Summary of the Hydrologic Situation on Long Island, New York, as a Guide to Water-Management Alternatives

By O. L. FRANKE *and* N. E. McCLYMONDS

HYDROLOGY AND SOME EFFECTS OF URBANIZATION ON LONG ISLAND, NEW YORK

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Prepared in cooperation with the New York State Department of Conservation, Division of Water Resources; the Nassau County Department of Public Works; the Suffolk County Board of Supervisors; and the Suffolk County Water Authority

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SUMMARY OF THE HYDROLOGIC SITUATION ON LONG ISLAND, NEW YORK, AS A GUIDE TO WATER-MANAGEMENT ALTERNATIVES

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ABSTRACT

Long Island has a total area of about 1,400 square miles and includes four counties—Kings, Queens, Nassau and and Suffolk. This report describes mainly the "water-budget area," which includes about 760 square miles of Nassau and Suffolk Counties.

The ground-water reservoir of Long Island is a wedge-shaped mass of saturated unconsolidated deposits that overlie nearly impermeable consolidated bedrock and attain a maximum thickness of about 2,000 feet. The boundaries of the fresh ground-water reservoir are the water table, the fresh-salt water interfaces, the bedrock surface, and the streams. The estimated volume of material saturated with fresh ground water in the water-budget area is about 180 cubic miles, and an estimated 10–20 trillion gallons of fresh water would drain from these deposits if they could be unwatered.

Under natural conditions, precipitation was the ultimate source of virtually all the fresh water on Long Island. The average annual precipitation on the island is about 44 inches, which averages about 1,600 mgd (million gallons per day) for the water-budget area. About 5 percent of the streamflow (roughly 20 mgd) that discharges into the sea is direct runoff. Evapotranspiration of precipitation, which averages about half the average annual precipitation, represents the largest element of fresh-water discharge from the hydrologic system of the water-budget area. Evaporation from open bodies of water is negligible in terms of the overall water budget.

The principal elements of discharge from the ground-water reservoir are base flow of streams, subsurface outflow of ground water, and evapotranspiration of ground water; these elements are estimated to average about 320, 450, and 15 mgd, respectively, in the water-budget area. One of the most significant features of the fresh water on Long Island is its very low dissolved-solids content—less than 50 milligrams per liter under natural conditions.

At present, more than 2,000 recharge basins in Nassau and Suffolk Counties recharge the ground-water reservoir with substantial quantities of direct runoff. The estimated average annual inflow to these basins is about 80 mgd. An estimated additional 60 mgd of direct runoff from urban areas discharges on the average to streams or directly to salty water in Nassau and Suffolk Counties.

Gross ground-water pumpage in the two counties increased from about 100 mgd in 1940 to about 330 mgd in 1965. The total treated sewage effluent discharged from Nassau and Suffolk Counties increased from about 15 mgd in 1950 to about 75 mgd in 1965. Most of this increased sewage effluent was derived from the ground-water reservoir in the southwestern part of Nassau County, and has caused a lowering of ground-water levels in that area. Much of the shallow ground water is contaminated with domestic wastes that were discharged into the ground through cesspools and septic tanks.

The hydrologic system of Long Island must respond to any water-management program in a way that is consistent with the water-budget equation. The amount of fresh ground water in storage ultimately will be depleted if total outflow perpetually exceeds total inflow. The safe yield of the ground-water reservoir of Long Island—the amount of water which can be withdrawn from it annually without producing an undesired result—can range between wide limits depending upon (1) future management decisions, (2) the amount of natural discharge that is salvaged, and (3) the amount of additional ground-water recharge that is induced. Proposals to manage the water resources of Long Island include barrier injection wells, shallow skimming wells, recharge of treated sewage effluent through wells or shallow basins, and planned encroachment of salty ground water.

INTRODUCTION

BACKGROUND, PURPOSE, AND SCOPE OF THE WATER-BUDGET STUDY

Long Island, which extends from the southeastern part of the mainland of New York State eastward about 120 miles into the Atlantic Ocean, has a total area of about 1,400 square miles (fig. 1). Kings and Queens Counties, which are part of New York City, occupy slightly less than 200 square miles of the western part of the island, and have a combined population of more than 4.5 million people. Nassau and Suffolk Counties have areas of about 290 and 920 square miles, respectively, and had a combined population of about 2.3 million people in 1965.

Although the New York City part of Long Island derives most of its water supply from surface-water sources in central New York State, the people of Nassau and Suffolk Counties derive their entire water supply from wells tapping the underlying ground-water reservoir. Because of present large demands on the local ground-water system, particularly in Nassau and Suffolk Counties, and because of the prospect of

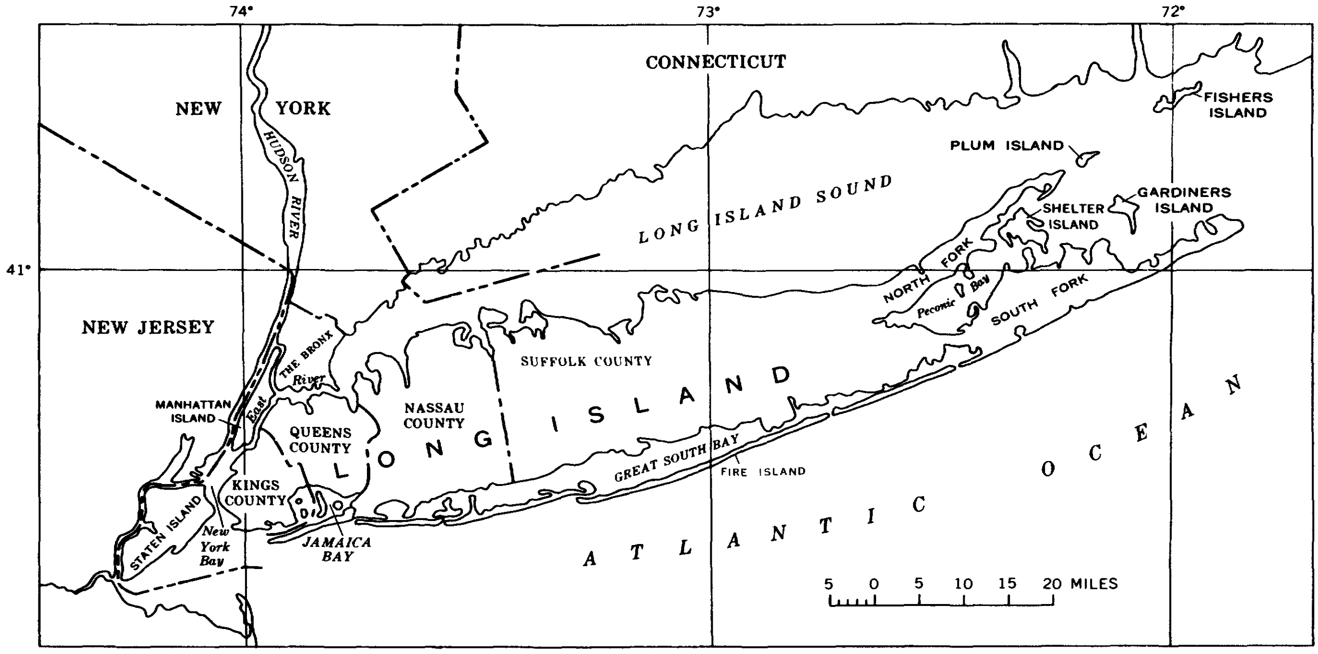


FIGURE 1.—Location and general geographic features of Long Island, N.Y.

increased demands as Long Island continues to rapidly develop, knowledge about the hydrologic system—with special emphasis on water conservation and management—is a matter of vital concern to the present population and to the millions of people who will depend on the ground water in the future.

Considerable information is available about the water resources of Long Island as a result of studies made during more than 30 years by the U.S. Geological Survey in cooperation with New York State and county agencies. Although those studies meet many of the needs for information on specific problems and areas of Long Island, better quantitative information about the islandwide hydrologic system, and the relations between the various components of the system, is needed for water-management purposes. To provide that water information, a comprehensive water-budget study presently is being made by the U.S. Geological Survey in cooperation with the New York State Department of Conservation, Division of Water Resources; Nassau County Department of Public Works; Suffolk County Board of Supervisors; and Suffolk County Water Authority.

The major objectives of the water-budget study are (1) to summarize and interpret pertinent existing information about the hydrologic system of Long Island and (2) to fill several gaps in the knowledge of the hydrologic system. The results of these studies are being published in a series of coordinated reports. In some of the reports, information is developed for all of Long Island; in others, however, the primary area of concern is limited to most of Nassau and Suffolk Counties.

PURPOSE AND SCOPE OF THIS REPORT

The present report, which is the summary report of the series, describes and discusses (1) how the hydrologic system of Long Island functioned under natural conditions, (2) how man has modified the natural hydrologic system, and (3) the water-management implications of this hydrologic analysis with particular reference to the concept of "yield" of the system and long-term responses of the system to various water-management alternatives.

LOCATION AND GENERAL GEOGRAPHIC FEATURES OF THE AREA

LOCATION AND EXTENT OF AREA

Long Island is bounded on the north by Long Island Sound, on the east and south by the Atlantic Ocean, and on the west by New York Bay and the East River (fig. 1). Several smaller islands are included in the political boundaries of Long Island; the better known of these are Fire, Shelter, Gardiners, Fishers, and Plum Islands. The total area of Long Island (including the smaller islands within the political boundaries of the island, but excluding the bordering bays) is about 1,400 square miles; its maximum width is about 23 miles.

Fire Island is the longest of several barrier beaches t parallel the south shore of Long Island. It ranges m about a quarter of a mile to a mile in width, d is separated from the main island by Great uth Bay, a shallow body of salty water that has naximum width of about 5 miles. The other barrier aches along the south shore are also separated from main island by salty bays, the best known of iich is Jamaica Bay along the south shore of Kings d Queens Counties.

The northern and eastern coast lines of Long Island indented by deep bays that form excellent harbors. conic Bay, which is about 30 miles long, divides the tern end of the island into two long, narrow penin- as that are locally referred to as the North and uth Forks.

Some of the succeeding hydrologic information pre- nted in this report relates to all of Long Island. st of the information, however, relates primarily the "water-budget area." The various areas and bareas of Long Island (fig. 2), which are defined this report to facilitate the hydrologic analyses, as follows: (1) The water-budget area—subdivided to a northern part and a southern part; (2) the arshore area—also subdivided into northern and uthern parts; (3) the North and South Forks; and the New York City part of Long Island.

The water-budget area, which includes about 760 uare miles, is bounded on the west by the border tween Nassau and Queens Counties; the eastern undary is long 72°40′ W., which is near the stream- ging station on the Peconic River; the northern undary generally follows the northern shoreline; d the southern boundary is a curved line that joins e streamflow-measuring stations on the major streams that drain into the bays along the south shore. The northern and southern parts of the water-budget are are separated by the ground-water divide on the water-table coutour map for September 1965 (Cohen and others, 1968, p. 23), and have areas of about 310 and 450 square miles, respectively.

The nearshore areas are located just north and south of the water-budget area and comprise those parts of the mainland of Long Island lying between the northern and southern boundaries of the water-budget area and the adjacent salty water of Long Island Sound and the bays adjacent to the south shore. The areas of the northern and southern nearshore areas are about 15 and 80 square miles, respectively.

The North and South Forks, as here designated, include all the parts of the main island areas east of long 72°40′ W., which total about 240 square miles. The New York City part of Long Island (Kings and Queens Counties) has an area of slightly less than 200 square miles.

The water-budget area comprises the bulk of that part of Long Island where public-supply water is derived from the underlying ground-water reservoir. Furthermore, most of the fresh ground-water reservoir of Long Island is located beneath the water-budget area, and therefore, most of the subsequent development of the local water resources will take place within this area. The Forks have been designated as a separate area because, hydrologically, they are virtually independent of the main part of Long Island. Finally, the New York City part of Long Island is a logical area for separate discussion because most of its water supply is imported from upstate surface-water sources.

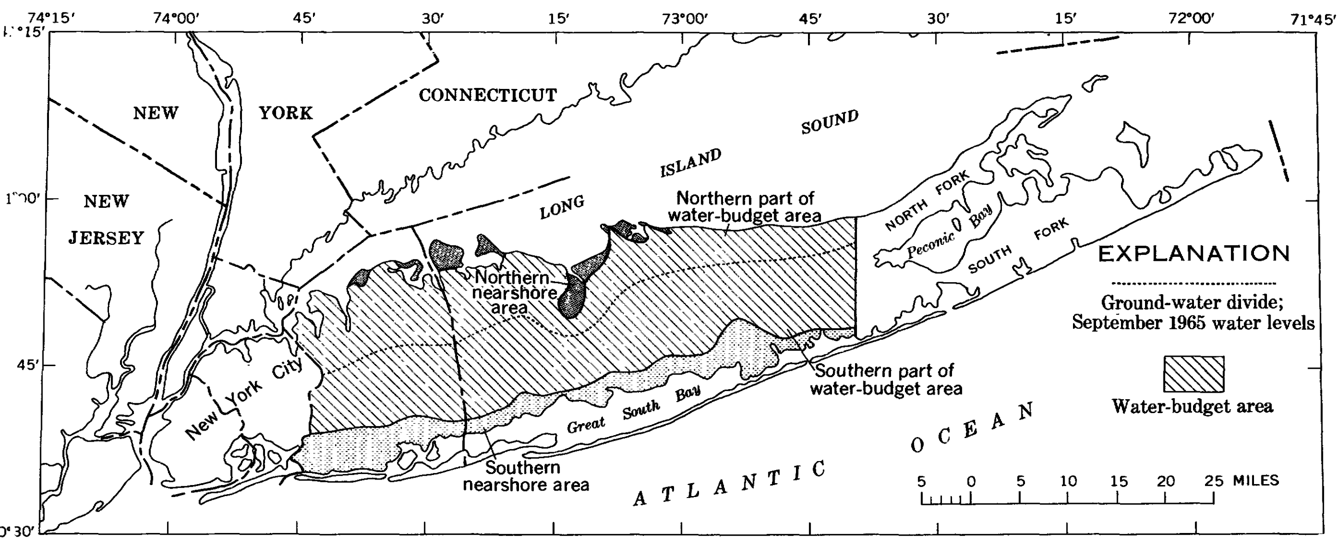


FIGURE 2.—Location of areas and subareas used in this report.

TOPOGRAPHIC AND GENERAL PHYSIOGRAPHIC FEATURES

Most of the major features of the present-day topography of Long Island (fig. 3) are related to the last ice age, which ended about 10 thousand years ago. The most prominent physiographic features are (1) the east-trending hills in the northern and central parts of the island, and their eastward extensions which form the "Forks," (2) the gently sloping plain that extends southward from the hills, (3) the deeply eroded headlands along the north shore, and (4) the barrier beaches along the south shore.

The two lines of hills, which are terminal moraines and which reach a maximum altitude of about 400 feet, are separate and distinct in the central and eastern parts of the island, but they converge in the western part. The southernmost line of hills, the Ronkonkoma moraine, extends eastward to form the South Fork. The northern line of hills, the Harbor Hill moraine, extends eastward to form the North Fork.

The moderately flat surface that extends southward from the Ronkonkoma moraine to the south-shore bays is a glacial-outwash plain. It generally heads at an altitude of about 100–150 feet, and slopes southward at about 20 feet per mile until it merges with Holocene lagoonal deposits along the coast.

The eroded headlands along the north shore are composed mainly of various types of glacial deposits. After the ice sheets melted, the land surface of Long Island rose slightly with respect to sea level, the headlands were deeply eroded, and the many wide and deep harbors along the north shore were carved by northward-flowing streams. Wave erosion has steepened the northern slopes of the headlands into nearly vertical bluffs that, in places, are about 100 feet high.

