basal Magothy(?) directly beneath the station (pl. 3, *C–C′*). Test drilling at the pumping station is needed to define the extent of this clay north of well N6581. Also, observation wells in the Magothy(?) Formation and in the clay member and the Lloyd Sand Member of the Raritan Formation at the station would be useful for monitoring further lateral and vertical encroachment of salty water directly beneath the existing well field. Although supply wells in the Jameco Gravel at the pumping station are in no danger of being contaminated for many years, data from the proposed observation wells would be valuable also for planning the operational pattern and for determination of the life expectancy of the pumping station.

The regional advance of the toe of the deep salty-water wedge in southern Nassau County will be detected by increases in the chloride content of the water at well N3867 near Woodmere, at well N6928 at Bay Park, and well N6850 at Lido Beach, screened at the bottom of the Magothy(?) Formation. Wells N3866 at Hewlett and N3865 at Oceanside are screened about 150 to 200 feet above the bottom of the the Magothy(?) Formation. Because the toe of the deep wedge travels along or near the base of the Magothy(?), it will pass under the screens of these wells unnoticed unless they are deepened or unless deeper wells are constructed nearby. Actually, salty water may have already reached the basal Magothy(?) beneath well N3866.

An observation well screened in the toe of the deep wedge at Island Park southwest of well N3865 in Oceanside and another well screened in salty water at the bottom of the Magothy(?) Formation near well N41 in central Long Beach would be useful for monitoring the gradients and the rate of encroachment northeastward from Long Beach toward the Oceanside-Baldwin area.

It may also be desirable to construct observation wells at the base of the Magothy(?) between Lido Beach and Jones Beach, but only after the chloride content of well N6850 at Lido Beach has increased to at least several thousand parts per million. The supply wells at

Jones Beach State Park will serve as outpost wells for monitoring water-level and chloride changes in the upper and lower parts of the Magothy(?) Formation. They would in fact be contaminated decades before the salty water moved 5 miles north from Jones Beach State Park to the public-supply wells near Sunrise Highway. The chloride content, however, of water between −400 and −700 feet msl at Jones Beach should be determined by test drilling inasmuch as the electric log of supply well N5129 suggests that the water in that interval may be slightly salty.

Landward encroachment of the upper part of the deep wedge in the deposits at or near the 150-foot (msl) depth in southeastern Queens County will be revealed by the decline in head and the increase in chloride content at well Q1237 in South Ozone Park, at such new observation wells as may be drilled in the International Airport area, at well N3734 at Inwood, and at wells N3862 and N4062 at Lawrence.

Landward encroachment of the intermediate wedge of salty water in southern Nassau will be indicated by the increase in chloride concentration of water at the following wells screened near the salt-water front: N3246 at Lawrence, N6705 at Atlantic Beach, N3078 and N7020 at Island Park, and N6852 at Lido Beach. The position and direction of movement of the intermediate body of salty water is now known only approximately. Further investigation based on test drilling is recommended. It should include observation wells in the intermediate wedge and in the underlying fresh water at Island Park and Long Beach.

Downward encroachment of the bottom surface of the deep wedge through the clay member to the Lloyd Sand Member will be detected at wells N6701 at Atlantic Beach and N6849 at Lido Beach, both screened near the bottom of the clay member. An observation well screened in the lower part of the clay member is needed in the vicinity of well N41 at Long Beach for monitoring downward encroachment in the central part of Long Beach. Also, an observation well in the upper part of the Lloyd Sand Member is needed in the same vicinity to help establish the source of the salty water pumped at well N41. Such information would be useful also in planning the operation and maximum utilization of the supply wells at Long Beach.

The bottom surface of the deep salty-water wedge has undoubtedly penetrated the uppermost beds of the Lloyd Sand Member offshore from the barrier beach between Rockaway Park and Lido Beach and the entire thickness of the Lloyd farther offshore. Encroachment in the Lloyd Sand from offshore areas will be monitored at the observation well at Rockaway Park and by the public-supply wells screened in the upper and intermediate beds between Atlantic Beach and Lido Beach (pl. 2 and fig. 12).

SUMMARY

Shallow, intermediate, and deep salty-water wedges in unconsolidated deposits extend landward from an extensive body of salty water connected with the bays and ocean into the fresh-water reservoir of southeastern Queens and southern Nassau County.

The unconsolidated deposits thicken to the southeast from about 700 to 1,700 feet and are divided into the following geologic units overlying the southeastward sloping bedrock surface: Lloyd Sand Member and clay member of the Raritan Formation; Magothy(?) Formation; Jameco Gravel; Gardiners Clay; upper Pleistocene deposits, including the "20-foot" clay; undifferentiated Pleistocene and Recent deposits; and Recent deposits. The unconsolidated deposits consist chiefly of beds of sand, gravel, and silt, most of which have moderate to high permeability. They serve as conduits for the salty ground water as well as for the fresh ground water.

The intake areas for the salty water under present (1961) conditions are predominantly in the bays of southeastern Queens and in offshore areas; the "20-foot" clay and Gardiners Clay are known or believed to be missing.

The "20-foot" clay and Gardiners Clay, which are generally at about −20 to −80 feet msl, restrict the downward movement of shallow salty water in the embayments and adjacent areas of southern Nassau County. The clay member of the Raritan Formation is an extensive and relatively impermeable geologic unit, 130 to 200 feet thick, found at depths increasing from about −300 feet msl in the northwestern part of the study area to about −1,000 feet msl in the southeastern part. The clay member, along which the toe of the deep wedge is moving, thus restricts the downward movement of the deep salty water and has kept the underlying water fresh in areas landward and seaward of the barrier beaches.