Along the south shore, waves and ocean currents have formed offshore bars, or "barrier beaches." In terms of geologic time, these bars are ephemeral features that are gradually being eroded by wave action. Sand and silt deposited by the wind, streams, and tidal currents, as well as organic deposits, have partially filled and are continuing to fill the shallow bays behind the barrier beaches.

SUMMARY OF CLIMATIC CONDITIONS

Long Island is located between 40° and 42° north latitude in a temperate-climate belt. The mean annual temperature on the island, about 51°F (11°C), is several degrees higher than the average for all of New York State because of the modifying influence of the bordering Atlantic Ocean and Long Island Sound. Minimum average monthly temperatures on Long Island occur in February and range from about 28° to 32°F (−2°–0°C); maximum average monthly temp atures occur in July and range from about 69° to 7 (21°–24°C). In general, average temperatures decr from west to east, and south-shore temperatures slightly less than north-shore temperatures at same longitude. Maximum and minimum temp tures of record on Long Island are 103°F and −1 (39° and −26°C), respectively.

Precipitation averages about 44 inches per year is fairly evenly distributed thoughout the year Long Island.

The prevailing wind direction on Long Island northwest during most of the year, except during summer months when south and southwest wi prevail.

POPULATION AND LAND USE

Population figures for Kings, Queens, Nassau, Suffolk Counties and totals for all of Long Isl are given in table 1 for the period from 1900 to 19 During the first three decades of the century, b magnitude of population and rate of population gro on Long Island were greatest in Kings County, wh at that time, was moderately industrialized and characterized mainly by multiple-family dwellin Queens County was largely suburban, and Nassau Suffolk Counties were rural. In the next decade (1930's), the largest increase in population occurred Queens County, mainly as a result of the rapid crease in construction of multiple-family dwelli and the growth of industry in that county.

Beginning soon after the end of World War and extending into the late 1940's and the 195 marked suburban expansion into Nassau Cou caused a dramatic increase in the population of t county. The wave of suburban expansion, charact ized mainly by large-scale developments of sing family homes, has been moving eastward with ti As a result, the population of central and east

TABLE 1.—*Population by county and total population of L Island, N.Y., 1900–65* [1]

[In thousands of people]

Year	County				Tot
	Kings	Queens	Nassau	Suffolk	
1900	1, 167	153	55	78	1,
1910	1, 634	288	84	96	2,
1920	2, 018	469	126	110	2,
1930	2, 560	1, 079	303	161	4,
1940	2, 698	1, 298	407	197	4,
1950	2, 738	1, 551	673	276	5,
1960	2, 627	1, 810	1, 300	667	6,
1965			1, 418	893	

[1] Data from U.S. Census Bureau.

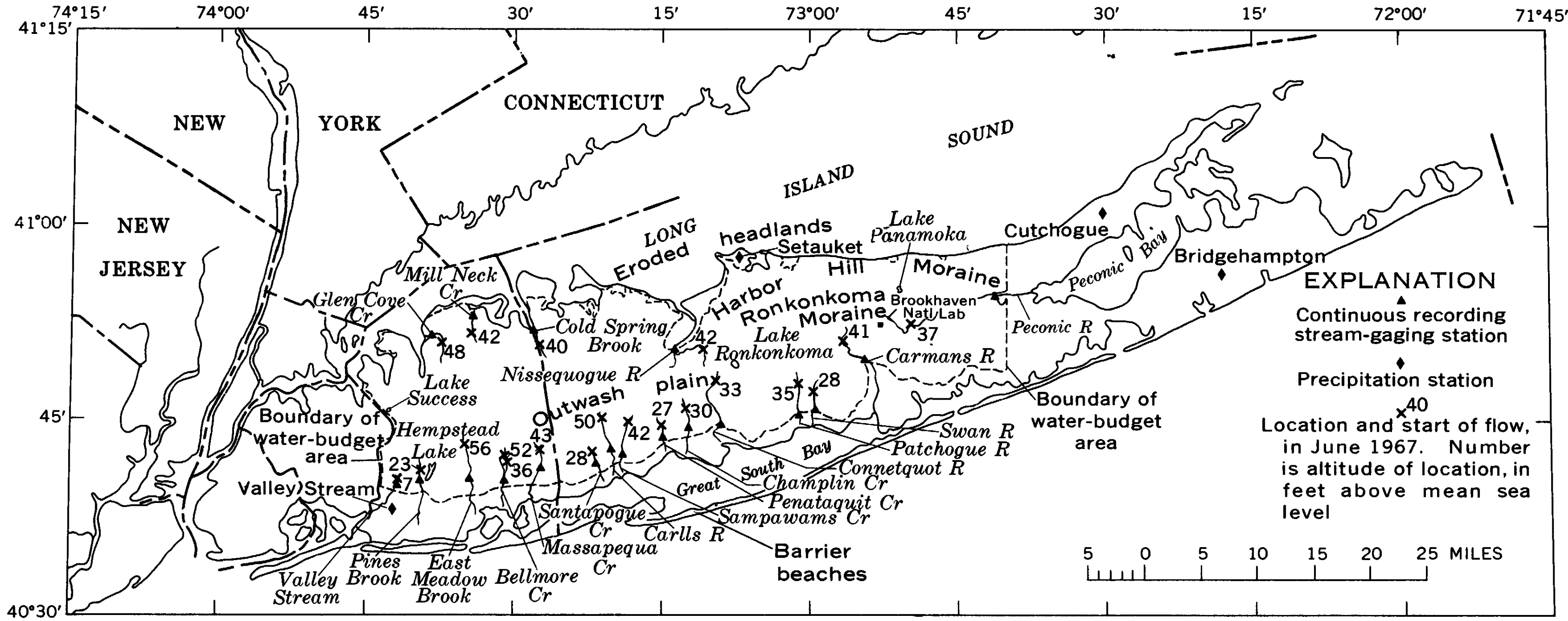


Figure 3.—Landforms, location of major surface-water bodies, and location of start of flow in selected streams in June 1967.

Nassau County increased rapidly in the mid-1950's. The population of western Suffolk began to increase markedly in the late 1950's, and has been increasing more rapidly than the population of any other area on Long Island during the past few years.

The present (1968) population density on Long Island ranges from very dense in the western part to sparse in the eastern part. The pattern of population density (fig. 4) mainly reflects the gradual eastward transition from highly urban communities characterized by high-rise apartment buildings in Kings County, to suburban communities in Nassau and western Suffolk Counties, and finally to the rural areas in eastern Suffolk County. In addition to the general pattern of progressive eastward decrease in population density, there has been a trend of preferential urban development along the north and south shores.

A summary of land use for each county on Long Island is shown in figure 5. This information was

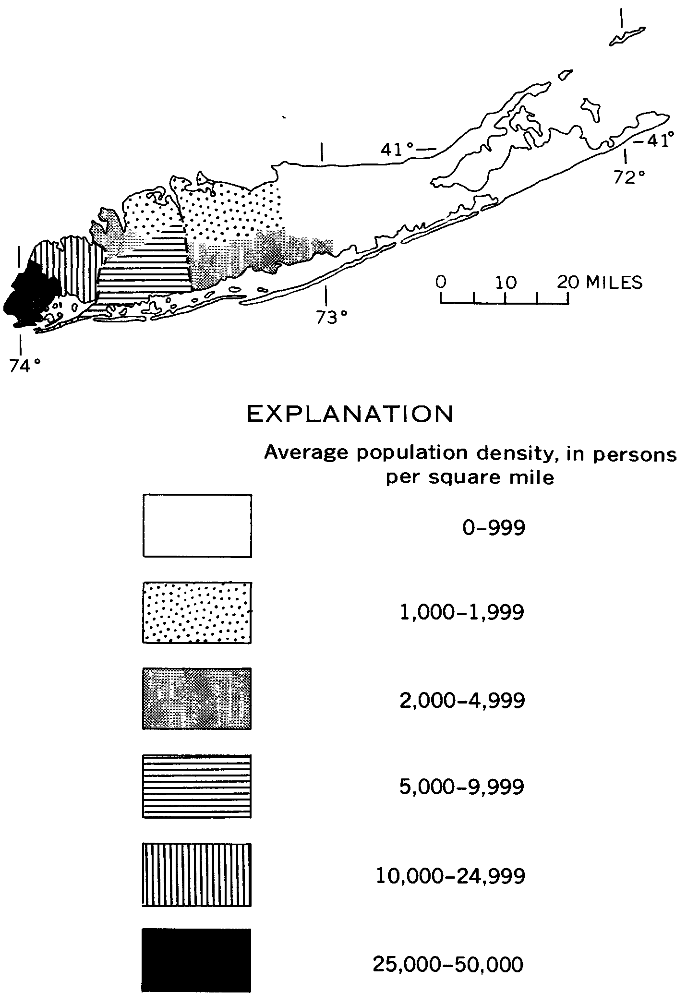


FIGURE 4.—Average population density in 1965. After Cohen, Franke, and Foxworthy (1968, pl. 1C).

compiled from reports prepared by the Nassau Count Planning Commission (1959), the Suffolk Count Planning Commission (1962), and the New York Cit Department of Planning (1962), and the data a not for exactly the same time. Furthermore, the thr agencies did not use precisely the same land classi cations nor the same methods of obtaining and eval ating the data. Despite these inconsistencies, the da shown in figure 5 are reasonably representative f the early 1960's, and provide considerable insight the general characteristics of land use on Long Islan at present (1968).

The percentage of land occupied by streets ar parkways, which is a reasonably accurate measure the intensity of urban development, is greatest Kings County (about 30 percent), decreases progre sively to the east, and is least in Suffolk County (le than 10 percent). Conversely, the percentage of vaca land and land that is classified as "open" increas toward the east—from less than 10 percent in Kin County to nearly 75 percent in Suffolk County. T highly suburban character of Nassau County is ind cated by the fact that nearly 50 percent of the lar is classified as residential, and that land is occupie mainly by single-family homes.

At present (1968), very little land is devoted agriculture in Nassau County; in Suffolk County 1966 slightly less than 65,000 acres, or about 101 squa miles, was classified as agricultural land by the Suffo County Planning Commission. Much of this farn land is in the northeastern part of Suffolk Coun and on the adjacent North Fork.

The major industries of Nassau and Suffolk Counti are aviation, instruments, electronics, and fabricati of metals; smaller industries include furniture, prin ing and publishing, textiles, and apparel. Most co cerns are small, employing fewer than 100 peopl several aviation plants, however, employ several tho sands of persons.

RELATED INVESTIGATIONS

Considerable information in this report was deriv from previously published reports of the U.S. Ge logical Survey, as well as from published reports other agencies and individuals. Many of these repor are referred to in the text, and major sources of add tional information are listed among the references.

The water-budget area was first defined and studi in moderate detail in, "An Atlas of Long Islan Water Resources," by Cohen, Franke, and Foxwort (1968). The present report contains much informati that is not available in the atlas and evaluates ma

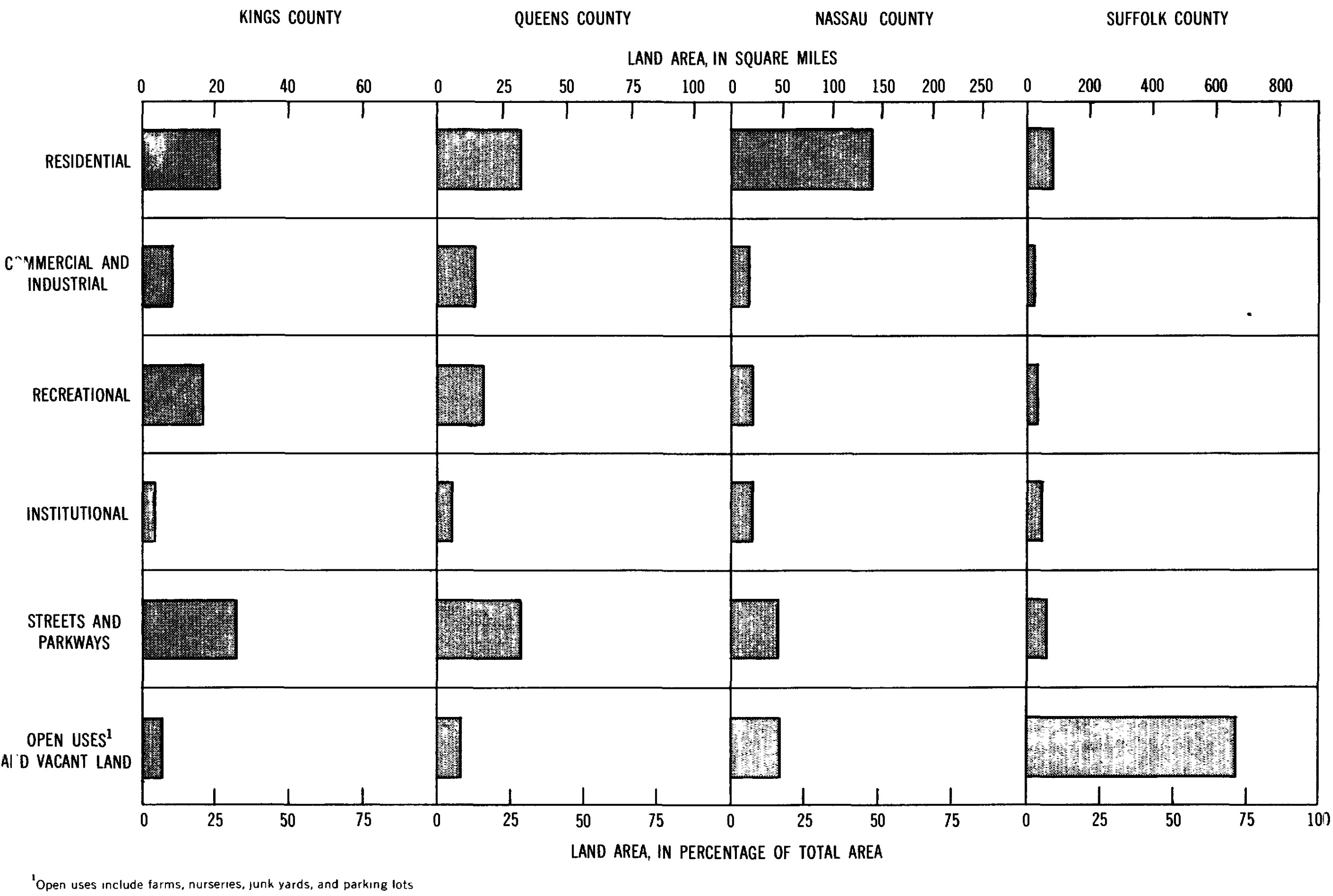


Figure 5.—Land use in the early 1960's. After Cohen, Franke, and Foxworthy (1968, pl. 1*D*).

s ects of the hydrology of Long Island in considerbly more detail than was possible in the atlas.

ACKNOWLEDGMENTS

The authors wish to express their appreciation for e generous assistance and the data received from any individuals and public agencies. Unpublished ata not contained in the files of the U.S. Geological rvey were obtained primarily from the New York tte Water Resources Commission, Nassau County partment of Public Works, Nassau County Planing Commission, Suffolk County Planning Commisn, and the Brookhaven National Laboratory.

The report was prepared under the immediate superion of Bruce L. Foxworthy, former Hydrologist-inarge, and Philip Cohen, Hydrologist-in-Charge of e Long Island subdistrict, and under the general irection of Ralph C. Heath and Garald G. Parker, merly District Chiefs, and Robert J. Dingman, strict Chief, New York District of the U.S. Geoical Survey. Special thanks is due to our colleague ilip Cohen, who played an important role in initiating, and gave invaluable assistance in, the course of this study.

THE NATURAL HYDROLOGIC SYSTEM

The following section of the report briefly summarizes how the hydrologic system of Long Island functioned under natural conditions. The discussion relates primarily, but not exclusively, to the previously defined water-budget area of central Long Island. Man's activities have markedly altered the hydrologic system in some parts of the water-budget area during the past 50 years, and have affected the hydrologic system in virtually the entire water-budget area. However, the effects of man's activities on most of the data presented in the following discussion are small or negligible, unless otherwise noted.

Those aspects of the hydrologic system which are particularly important from the point of view of water management are emphasized in the following discussion, and the information presented in some sections of the report is directed primarily to the information needs of the water manager.

In this section of the report the basic time unit for presenting hydrologic information is the water year, which is the 12-month period beginning on October 1 and ending on September 30; it is designated by the calendar year in which it ends.

HOW AND WHERE THE WATER OCCURS

On Long Island and its environs, water occurs as vapor, as a liquid, and at times during the winter as a solid in the form of ice or snow. The water vapor occurs primarily in the atmosphere and in the zone of aeration. In this study the water vapor of the atmosphere is not of concern until it condenses and reaches the land surface as precipitation.

Liquid water occurs mainly in bodies of surface water and as ground water. Fresh surface-water bodies include lakes and streams. In addition, Long Island is surrounded by the salty water of Long Island Sound and the Atlantic Ocean. Brackish surface water occurs in the estuaries and bays between the fresh-water streams and ocean water.

Most of the fresh ground water occurs from the bedrock surface to the water table beneath the entire mainland of Long Island, except for the Forks where only the upper layers contain fresh ground water. Locally, small, and probably insignificant, amounts of fresh ground water occur in fractures and in the upper part of the bedrock where it is highly weathered. The occurrence of fresh ground water beneath the adjacent bays and barrier beaches varies with depth and specific location, and salty ground water occurs seaward of fresh ground water around the entire perimeter of Long Island.

BODIES OF SURFACE WATER

Several lakes and most of the principal streams on Long Island are shown in figure 3. Lake Ronkonkoma, with an area of about 0.35 square mile, is the largest lake on Long Island. The northward-flowing Nissequogue River has the greatest average discharge—about 42 cfs (cubic feet per second) for the period 1940–65—of any stream on Long Island. The eastward-flowing Peconic River is the longest stream, having a main wet-channel length of about 9–10 miles upstream from the gaging station. The remaining larger streams flow southward into Great South Bay. Relative to the southward-flowing streams—except for the Nissequogue River—the northward-flowing streams are short, few in number, and discharge relatively small amounts of water.

ZONE OF AERATION

The zone of aeration is that part of the solid earth lying above the water table. The interstices in this zone are largely filled with atmospheric gases (incl ing water vapor) and liquid water. The extrem significant process of evapotranspiration occurs p marily on and within several feet of the upper surf of the zone of aeration (land surface), and most the water that recharges the ground-water reserv passes through the zone of aeration.

The volumes of the zone of aeration for all Long Island and for the water-budget area w about 11 and 10 cubic miles, respectively, in Septe ber 1965. If the specific retention of the deposits the zone of aeration is assumed to be 10–15 perc (see section on "Infiltration to the Zone of Aeratio p. F20), an average of about 1 cubic mile of water v stored in this zone on Long Island at that time. Ho ever, this water cannot move into a well and, therefo is not available for direct use by man.

The distribution of areas with various depths the water table in the water-budget area and immediately adjacent nearshore areas is shown in figu 6. The data show that the depth to the water ta is less than 10 feet for about 14 percent, or for abo 120 square miles of this area. Within the water-budg area, however, the depth to the water table is less th 10 feet in only about 50 square miles.

Figure 7 shows the depth to the water table in typical area in the southern part of Long Islan based on water levels in October 1961. An appreciab area near the south shore is characterized by dept to the water table that are less than 10 feet; the dep to the water table generally increases gradually nort ward to the terminal moraine. In most of the are

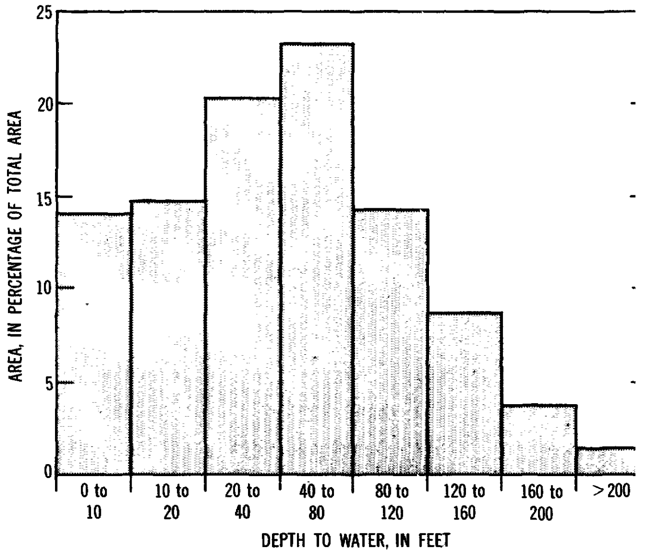


FIGURE 6.—Distribution of depths to the water table in th water-budget and adjacent nearshore areas, based on groun water levels in September 1965.

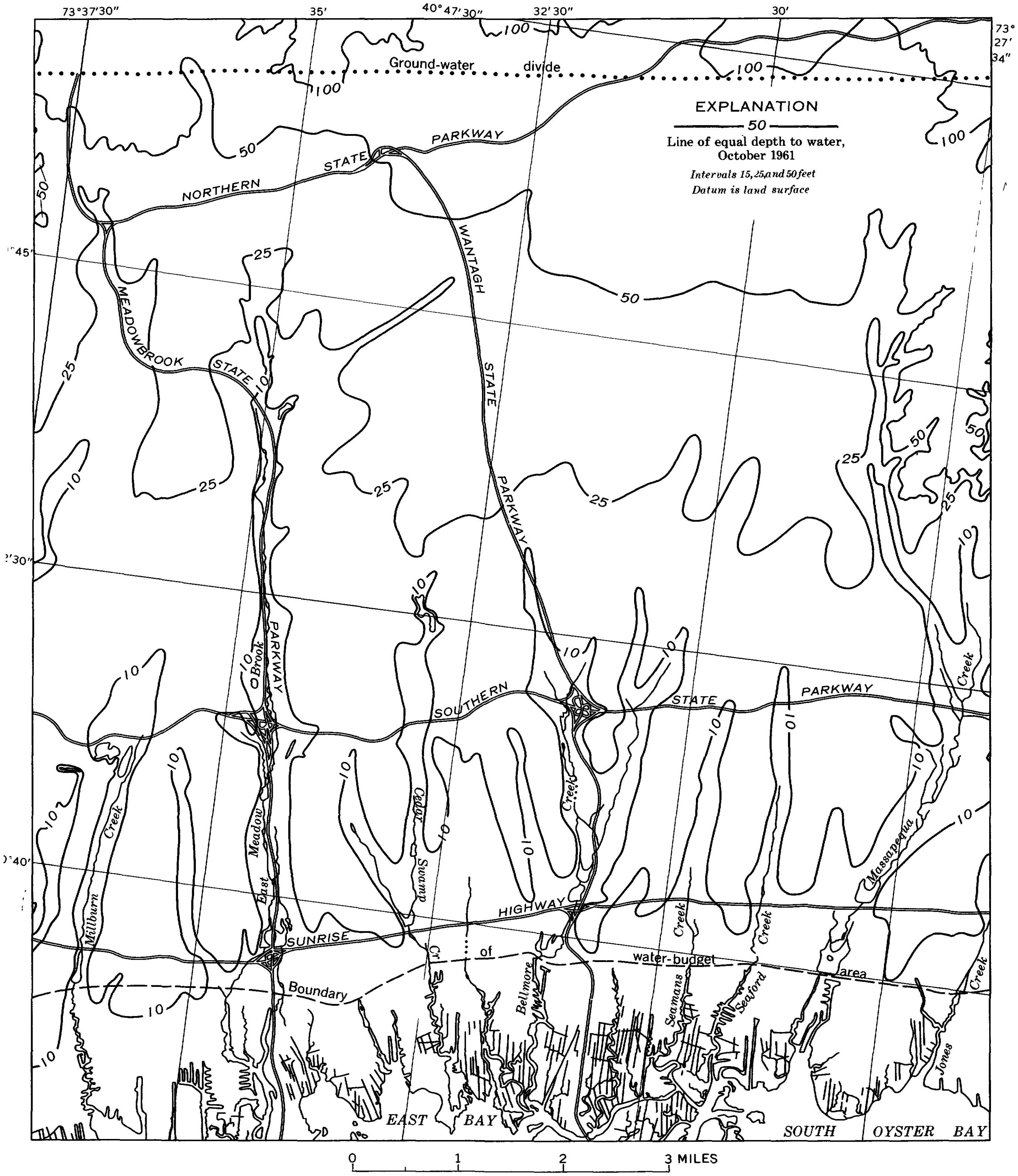


FIGURE 7.—Depth to the water table in southeastern Nassau County in October 1961.

underlain by terminal-moraine deposits, the depth to the water table is more than 50 feet, and in small areas the depth to the water table is more than 200 feet. Depths to the water table near the northern coast of the island generally are more than 20 feet, except adjacent to stream channels or in narrow bands near the shoreline.

GROUND-WATER RESERVOIR

HYDROLOGIC FEATURES OF THE GROUND-WATER RESERVOIR

The overall hydrogeologic setting of Long Island was described in considerable detail by Veatch (1906), Fuller (1914), and Suter, De Laguna, and Perlmutter (1949). The geology and related hydrology of several smaller areas of Long Island have been studied in greater detail by others, including De Laguna (1963), Isbister (1966), Lubke (1964), Lusczynski and Swarzenski (1966), Perlmutter and Geraghty (1963), Pluhowski and Kantrowitz (1964), and Swarzenski (1963).

Long Island is underlain by consolidated bedrock which, in turn, is overlain by a wedge-shaped mass of unconsolidated rock materials (fig. 8).[1] These materials, which constitute Long Island's ground-water reservoir, consist primarily of a series of Pleistocene glacial deposits and Cretaceous fluvial or deltaic deposits composed of gravel, sand, silt, clay, and mixtures thereof. The Cretaceous deposits were eroded by

[1] The actual dip of the upper bedrock surface is slightly less than 1° to the southeast. The much greater inclination of the bedrock surface and the Magothy aquifer shown in figure 8 is due to the large vertical scale exaggeration of this cross section.

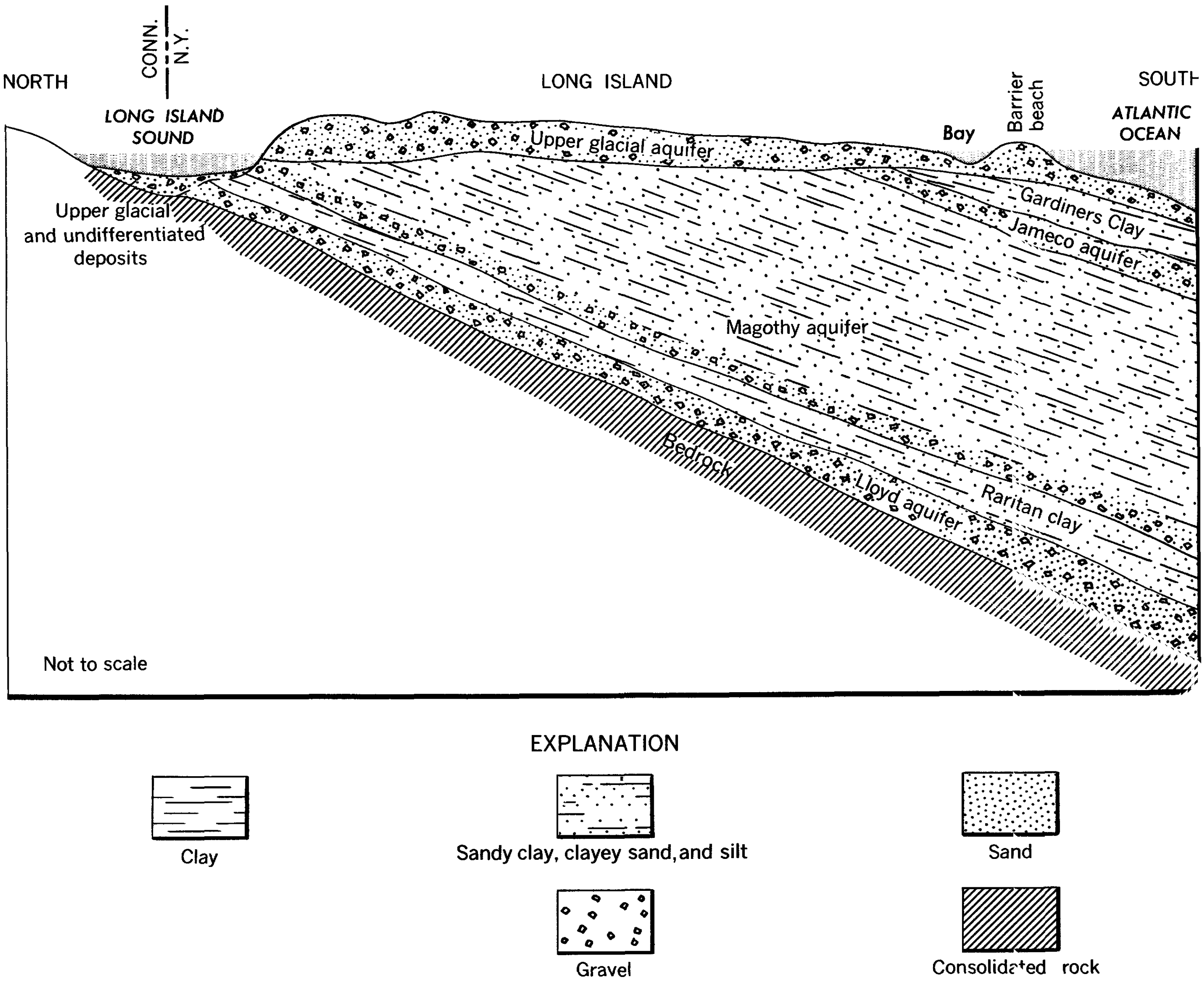


FIGURE 8.—Geologic features of the ground-water reservoir.

streams and glaciers so that the Pleistocene deposits lie on an irregular Cretaceous surface, and in places the Pleistocene deposits fill valleys cut by preglacial and glacial streams. These valleys have been fairly well defined in Kings and Queens Counties and along the northern margin of the island eastward to the middle of Suffolk County. In eastern Suffolk County, however, data on the contact between the Pleistocene and the Cretaceous are very sparse.

The upper surface of the Cretaceous deposits is above sea level in a large area in northern Nassau and western Suffolk Counties, and in all but a few small areas, the Pleistocene deposits cover the Cretaceous deposits throughout Long Island. Pertinent information concerning the principal hydrogeologic units within the ground-water reservoir are briefly summarized in table 2.

Ground water in the uppermost part of the zone of saturation on Long Island (mainly in the upper glacial aquifer, but locally also in the Magothy aquifer) is generally under water-table conditions. Artesian conditions predominate in most of the other parts of the ground-water reservoir of Long Island, where the saturated deposits are overlain and confined by silty and clayey layers of low hydraulic conductivity. The hydraulic head in the confined aquifers ranges from several feet below the water table to nearly 20 feet above it. At places along the north and south shores and on the barrier beaches, the head in the Lloyd aquifer is high enough to cause some wells which penetrate this aquifer to flow.

In addition to the Raritan clay, which confines water in the Lloyd aquifer, the other major well-defined confining layer in the ground-water reservoir is the Gardiners Clay. This unit locally confines water in the Jameco and Magothy aquifers. Numerous clayey and silty layers in the Magothy aquifer and clay beds in the glacial deposits also are significant confining layers. Normally, the degree of confinement in the Magothy aquifer increases with depth as more and more clayey layers intervene between the deep zone and the water table.