Salty water having chloride concentrations as great as 16,500 ppm was found not only in the permeable deposits but also in the shallow and deep clays. Salty water in the clays at shallow depths may be a natural occurrence; that in the clay member is the result of downward encroachment.

The salty-water wedges have zones of diffusion as much as 6 miles wide and 500 feet thick. The chemical composition of the diffused water is not the same as would be obtained by mixing proportionate amounts of fresh and salt water. Modifications from the theoretical mixture are caused by possible chemical and physical processes in the different kinds of water and also by reactions between the water and the rocks that constitute the reservoir. Another significant influence is dispersion resulting from the movements of water and its salt mass and from diffusion.

The intermediate and deep wedges actually have advanced very little regionally from positions predating the start of ground-water development at the turn of the century. This is due in part to the fact that the net withdrawals in inland areas have not yet reduced significantly the seaward flow of fresh water above the wedges. Most of the net withdrawal from the Magothy(?) Formation and overlying deposits in Nassau County is north of Sunrise Highway, several miles inland from the wedges, and this withdrawal will cause a reduction in fresh-water outflow at the wedges sometime in the future. The wedges are, therefore, presently (1961) seaward of the positions that would represent an equilibrium with the present withdrawals.

The deep salty-water wedge is principally in the Magothy(?) Formation and the clay member of the Raritan Formation. It extends about 7 miles inland from the Atlantic Ocean to South Ozone Park in southeastern Queens County and more than 4 miles inland to Woodmere in southwestern Nassau County. The toe of the wedge is probably about 1 or 2 miles north and east of Lido Beach and no more than 2 miles south of Jones Beach. The toe of the deep wedge, moving on the surface of the clay member at a rate of about 160 feet a year, advanced 3,500 feet in response to local withdrawals at South Ozone Park between 1938 and 1960. It moved landward on the clay member at a rate of about 300 feet a year between 1952 and 1960 in Woodmere, where it has advanced about a mile in the past 50 or 60 years in response to local and regional withdrawals. Elsewhere the toe of the deep wedge, moving landward under the influence of regional pumping in inland areas, is apparently moving no faster than 10 feet a year. This slow rate of movement of the toe is due in part to the seaward return, in the upper part of the zone of diffusion, of some salty water advancing landward in the lower part of the deep wedge in the Magothy(?) Formation. The regional advance of the deep wedge probably has not exceeded 1,000 feet since 1900.

There are no places in Nassau County where the deep wedge presents an immediate threat to existing supply wells; at its present (1961) rates of advance, the deep wedge should be no serious threat for at least two decades, even in places where encroachment is fastest—such as in Woodmere. There, the existing supply wells are screened in a zone about 400 feet above the top of the wedge so that the deep wedge may actually pass under them and first contaminate the deeper supply wells at or near Sunrise Highway 1 or 2 miles north of Woodmere.

The toe of the deep wedge is already at supply well Q314 in South Ozone Park in southeastern Queens. The chloride content of the water from that well—about 21 ppm in 1961—will increase slowly if pumping from that and nearby wells is continued at a rate about as great as, or greater than, the 1961 rate.

If the present rates of withdrawal and probable future developments are considered, it is estimated that by year 2000 the toe of the deep wedge may reach areas not much more than a mile inland from well Q314 and at least the vicinity of Sunrise Highway at Valley Stream and Lynbrook. Elsewhere the advance regionally will be much less than a mile. These estimates are based on the assumption that no artificial controls will be used to reduce or prevent encroachment.

At and west of Lido Beach, the underside of the deep salty wedge, already near the bottom of the clay member, is moving downward toward the fresh water in the Lloyd Sand Member. This movement presents no serious threat to most of the supply wells because the encroachment through the relatively impermeable clay member overlying the Lloyd Sand is apparently very slow.

Regionally the underside of the deep wedge apparently has reached the upper beds of the Lloyd Sand Member not far offshore from the barrier beaches. The indications are that salty water is in part of the Lloyd Sand Member locally along the barrier beach between Rockaway Park and Long Beach, and probably no more than 2 miles offshore from Jones Beach. The salty water offshore is moving landward within the cones of depression of wells being pumped along the barrier beaches. However, lateral encroachment from offshore areas to supply wells may not be an immediate threat, as encroachment is slow and fresh water in that aquifer is still moving south from inland areas. Thus, the chloride content of water pumped from the supply wells tapping the Lloyd in that part of the area should remain within permissible limits during at least the next two decades.

The intermediate wedge of salty water is in the Gardiners Clay, Jameco Gravel, and the upper part of the Magothy(?) Formation along and north of the barrier beach in southwestern Nassau County; it extends from offshore areas to north of Island Park, where it is apparently moving landward at less than 10 to 20 feet a year. The intermediate wedge advanced regionally less than 1,000 feet since 1900. Lateral encroachment of the intermediate wedge is reduced by the upward migration of salty water to shallower beds and to the bay. The chloride content of water pumped at commercial wells in the proximity of the intermediate wedge at Island Park has been increasing slowly. On the basis of present encroachment rates and of present and probable future development of ground water, it is estimated that the intermediate wedge will advance less than a mile by year 2000.

Downward movement of the shallow salty water beneath the embayments, lagoons, and estuaries, and in the adjacent marshes in southern Nassau County is prevented by the shallow clay beds and by the higher heads in the underlying fresh water.

Proposed monitor wells, together with the present network of observation, public-supply, commercial, and private wells, will be adequate for monitoring trends of water levels and chloride content and for predicting more accurately future positions of the wedges of salty water in the study area. The data obtained will be valuable for the planning and development of the full potential of fresh-water supplies in Nassau County.

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