BOUNDARIES OF THE FRESH GROUND-WATER RESERVOIR

The boundaries of the fresh ground-water reservoir are the water table, the fresh-salt water interface, and the bedrock surface. The estimated average position of the water table under natural conditions is shown in figure 9. The position of the contours is based on a map of the water table in Kings, Queens, and Nassau Counties in 1903 (prepared by Veatch in 1906), and on later water-table maps of Suffolk County. Major features of this map are the two areas of highest ground-water altitude (represented by closed 80-ft and 60-ft contours) which extend approximately westward in the north-central parts of Nassau and Suffolk Counties. Also noteworthy are the steep water-level gradients near the north shore of Long Island compared to the gradients near the south shore.

The water table, which is the upper boundary of the ground-water reservoir, is a dynamic (moveable) feature. Present information indicates that recharge to the water table occurs throughout virtually all of Long Island. Therefore, the water table is not, from the point of view of potential theory, a stream surface. It is instead a surface characterized by a constantly varying potential which is equal to the altitude of the water table at any point. Because the water table on Long Island is largely a recharging potential boundary of the ground-water reservior, streamlines flow perpendicularly from the water table into the ground-water reservoir. Locally, as near the shorelines where ground water is lost by evapotranspiration, the water table is a discharging potential boundary.

The ground-water reservoir is bordered laterally by a second moveable boundary—the fresh-salt water interface. The position of this interface (or these interfaces) is fairly accurately known only in southwestern Nassau and southeastern Queens Counties as a result of an intensive investigation by Lusczynski and Swarzenski (1966). A north-south cross section through the ground-water reservoir in this area (fig. 10) shows three separate salt-water wedges—a shallow wedge in the glacial aquifer and intermediate and deep wedges in the Magothy aquifer. Furthermore, a fourth wedge exists in the Lloyd aquifer somewhere seaward of the barrier beaches.

The occurrence of fresh ground water in the Lloyd aquifer below salty ground water in the lower part of the Magothy aquifer has never been adequately explained. However, this occurrence must be related in some way to the relatively impermeable Raritan clay overlying the Lloyd aquifer. At least four separate wedges of salty ground water with relative positions approximately as indicated in figure 10 probably occur for a considerable distance eastward from western Nassau County (on the order of tens of miles) along the south shore of Long Island.

Very scanty information indicates that the Lloyd aquifer and the deep Magothy aquifer contain salty ground water beneath the Forks of Long Island. The fresh ground water beneath the Forks occurs in a lens ranging in thickness from a few feet to several hundred feet.

TABLE 2.—*Summary of the rock units and their water-bearing properties, Long Island, N.Y.*

[After McClymonds and Franke, 1971]

System	Series	Geologic unit	Hydrogeologic unit	Approximate maximum thickness (feet)	Depth from land surface to top (feet)	Character of deposits	Water-bearing properties
Quaternary	Holocene	Artificial fill, salt marsh deposits, stream alluvium, and shoreline deposits.	Holocene deposits	50	0	Sand, gravel, clay, silt, organic mud, peat, loam, and shells. Colors are gray, brown, green, black, and yellow. Holocene artificial-fill deposits of gravel, sand, clay, and rubbish.	Permeable sandy beds beneath barrier beaches yield fresh water at shallow depths, brackish to salty water at greater depth. Clay and silt beneath bays retard salt-water encroachment and confine underlying aquifers. Stream-flood-plain and marsh deposits may yield small quantities of water, but are generally clayey or silty and much less permeable than underlying upper glacial aquifer.
	Pleistocene	Upper Pleistocene deposits	Upper glacial aquifer	600	0–50	Till (mostly along north shore and in moraines) composed of clay, sand, gravel, and boulders. Forms Harbor Hill and Ronkonkoma terminal moraines. Outwash deposits (mostly between and south of terminal moraines, but also interlayered with till) consist of quartzose sand, fine to very coarse, and gravel, pebble to boulder sized. Glaciolacustrine deposits (mostly in central and eastern Long Island) and marine clay (locally along south shore) consist of silt, clay, and some sand and gravel layers; includes "20-foot clay" in southern Nassau County and Queens County. Colors are mainly gray, brown, and yellow; silt and clay locally are grayish green. Contains shells and plant remains, generally in finer grained beds; also contains Foraminifera. Contains chlorite, biotite, muscovite, hornblende, olivine, and feldspar as accessory minerals; "20-foot clay" commonly contains glauconite.	Till is poorly permeable; commonly causes perched-water bodies and impedes downward percolation of water to underlying beds. Outwash deposits are moderately to highly permeable; specific capacities of wells tapping them range from about 10 to more than 200 gpm per foot of drawdown. Good to excellent infiltration characteristics. Glaciolacustrine and marine clay deposits are mostly poorly permeable, but locally have thin moderately permeable layers of sand and gravel; generally retard downward percolation of ground water. Contains fresh water, except near the shorelines. Till and marine deposits locally retard salt-water encroachment.
		—Unconformity?—					
		Gardiners Clay	Gardiners Clay	300	50–400	Clay, silt, and few layers of sand and gravel. Colors are grayish green and brown. Contains marine shells, Foraminifera, and lignite; also glauconite, locally. Altitude of top generally is 50–80 ft below mean sea level. Occurs in Kings and Queens Counties, southern Nassau County, and Suffolk County; similar clay occurs in buried valleys near north shore.	Poorly permeable; constitutes confining layer for underlying Jameco aquifer. Locally, sand layers yield small quantities of water.
		—Unconformity?—					
		Jameco Gravel	Jameco aquifer	300	50–550	Sand, fine to very coarse, and gravel to large-pebble size; few layers of clay and silt. Gravel is composed of crystalline and sedimentary rocks. Color is mostly dark brown. Contains chlorite, biotite, muscovite, hornblende, and feldspar as accessory minerals. Occurs in Kings and Queens Counties, and southern Nassau County; similar deposits occur in buried valleys near north shore.	Moderately to highly permeable; contains mostly fresh water, but brackish water and water with high iron content locally in southeastern Nassau County and southern Queens County. Specific capacities of wells in the Jameco range from about 20 to 150 gpm per foot of drawdown.
		—Unconformity—					
Tertiary(?)	Pliocene(?)	Mannetto Gravel	(Commonly included with upper glacial aquifer.)	300	0–120	Gravel, fine to coarse, and lenses of sand; scattered clay lenses. Colors are white, yellow, and brown. Occurs only near Nassau-Suffolk County border near center of island.	Highly permeable, but occurs mostly above water table. Excellent infiltration characteristics.
		—Unconformity—					
Cretaceous		Magothy Formation	Magothy aquifer	1,100	0–600	Sand, fine to medium, clayey in part; interbedded with lenses and layers of coarse sand and sandy and solid clay. Gravel is common in basal 50–200 ft. Sand and gravel are quartzose. Lignite, pyrite, and iron oxide concretions are common; muscovite, magnetite, rutile, and garnet are accessory minerals. Colors are gray, white, red, brown, and yellow.	Most layers are poorly to moderately permeable; some are highly permeable locally. Specific capacities of wells in the Magothy generally range from 1 to about 30 gpm per foot of drawdown, rarely are as much as 80 gpm per ft. Water is unconfined in uppermost parts, elsewhere is confined. Water is generally of excellent quality but has high iron content locally along north and south shores. Constitutes principal aquifer for public-supply wells in western Long Island, except Kings County where it is mostly absent. Has been invaded by salty-ground water locally in southwestern Nassau County and southern Queens County, and in small areas along north shore.

TABLE 2.—*Summary of the rock units and their water-bearing properties, Long Island, N.Y.*—Continued

System	Series	Geologic unit		Hydrogeologic unit	Approximate maximum thickness (feet)	Depth from land surface to top (feet)	Character of deposits	Water-bearing properties
		—Unconformity—						
Cretaceous	Upper Cretaceous	Raritan Formation	Clay member	Raritan clay	300	70–1,500	Clay, solid and silty; few lenses and layers of sand; little gravel. Lignite and pyrite are common. Colors are gray, red, and white, commonly variegated.	Poorly to very poorly permeable; constitutes confining layer for underlying Lloyd aquifer. Very few wells produce appreciable water from these deposits.
			Lloyd Sand Member	Lloyd aquifer	500	200–1,800	Sand, fine to coarse, and gravel, commonly with clayey matrix; some lenses and layers of solid and silty clay; contains thin lignite layers and iron concretions locally. Locally, has gradational contact with overlying Raritan clay. Sand and most of gravel are quartzose. Colors are yellow, gray, and white; clay is red locally.	Poorly to moderately permeable. Specific capacities of wells in the Lloyd generally range from 1 to about 25 gpm per foot of drawdown, rarely are as much as 50 gpm per ft. Water is confined under artesian pressure by overlying Raritan clay; generally of excellent quality but has high iron content locally. Has been invaded by salty ground water locally in necks near north shore, where aquifer is mostly shallow and overlying clay discontinuous. Called deep confined aquifer in some earlier reports.
		—Unconformity—						
Precambrian		Bedrock		Bedrock	----------	0–2,700	Crystalline metamorphic and igneous rocks; muscovite-biotite schist, gneiss, and granite. A soft clayey zone of weathered bedrock locally is more than 100 ft thick.	Poorly permeable to virtually impermeable; constitutes virtually the lower boundary of ground-water reservoir. Some hard, fresh water is contained in joints and fractures, but is impracticable to develop at most places; however, a few wells near the western edges of Qneens and Kings Counties obtain water from the bedrock.

The fresh-salt water interface is not a sharp boundary. The horizontal distance over which the dissolved-solids content of ground water changes from completely fresh to completely salty is generally on the order of 2–3 thousand feet near the south shore of Long Island. Over this distance, the dissolved-solids content of the ground water increases at first gradually in the direction of the salty ground water and then more rapidly.

The fresh-salt water interface is a complex streamline surface, and fresh ground water discharging into the ocean and bays moves parallel to the interface and not across it. The hydrodynamics of a stable interface and, to an even greater degree, an unstable interface that changes position in response to changes in head within the ground-water reservoir, is complicated and beyond the scope of this report. (See Lusczynski, 1961; Cooper, 1964; and Kohout, 1964.)

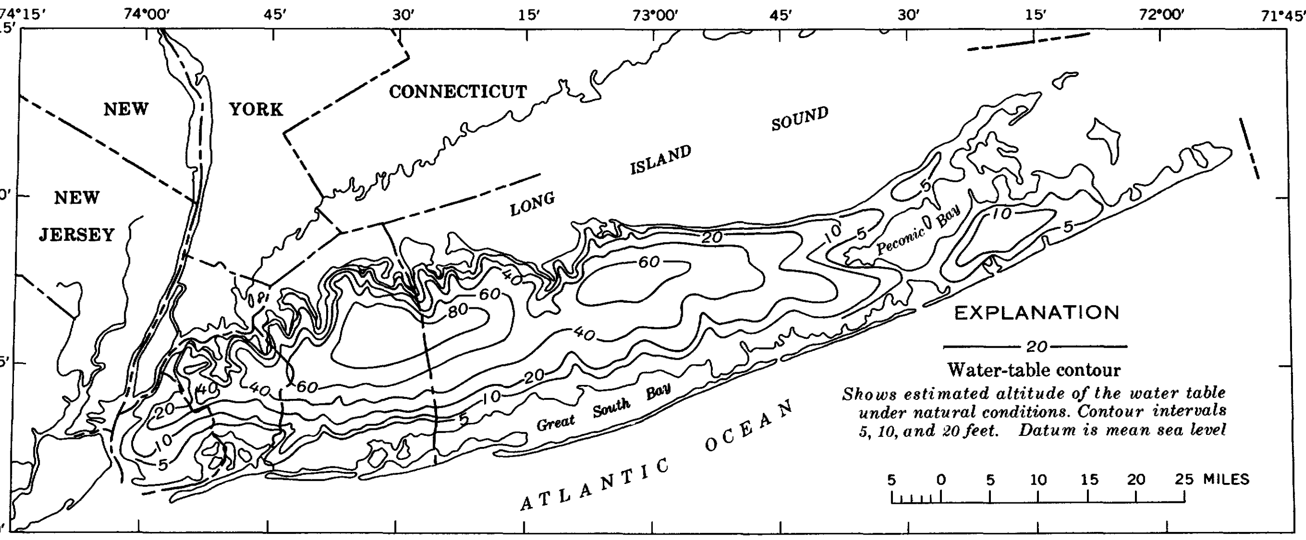


FIGURE 9.—Estimated average position of the water-table under natural conditions.

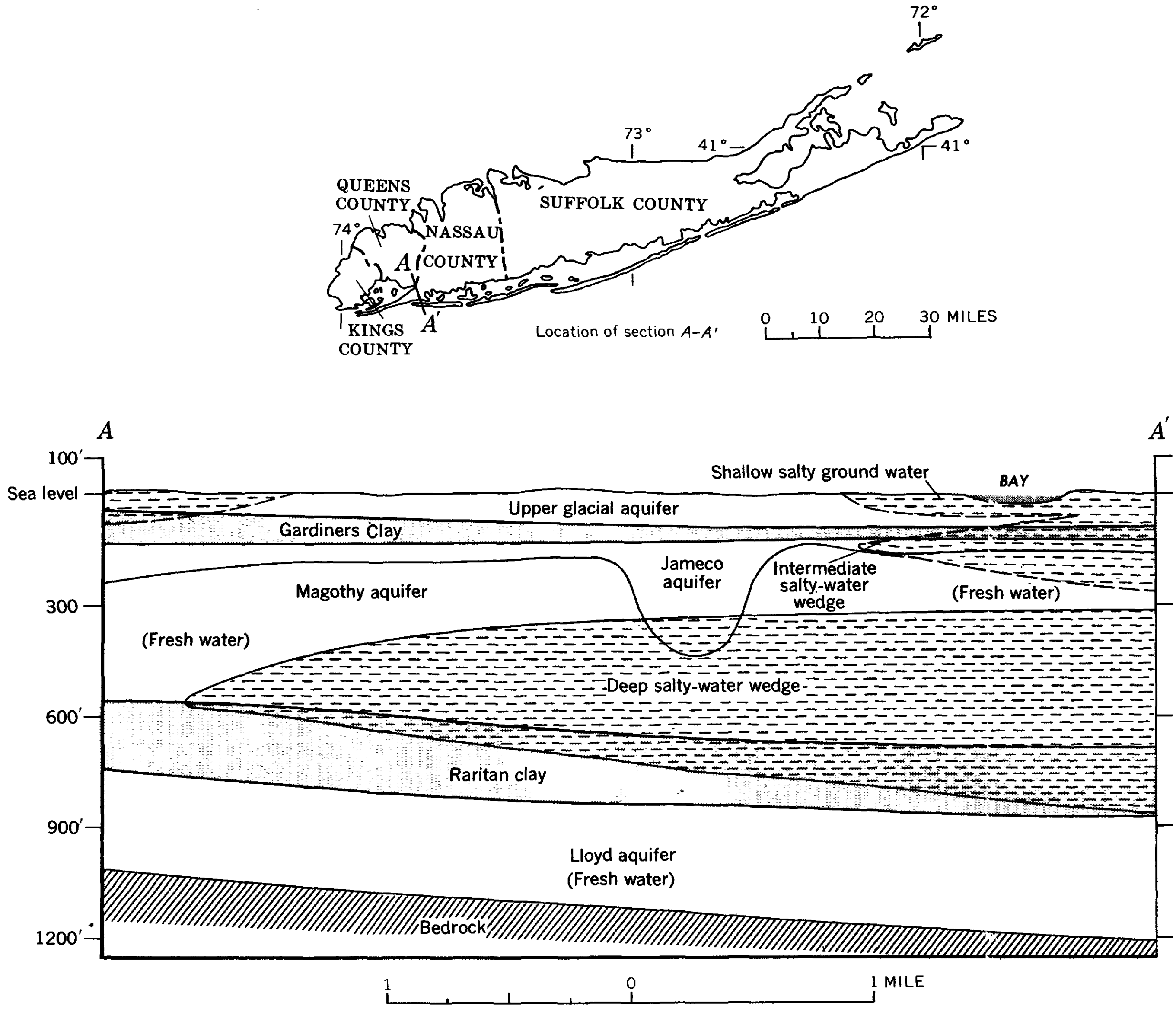


FIGURE 10.—Occurrence of salty ground water in southwestern Nassau County, in 1961. Adapted from Lusczynski and Swarzenski (1966, pl. 3).

The top of the bedrock surface, which outcrops in western Queens County, dips southeast on the average about 65 feet per mile, or slightly less than 1°, to an estimated depth of about 2,000 feet in south-central Suffolk County (fig. 11). The number of control points on the bedrock surface, particularly in Suffolk County, is small; therefore, the surface undoubtedly is more irregular than is indicated in figure 11.

For practical purposes the bedrock surface is the impervious bottom of the ground-water reservoir. Hydraulically, therefore, the top of the bedrock is a stream surface; ground water flows parallel to the bedrock and not across it, and equipotential lines or surfaces intersect the bedrock at right angles.

Generally, the flowing parts of the streams on Lon Island are ground-water drains, and the ground wate continually discharges into these parts under natura conditions. Therefore, in relation to the ground-wate reservoir, the streams are discharging potential bound aries. The potential at a given point on the strea is equal to the altitude of the stream at that poin Thus, the potential along the stream channel varie continuously from the altitude of start of flow of th stream to the altitude of the surrounding bay c ocean.

The approximate location and altitude of the poi of start of flow for several streams in June 1967 a shown in figure 3. Because ground-water levels an

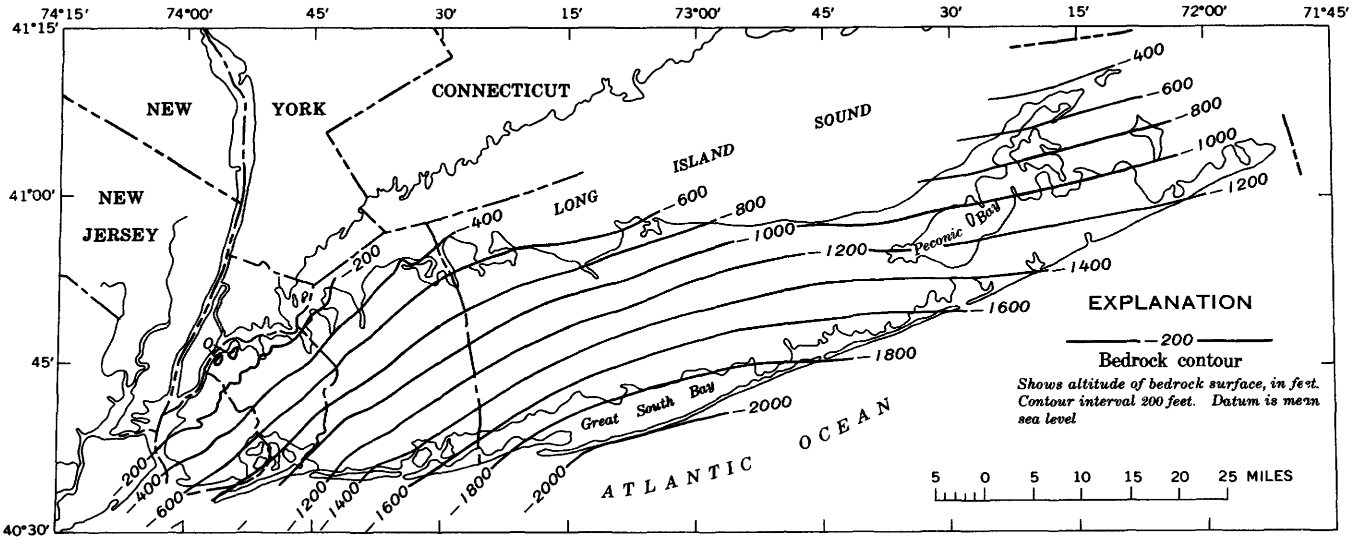


FIGURE 11.—Contour map of the bedrock surface. Modified from Suter, De Laguna, and Perlmutter (1949, pls. 8–10).

streamflow were below average for this month, these altitudes are slightly lower than (on the order of 5 ft) and the points of start of flow are slightly seaward (on the order of several hundred feet) of their average positions. The points of start of flow of the streams are points on the water table, and the locations of these points reflect local conditions relating to topography and position of the water table.

SIZE OF THE FRESH GROUND-WATER RESERVOIR

The volumes of various parts of the fresh ground-water reservoir are given in table 3. The estimates of the volumes of unconsolidated deposits saturated with fresh ground water (col. 2) were derived mainly from a map showing the saturated thickness of the ground-water reservoir in 1965 (fig. 12). The water table at this time, particularly in Kings, Queens, and western Nassau Counties, was considerably lower than the water table under natural conditions. However, the difference in the total volume of fresh ground water in the ground-water reservoir in 1965 compared to the volume under natural conditions is negligible compared to the total volume of fresh ground water in the ground-water reservoir.

The values in column 2 of table 3 are probably accurate to within about 10 percent, except for one entry—the volume of deposits "beneath areas adjacent to the water-budget area" (item *c*). The magnitude

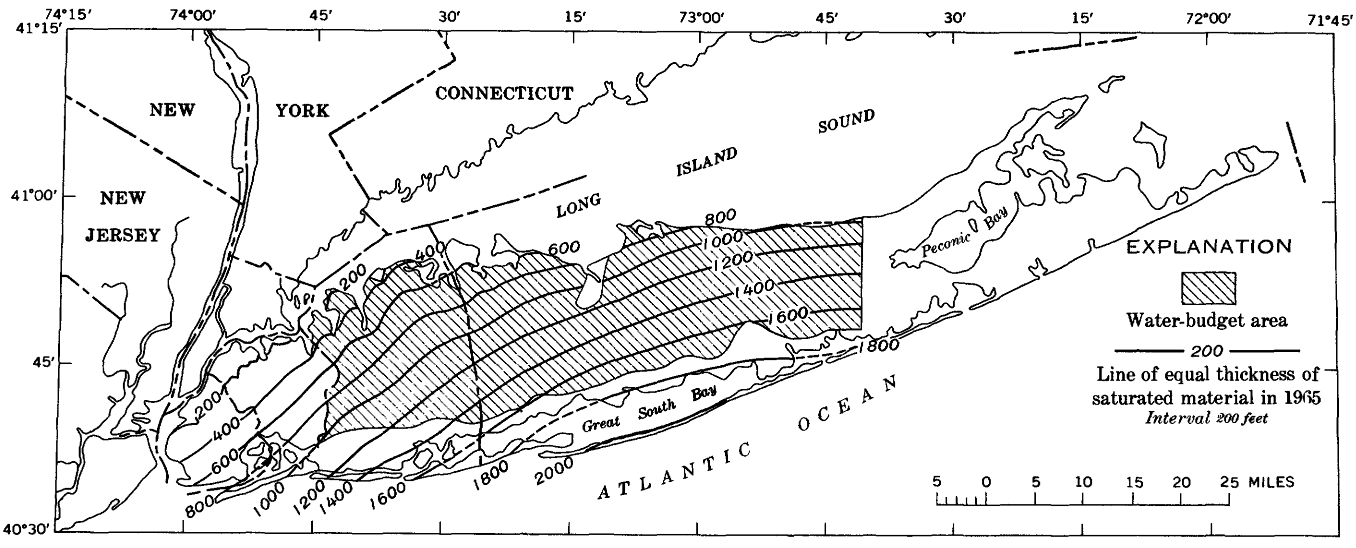


FIGURE 12.—Thickness of unconsolidated deposits saturated with fresh ground water in 1965. After Cohen, Franke, and Foxworthy (1968, pl. 2G).

TABLE 3.—*Estimated volume of fresh ground water beneath parts of Long Island, N.Y.*

Item	Volume designation	Volume of deposits saturated with fresh ground water (cubic miles)	Total volume of fresh ground water (gallons)	Range in estimated storage capacity (gallons)
	(1)	(2)	(3)	(4)
(a)	Above sea level in water-budget area	5	1,600,000	280,000-560,000
(b)	Beneath entire water-budget area	180	59,000,000	10,000,000-20,000,000
(c)	Beneath areas adjacent to water-budget area [1]	100	33,000,000	5,500,000-11,000,000
(d)	Sums of items *b* and *c* (rounded)	280	92,000,000	15,000,000-31,000,000
(e)	Beneath mainland Kings and Queens Counties	10	3,300,000	550,000-1,100,000
(f)	Sums of items *d* and *e* (rounded)	290	95,000,000	16,000,000-32,000,000

[1] Includes volume beneath the nearshore areas and the adjacent bays.

of this entry depends on the location of the fresh-salt water interface which is not known along much of the perimeter of Long Island.

To obtain the values of "total volume of fresh ground water" in column 3, the entries in column 2 were multiplied by 0.30 (the estimated average porosity), and the result was converted to millions of gallons. This estimate probably is conservative because many of the finer deposits (clays) within the ground-water reservoir probably have a higher porosity.

The storage capacity of the ground-water reservoir is the total volume of water in the ground-water reservoir minus the volume of water that would be retained against the force of gravity if the reservoir were drained—that is, the average porosity minus the average specific retention times the total volume of deposits saturated with water. The average porosity minus the average specific retention is equal to the average specific yield. Previous investigators estimated the average specific yield of deposits in the Long Island ground-water reservoir to be about 5–10 percent (Cohen and others, 1968, p. 26). The specific yield for individual layers in the ground-water reservoir probably ranges fom less than 1 to 25–30 percent. The values in column 4 of table 3 were obtained by multiplying the values in column 2 by 0.05–0.10 (or 5–10 percent) and converting the result to millions of gallons.

As a result of the assumptions that were made, the values of storage capacity in column 4 are probably conservative. However, because of uncertainty about the process of salt-water encroachment and the large volume of fine-grained deposits (silt and clay) in the ground-water reservoir, such conservative estimates are necessary to ensure dependable figures for water-management purposes.

SOURCE OF THE WATER AND INFLOW TO THE HYDROLOGIC SYSTEM

Reference to the accompanying flow diagram (fig. 13) facilitates the following discussion of the hydrologic system under natural conditions. Only flow paths that represent large quantities of water or those that are of special interest or significance are shown. Many other flow paths that commonly represent negligible quantities of water on Long Island, such as infiltration from bodies of surface water to the zone of aeration or direct runoff from the land surface to the ocean, are not discussed in this report.

PRECIPITATION

Under natural conditions, precipitation is the source of all the fresh water on Long Island—that is, it is the total input to the fresh-water hydrologic system. The aspects of the precipitation regimen on Long Island which are especially pertinent to this study are the areal distribution, averages, and ranges of annual, seasonal, and monthly precipitation. Most of the information regarding precipitation considered in the present report is derived from a detailed report that was prepared as part of the present water-budget study of Long Island (Miller and Frederick, 1969).

Information on the distribution by month of the number of days in which specified amounts of precipitation fell and on intensity and frequency of precipitation on Long Island, which was developed in the report by Miller and Frederick, is not considered here. In addition, the drought, which occurred in the Northeastern United States in 1962–66, and its hydrologic consequences on Long Island are evaluated in a separate report (Cohen and others, 1969).

Maps showing average annual, average warm-season (April-September), and average cool-season (October-March) precipitation for water years 1951–65 are shown in figure 14. The period 1951–65 was chosen for these maps because (1) complete or almost complete records were available for that period for the largest number of stations, and (2) data from stations with sufficiently long records showed that averages for the period 1951–65 were close to averages for the so-called normal period, 1931–60.

A significant feature in figure 14*A* is the area of high precipitation in north-central Suffolk County. Miller and Frederick (1969) state that this feature is probably largely related to two factors: (1) The greater distance of the area from the Atlantic Ocean and Long Island Sound and (2) its slightly higher altitude. The map for the average cool-season precipitation (fig. 14*B*) also shows an area of high precipitation in north-central Suffolk County. However, this

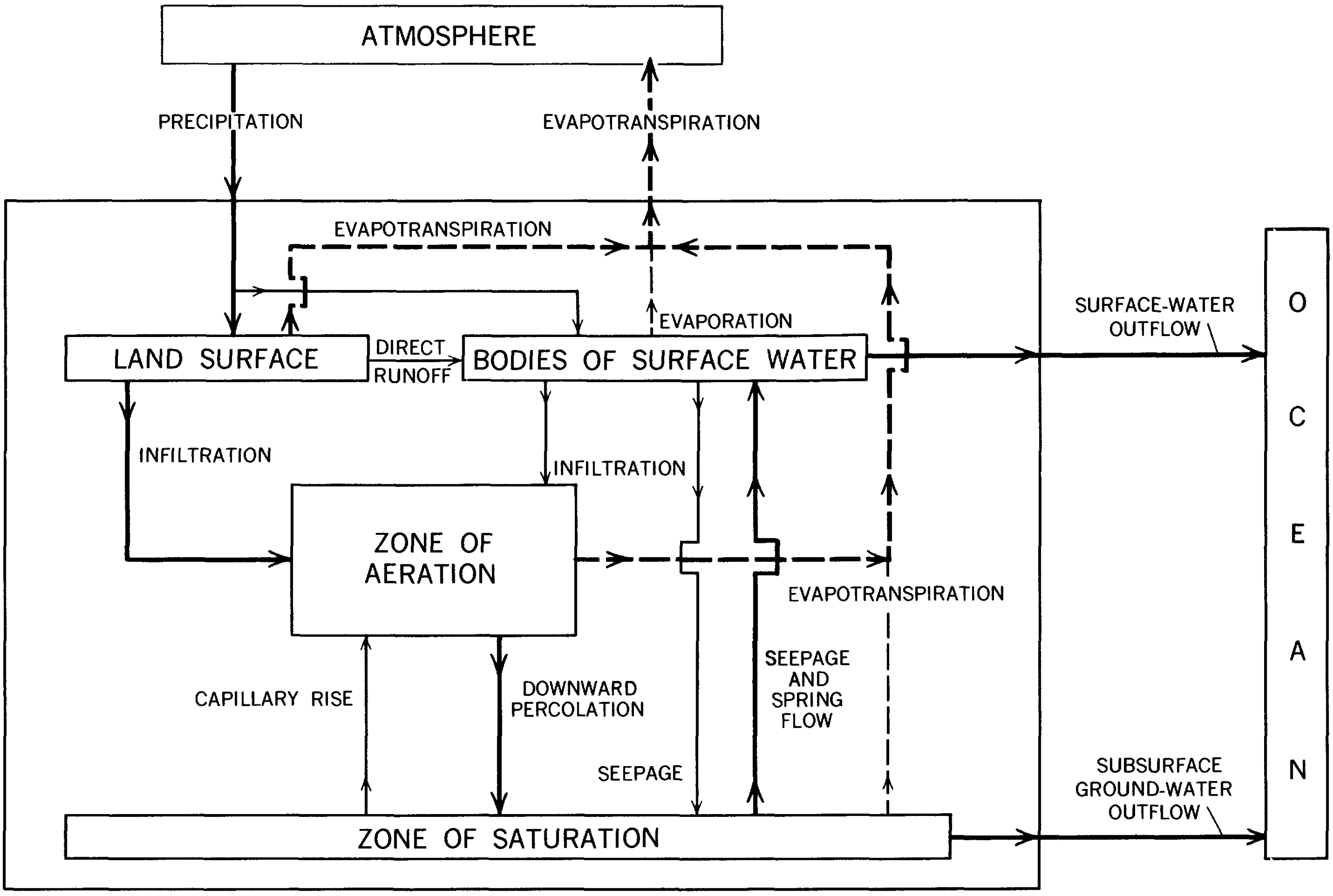


FIGURE 13.—Flow diagram of the hydrologic system under natural conditions. After Cohen, Franke, and Foxworthy (1968, pl. 6A).

feature is less evident in the warm season (fig. 14*C*), presumably because precipitation is more evenly distributed in the warm season than in the cool season.

Mean values of precipitation (derived from fig. 14) for all of Long Island (including the Forks) and for the water-budget area, and ranges in average precipitation are given in table 4. These values show that average warm-season precipitation and cool-season precipitation are almost equal on Long Island.

Composite average monthly precipitation for selected stations for the normal period 1931–60 (fig. 15) indicate that precipitation is distributed fairly evenly throughout the year, and that average monthly precipitation ranges from about 3 to more than 4 inches. During the winter, most of the precipitation on Long Island is derived from regional storms. In the summer, however, most of the precipitation is associated with local thunderstorms. On the average, the lowest monthly precipitation occurs in June—a month of transition between the period when regional storms predominate and the period when local thunderstorms supply most of the precipitation.

Precipitation data from Setauket, the station with the longest period of record (table 5), indicate that precipitation on Long Island ranges widely from month to month and from year to year. For example, although average annual precipitation at Setauket is about 44.5 inches, observed annual precipitation ranged from a low of about 31 inches in 1966 to a high of about 56 inches in 1898.

The values of precipitation described in the previous text are total values—that is, they include snow, snow mixed with rain, and rain alone. The average annual snowfall on Long Island is about 25–30 inches, or about 10–15 percent of the water equivalent of the cool-season precipitation. A tabulation of the number

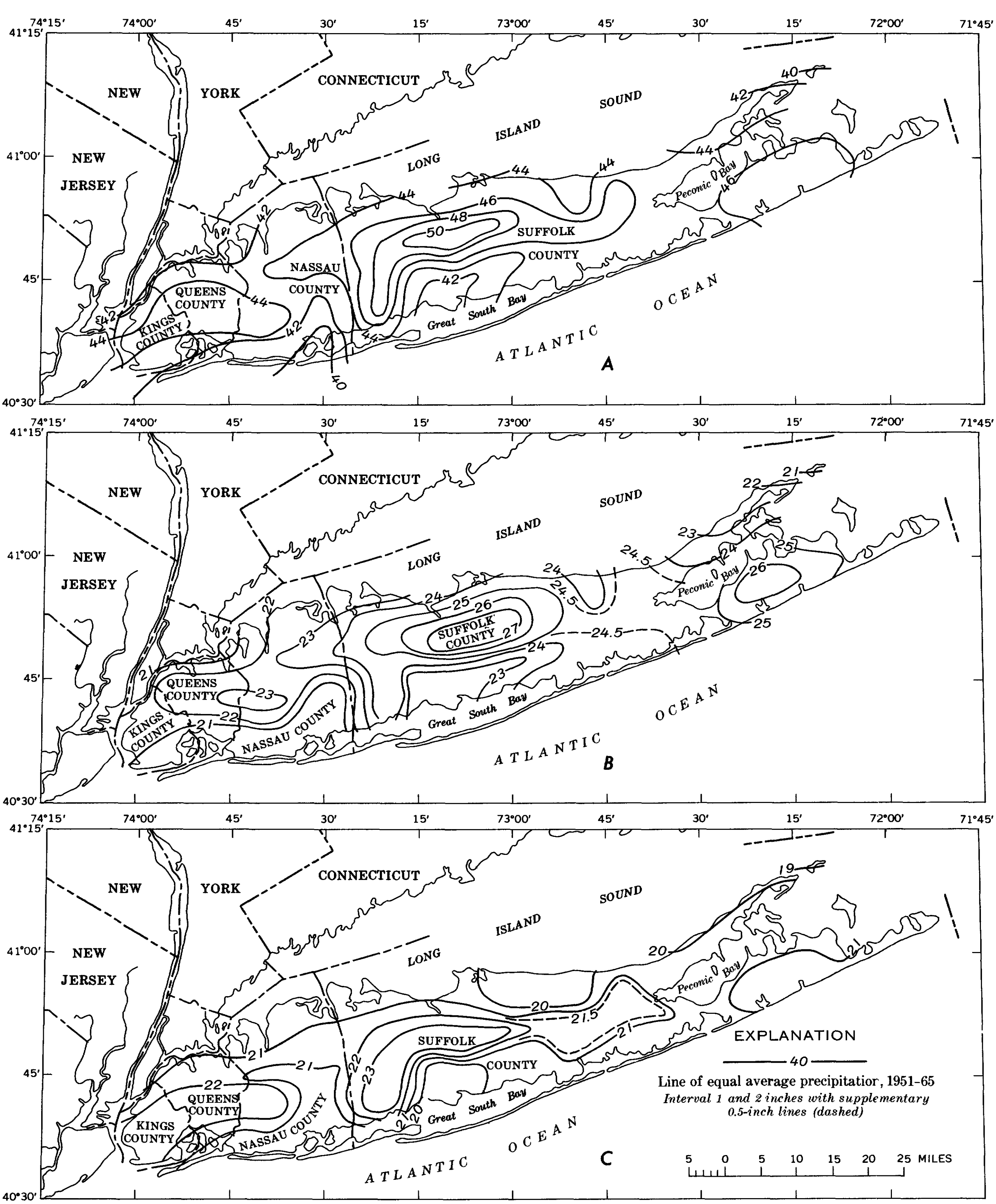


FIGURE 14.—Average annual (*A*), average cool-season (*B*), and average warm-season precipitation (*C*), water years 1951–65. After Miller and Frederick (1969).

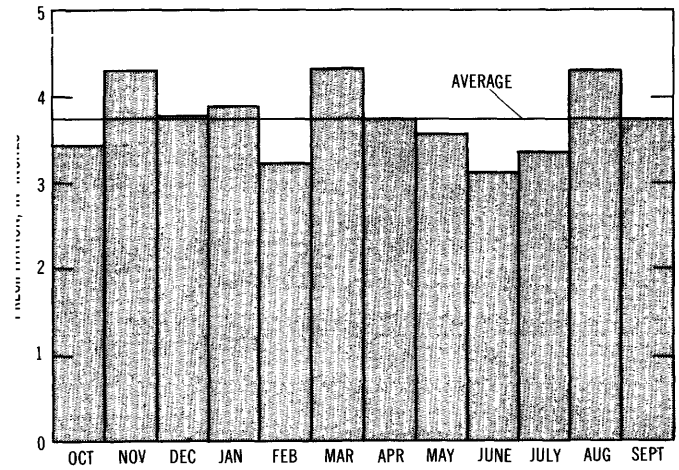


FIGURE 15.—Composite average monthly precipitation for selected stations for the normal period 1931–60.

TABLE 4.—*Average annual and average seasonal precipitation on Long Island, N.Y., and the water-budget area, water years 1951–65*

[In inches]

Area	Precipitation					
	Annual		Cool season		Warm season	
	Mean	Range	Mean	Range	Mean	Range
All of Long Island (including the Forks)	44.3	40–50	23.6	21–27	20.7	19–23
Water-budget area	44.8	41–50	23.8	21–27	21.0	20–23

of snowstorms greater than 6 inches for the New York Weather Bureau Office in Manhattan County for the period 1884–1960 (Miller and Frederick, 1969) showed that most of the large snowstorms were fairly evenly distributed between the first of December and the middle of March. The greatest number of large snowstorms occurred during the first half of February.

DISPOSITION OF PRECIPTATION

Precipitation on the land surface follows three main paths (fig. 13)—direct runoff to bodies of surface water (primarily streams), return to the atmosphere by evapotranspiration, and infiltration into the zone of aeration. Precipitation that infiltrates into the zone of aeration is either transpired by plants or percolates downward to the ground-water reservoir (zone of satuation).

TABLE 5.—*Mean and extreme values of precipitation at Setauket, Long Island, N.Y., water years 1888-1967*

[In inches]

	Precipitation			
	Annual	Warm season	Cool season	Monthly
Mean	44.5	21.7	22.8	3.7
Maximum	56.4	35.4	34.1	13.2
Time of occurrence	1898	1938	1899	Sept. 1938
Minimum	30.8	11.0	12.0	0.1
Time of occurrence	1966	1965	1947	June 1949

DIRECT RUNOFF

Values of direct runoff to selected streams, whose drainage areas have remained virtually unaffected by man, are given in table 6. Data for water years 1958 and 1964 were chosen for comparison because these were years of exceptionally high and low annual precipitation, respectively. On the basis of meager data, it appears that the amount of annual precipitation did not materially affect the percentage of total streamflow that was derived from direct runoff under natural conditions. Furthermore, the figures indicate that the percentage of direct runoff in the discharge of the two northward-flowing streams (Mill Neck Creek and Nissequogue River) was slightly greater than the percentage of direct runoff in the discharge of Carmans River, a southward flowing stream. Two factors probably accounted, at least in part, for this difference: (1) Slightly less permeable soils in areas underlain by glacial till near the north shore as compared to the highly permeable glacial outwash deposits near the south shore and (2) steeper land-surface gradients adjacent to the north-shore streams compared to the south-shore streams.

Because southward flowing streams include most of the streamflow on Long Island (about 75 percent), the data in table 6 suggest that under natural conditions an average of less than 5 percent of total measured streamflow is direct runoff. This quantity of water represents less than 1 percent of the precipitation that fell on the drainage areas of the streams in the water-budget area.

EVAPOTRANSPIRATION

Total evapotranspiration from the hydrologic system of Long Island includes evaporation from the land surface and surface-water bodies, evapotranspiration

TABLE 6.—*Annual direct runoff of selected streams on Long Island, N.Y., whose drainage areas closely approximate natural conditions, water years 1958 and 1964*

Stream	Water year 1958		Water year 1964	
	Average discharge (cubic feet per second)	Direct runoff (percentage of total discharge)	Average discharge (cubic feet per second)	Direct runoff (percentage of total discharge)
Mill Neck Creek	10.7	10	7.2	10
Nissequogue River	47.3	7	37.7	5
Carmans River	30.6	3	20.9	3

from the zone of aeration, and evapotranspiration directly from the ground-water reservoir (fig. 13). Total evapotranspiration excluding evapotranspiration of ground water is briefly discussed in this section of the report. Evapotranspiration of ground water is discussed in the section on "Discharge from the Ground-Water Reservoir."

Annual evapotranspiration constitutes the greatest unknown in the disposition of precipitation on Long Island. Previous investigators estimated average annual evapotranspiration by difference from other quantities in a hydrologic budget. Thus, any errors in the estimates of these other quantities were incorporated in the estimate of evapotranspiration. This procedure resulted in estimates of average annual evapotranspiration that were about one-half of average annual precipitation, or between about 20 and 25 inches. Information is not available to improve upon these estimates in the present investigation.

Average annual values of "potential" evapotranspiration derived by the application of methods developed by Thornthwaite and Mather (1955, 1957) and Meyer (1928) are about 29 and 32 inches, respectively. Thus, the upper limit of annual "potential" evapotranspiration for a specific year is probably on the order of 30–35 inches. Minimum warm-season precipitation for the months April to September for most stations ranges from about 12 to 15 inches. If it is assumed that most of this precipitation is discharged to the atmosphere and that some additional evapotranspiration occurs during the winter months, the minimum values of annual evapotranspiration are probably on the order of 10–15 inches.

Mean annual evaporation from a land pan in central Nassau County for the period 1949–60 was about 48 inches (Pluhowski and Kantrowitz, 1964), of which an average of about 36 inches, or about 75 percent evaporated during the summer months (April-September). This same seasonal distribution of average annual evapotranspiration was indicated by the monthly values of potential evapotranspiration derived from the methods of Thornthwaite and Mather and Meyer.

INFILTRATION TO THE ZONE OF AERATION

No data are presently available to estimate directly the quantity of water that infiltrates into the zone of aeration. However, systematic measurements of soil moisture provide an estimate of evapotranspiration from the zone of aeration and recharge to the water table through the zone of aeration. In addition, such measurements provide valuable information on the storage characteristics of the deposits in the zone of aeration and in the upper part of the zone o saturation.

Studies of soil moisture in glacial outwash deposit using a neutron meter have been underway for severa years at the Brookhaven National Laboratory unde the direction of G. M. Woodwell. The results of thes studies are included in a report by Reiners and Wood well (1966). Their report included a water budge based on soil moisture measurements for the summe and fall of 1963. Unpublished data from these studie for most of 1966, which include daily precipitation average water content of the upper 6 feet of the soi profile, and the depth to the water table in a shallov nearby well, are shown in figure 16. The followin observations can be made from this figure: (1) Whe the average water content of the 6-foot soil profil was between about 10 and 11 inches, as in April an late September, ground-water levels slowly declined (2) when the average water content of the soil pro file was greater than about 11 inches as during mos of May, ground-water levels rose; and (3) in th extremely dry period of late July and early August the average water content of the soil was betwee 5 and 6 inches and ground-water levels declined.

These data and data from Reiner and Woodwel (1966) suggest the following tentative conclusions con cerning the soils and uppermost deposits in the Brook haven area: (1) Field capacity of these soils is abou 10–15 percent; and (2) if the total porosity is assume to be about 30–35 percent, which is indicated by soil moisture measurements in the capillary fringe, th specific yield of these materials is on the order o 15–25 percent. Although these conclusions are base on very sparse data, they are comparable to con clusions concerning similar deposits elsewhere, an may, therefore, be reasonably representative of th glacial-outwash deposits of Long Island.

Additional observations by Reiner and Woodwel (1966) indicate that the effect of vegetation on soi moisture must occur primarily in the upper 3 fee on Long Island, because the root systems of mos indigenous vegetation do not extend below this depth Probably only the largest trees have any appreciabl effect on soil moisture below a depth of 10 feet.

RECHARGE TO THE GROUND-WATER RESERVOIR

Under natural conditions, virtually all ground-wate recharge on Long Island resulted from the infiltratio of precipitation into the zone of aeration and subse quent downward percolation through the zone o aeration to the water table (fig. 13). As with evapo transpiration, available data do not permit measure ment of recharge directly. In the present report, a

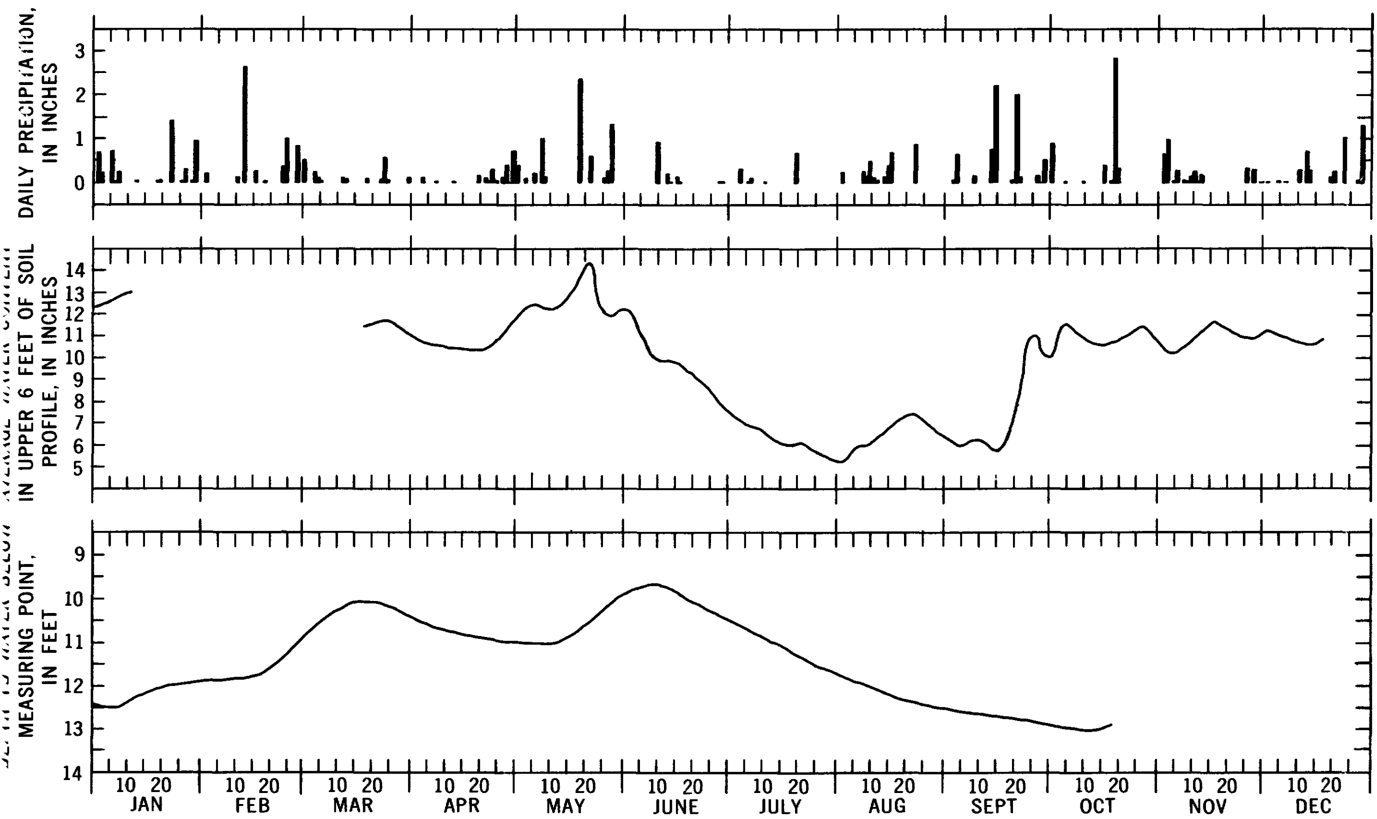


FIGURE 16.—Daily precipitation, average water content in the soil profile at one measuring site, and depth to water in an adjacent well, Brookhaven National Laboratory, in 1966. Data courtesy of G. M. Woodwell, Brookhaven National Laboratory.

estimate of average annual recharge to the ground-water reservoir can be made by first recognizing that under natural conditions long-term average annual recharge to, and discharge from, the ground-water reservoir were equal. An estimate of average annual recharge is obtained, therefore, by summing the estimates of average annual discharge for each element of discharge from the ground-water reservoir. These elements, which include base flow of streams, ground-water evapotranspiration, and subsurface outflow, are evaluated in a subsequent section of this report.

Previous investigators estimated average annual recharge by subtracting estimates of average annual evapotranspiration and other water-budget components from average annual precipitation. These estimates of average annual recharge were equal to about one-half the average annual precipitation (about 22–23 in. of water), or about 1 million gallons per day per square mile (Cohen and others, 1968, p. 44). The data presented subsequently in this report indicate that these previous estimates are in line with the best information presently available. Cohen, Franke, and Foxworthy also estimated that annual recharge ranged from about 10 to 35 inches of water.

Although no direct measurements of the quantity of recharge on Long Island are available, some information is available on the rate of movement of recharge water in the zone of aeration. Average times of travel through the zone of aeration in the till-covered areas of northeastern Nassau County as determined by Isbister (1966) are given in table 7. Isbister equipped several wells having different depths to the water table with water-level recorders. He then observed the time until the water levels in the wells responded to recharge from an identifiable large storm. Wells with progressively smaller depths to water generally showed smaller ranges in lag time. However, the response times in a single well ranged widely. For example, in a well where the depth to water was about 180 feet, the response time ranged from 5 to 16 months as compared to an average of 9–10 months (table 7).

Although the lag times given in table 7 may be considered reasonably representative for the till-covered northern part of Long Island, these times are undoubtedly too large for the more permeable glacial-outwash deposits in the southern part of Long Island. Wells in these deposits with depths to water of 30–40

TABLE 7.—*Relation of depth to the water table and average time lag in response to recharge in till-covered areas of northeastern Nassau County, Long Island, N.Y.*

[After Isbister (1966, table 10)]

Depth to water table (feet)	Average response time (months)	Depth to water table (feet)	Average response time (months)
0–10	0–1	80–100	5–6
10–25	1–2	100–120	6–7
25–40	2–3	120–140	7–8
40–60	3–4	140–160	8–9
60–80	4–5	160–180	9–10

feet often show a marked water-level response within hours or within a day or two after a large storm.

MOVEMENT WITHIN THE GROUND-WATER RESERVOIR

An idealized cross section of part of a ground-water reservoir is shown in figure 17. The dimensions of the cross section are similar to the Long Island ground-water reservoir in a north-south cross section south of the ground-water divide. The potential and flow lines in figure 17 were derived in part from an electric-analog model using graphite paper as the conducting medium (Wyckoff and Reed, 1935). In this model and in figure 17, the vertical exaggeration is about 15 to 1 compared to the Long Island ground-water reservoir. The water table was simulated by 10 discrete potential drops from the maximum potential in the system at the water-table divide (designated arbitrarily as 1000 in figure 17) to base level (zero potential or ground). No attempt was made to model a salt-fresh water interface.

The flow pattern in figure 17 was constructed for the following idealized conditions: (1) The flow was two dimensional, (2) the flow medium was homogeneous, (3) the upper boundary of the flow system (th water table) was a constant source of recharge, an (4) the lower boundary (impermeable bedrock) wa a stream surface. Despite the idealized assumption used to construct this flow net, several significan observations concerning the Long Island flow systen can be made from the net. Except for narrow area near the left- and right-hand margins of figure 17 the predominant directional component of flow i horizontal. In a model without vertical exaggeratio the horizontal character of the flow would be eve more pronounced. Furthermore, the flow line originating at the water-table divide follows a path neares the bedrock and discharges farthest from the shore line. The flow lines originating progressively shoreward of the water-table divide penetrate less deepl into the flow system and discharge nearer the shoreline

Another significant observation from figure 17 i that, with the particular geometry and potential fixed in the model, some discharge (electrical output) from the system occurs landward of the shoreline Because this model is reasonably analogous to th flow system of the Long Island ground-water reservoir the results suggest that some discharge mechanism ma also be acting in this area in the prototype. On Long Island this discharge mechanism is largely associated with the flowing parts of the streams.

Seepage of ground water to the streams is a majo factor in modifying the two-dimensional flow patter in the shallow part of the ground-water reservoi in figure 17. East-west flow components that ar perpendicular to the idealized flow section in figure 17 are clearly indicated in figure 18, which is a water-table contour map of the southeastern part o Nassau County. North of the flowing parts of th

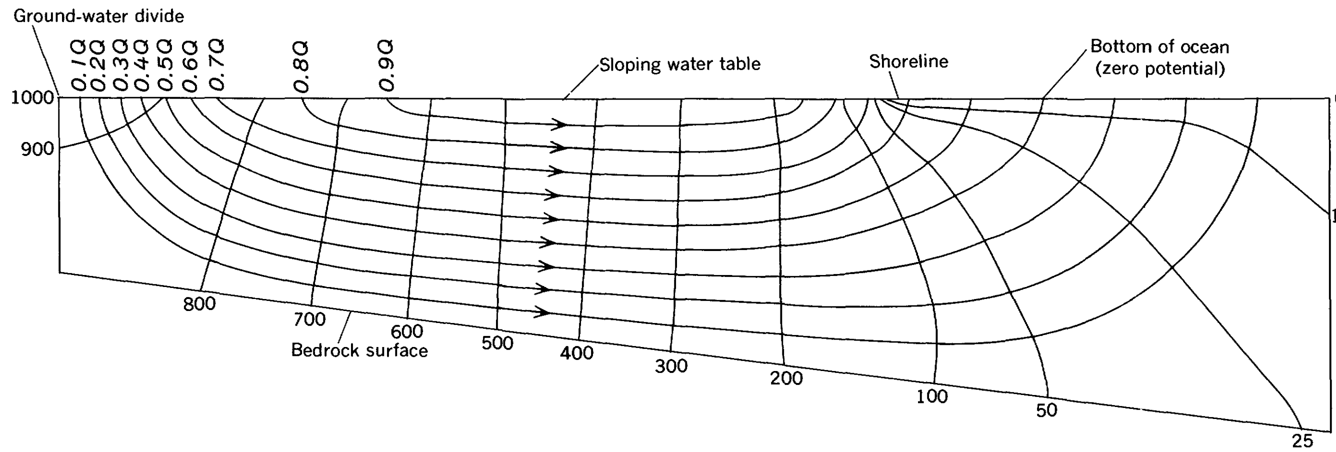


FIGURE 17.—Idealized cross section showing potential and flow lines in part of a homogeneous ground-water reservoir. Q is total discharge through system.

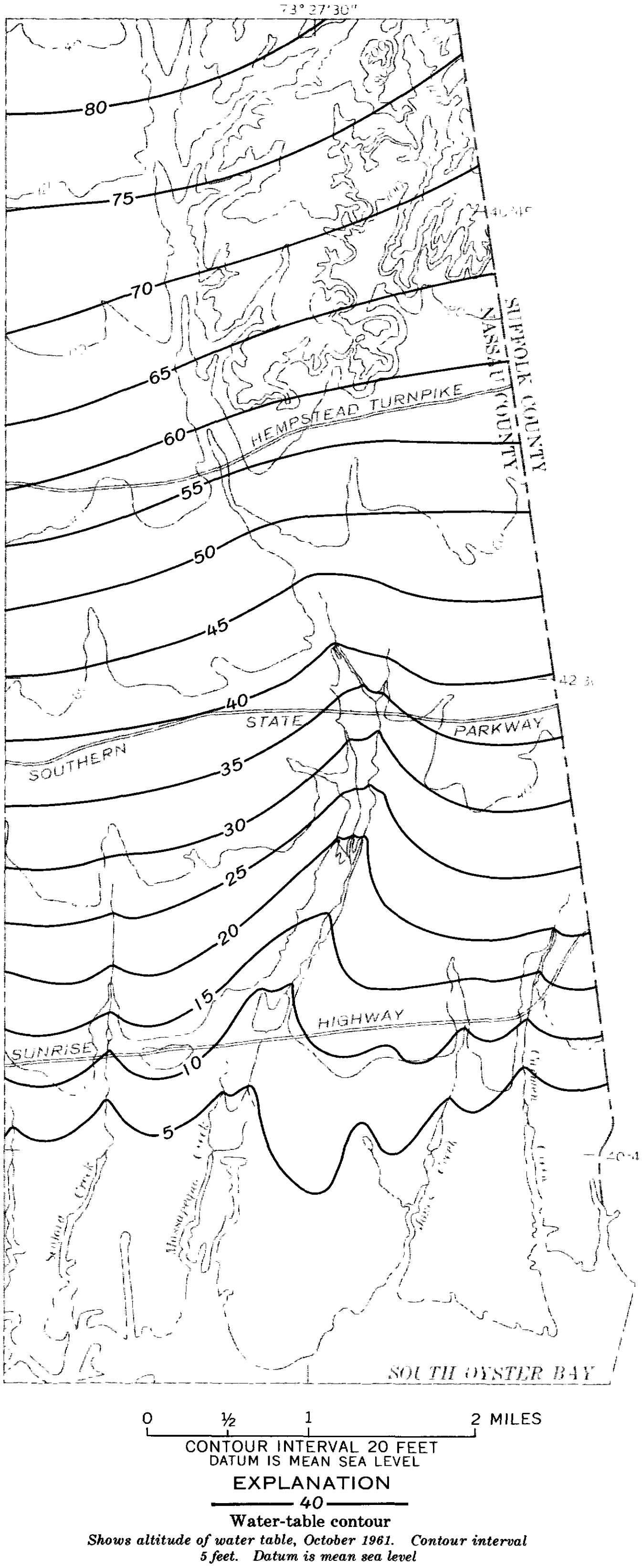


FIGURE 18.—Water-table contours near Massapequa Creek in October 1961.

streams, the water-table contours show relatively even and slight curvatures. In the neighborhood of their flowing parts, however, the water-table contours are bent sharply towards the streams, which clearly indicates that ground water discharges into them.

The ground-water system on Long Island can be divided into two general subsystems—a shallow circulating subsystem and a deep circulating subsystem. Ground water in the shallow subsystem, which is particularly well developed south of the main water-table divide, discharges mainly into the streams; ground water in the deep subsystem discharges into the bays, the Atlantic Ocean, and Long Island Sound. Flow paths in the deep subsystem range in length from one to several miles, and the flow is generally two dimensional (fig. 19). On the other hand, flow paths in the shallow subsystem range from a few feet to several thousand feet, and the flow is generally three dimensional.

Representative geohydrologic sections of the natural flow system in the northern and southern parts of Long Island are shown in figures 20 and 21, respectively. These sections show some of the principal geologic features of the ground-water reservoir that are responsible for modifying the idealized flow pattern shown in figure 17. The presence of almost horizontal and poorly permeable beds in the flow section tends to accentuate the horizontal components of flow, except near the ground-water divide and in discharge areas near the shorelines. Despite the obvious differences in detail, most of the major features of the flow pattern in figures 20 and 21 clearly are similar to those of the flow pattern in figure 17.

Profiles of heads in the major aquifers (fig. 22) show that a relatively small head difference occurs between the water table and the base of the Magothy aquifer as compared to the difference in head between the base of the Magothy aquifer and the Lloyd aquifer. This relatively large difference in head between the base of the Magothy aquifer and the Lloyd aquifer reflects the low hydraulic conductivity of the intervening Raritan clay, the principal confining layer of the Lloyd aquifer. Upward components of flow exist near the bottom of the Magothy aquifer seaward of the intersection of the piezometric surface at the bottom of the Magothy aquifer and the water table. Similarly, upward components of flow exist seaward of the intersection of the piezometric surface of the Lloyd aquifer and the piezometric surface at the bottom of the Magothy aquifer.

Another modification of the idealized flow pattern in figure 17 is caused by the salty ground water that

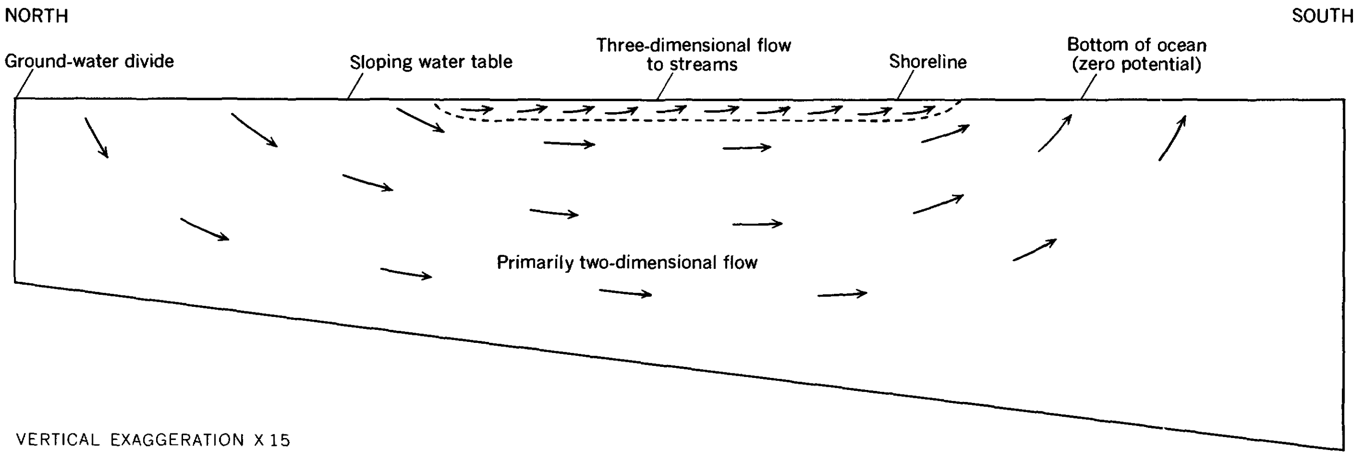
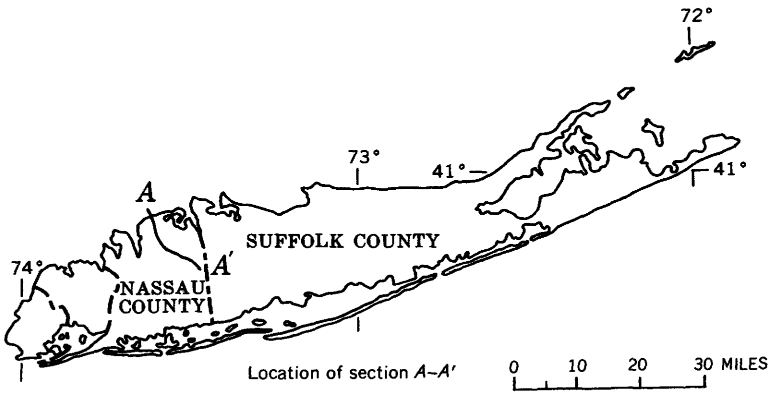


FIGURE 19.—Diagrammatic cross section of the southern half of the ground-water reservoir showing the part of the reservoir with primarily two-dimensional flow and the part of the reservoir with three-dimensional flow to streams.



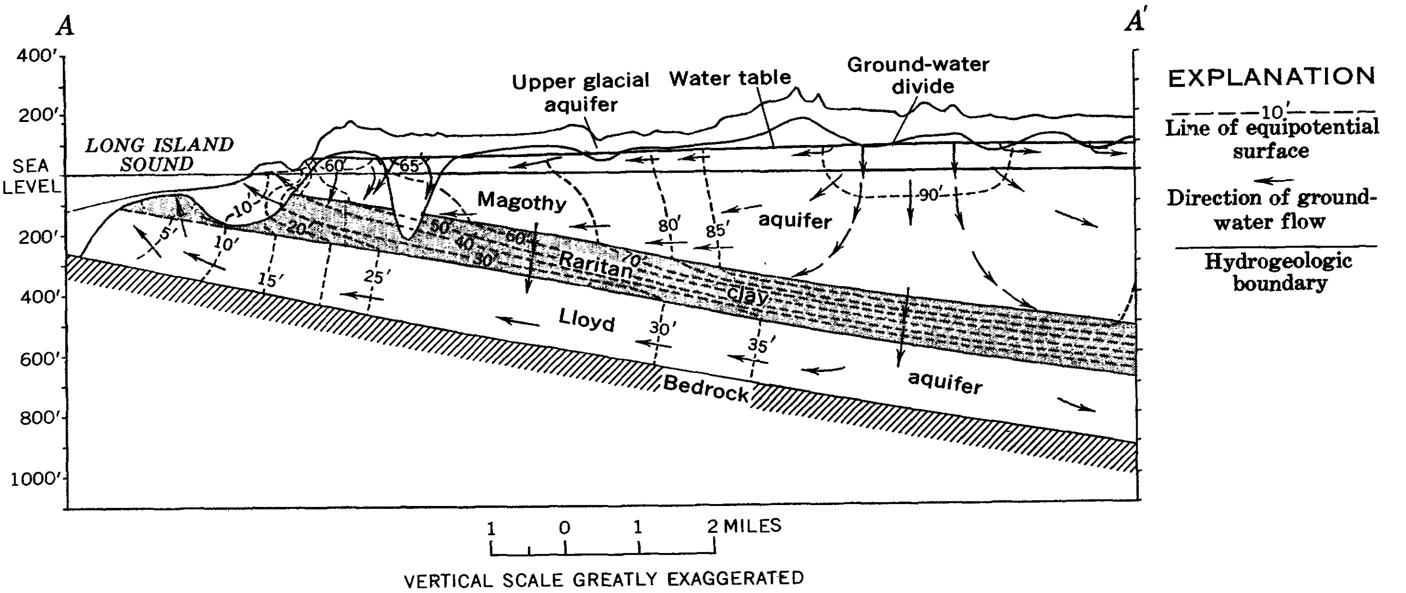


FIGURE 20.—Geohydrologic section of the ground-water reservoir in northeastern Nassau County in March 1961. Adapted from Isbister (1966, fig. 11).

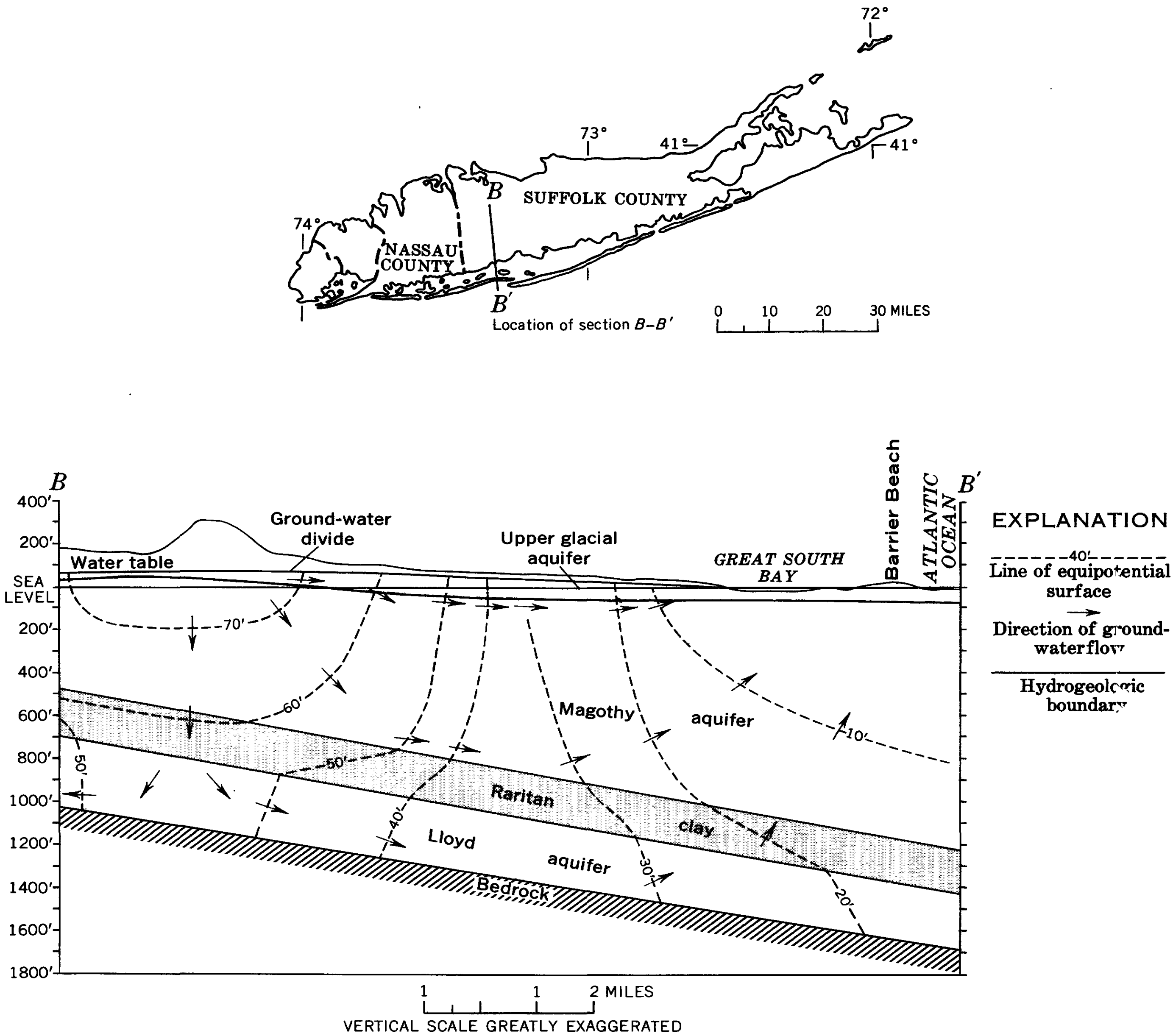


FIGURE 21.—Geohydrologic section of the ground-water reservoir in southwestern Suffolk County in October 1960. Adapted from Pluhowski and Kantrowitz (1964, fig. 13).

bounds the fresh ground-water reservoir of Long Island. The presence of the salty ground water results in several salt-fresh water interfaces at various depths in the Long Island ground-water reservoir. As stated previously, these interfaces are dynamic boundaries that change position in response to changes in head within the ground-water reservoir. The positions of these interfaces are undoubtedly at least partly related to the location of the relatively permeable and impermeable layers in the ground-water reservoir.

DISCHARGE FROM THE GROUND-WATER RESERVOIR

The main elements of discharge from the ground-water reservoir are seepage to streams and springs, ground-water evapotranspiration, and subsurface outflow (fig. 13).

STREAMFLOW AND SPRINGFLOW

Those aspects of streamflow that are emphasized in this report are the annual and daily streamflow from the water-budget area, streamflow in the near-

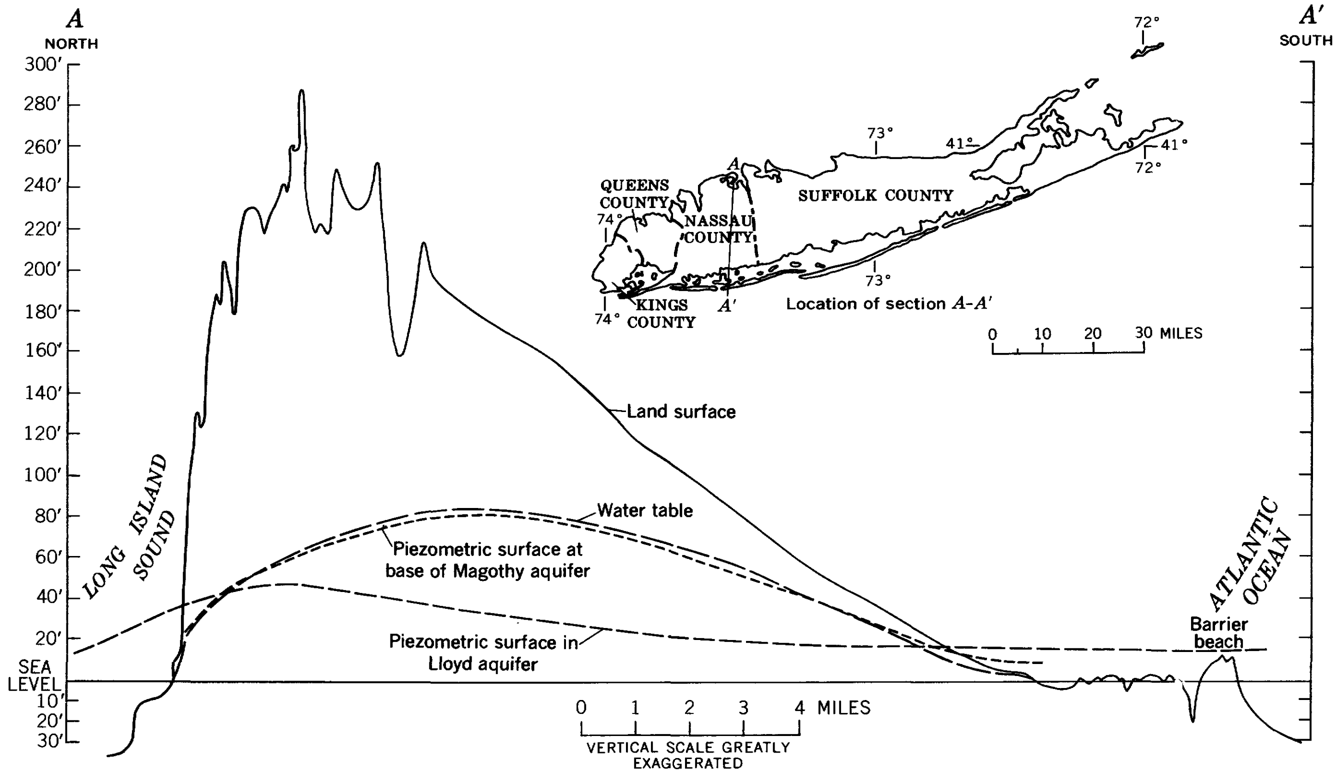


FIGURE 22.—Profiles of the water table and piezometric surfaces at the base of the Magothy aquifer and in the Lloyd aquifer in 1963. Based on unpublished maps prepared by John Isbisher (written commun., 1966).

shore areas, and the relation between ground-water levels and streamflow. Unless otherwise stated, all values of streamflow are for total streamflow and, therefore, include direct runoff. Most of the information presented in this section is derived from a summary of streamflow on Long Island by Vaupel and Spinello (written commun., 1968).

The average base flow of the streams (that is, seepage from the ground-water reservoir) is about 90–95 pecent of total average steamflow at present (1968). The percentage of total average streamflow that is direct runoff presently is somewhat greater than the estimate for natural conditions, because direct runoff to many streams has been materially increased by urban development. (See section on "Disposal of direct runoff to streams.")

In overall aspect, the present locations of Long Island's streams were determined mainly by the ancient drainage pattern that developed during the last ice age. Accordingly, most of the streams flow in broad, shallow valleys that were formed by the much larger streams that existed during melting of the ice sheet. All the southward-flowing streams have gentle gradients that, throughout most of their reaches, average about 10 feet per mile. The northward-flowing streams, especially in the western half of the island, generally have steeper gradients that average about 20–40 feet per mile. The lengths of these streams (distance from gaging station to start of flow along the main channel) range from less than 1 mile to somewhat less than 10 miles (fig. 3). In addition, all the streams are estuarine in their lower reaches.

The names, surface drainage areas and average flows at the gaging stations of the 19 continuously gaged streams in the water-budget area for the period water years 1940–65 are given in table 8. The gaging stations of these streams were established at points sufficiently upstream from the ocean, bays, and Long Island Sound so that the records would not be affected by tidal fluctuations. The data obtained at these stations, therefore, are not indicative of the total flow of these streams.

The average flows given in table 8 range from less than 5 cfs to slightly more than 40 cfs, and the total average discharge of the 19 streams is about 300 cfs. Moreover, the data in table 8 indicate that there is a very poor correlation between the surface drainage areas of the streams and their average flows.

The average annual discharge of all measured streams (continuously gaged and miscellaneous measuring sites) in the water-budget area for the period 1940–65 was about 475 cfs. A graph of the recurrence

TABLE 8.—*Surface drainage areas and average flows of the 19 continuously gaged streams in the water-budget area of Long Island, N.Y., water years 1940–1965*

Identification number of streamflow measuring station	Name of stream	Surface drainage area (square miles)	Average flow (cubic feet per second)
1-3025	Cedar Swamp Creek	11	7.2
3030	Mill Neck Creek	12	9.5
3035	Cold Spring Brook	7	4.6
3040	Nissequogue River	27	42.2
3045	Peconic River	75	35.5
3050	Carmans River	71	24.2
3055	Swan River	9	13.0
3060	Patchogue Creek	14	21.2
3065	Connetquot River	24	39.4
3070	Champlin Creek	7	7.5
3075	Penataquit Creek	5	6.2
3080	Sampawams Creek	23	9.8
3085	Carlls River	35	27.7
3090	Santapogue River	7	4.6
3095	Massapequa Creek	38	11.9
3100	Bellmore Creek	17	11.2
3105	East Meadow Brook	31	17.5
3110	Pines Brook	10	5.1
3115	Valley Stream	4	4.8

interval for annual average discharge of all measured streams from the water-budget area based on the period 1940–65 (fig. 23) indicates that the annual average discharge of all measured streams has varied from about 300 cfs to somewhat more than 600 cfs during this period. This variation in annual streamflow by a factor of about 2 over a period of more than 25 years is small compared to corresponding variations in the annual flow of streams in other areas of the humid Northeastern United States.

On the average, an estimated additional 25–50 cfs is discharged from the water-budget area in small unmeasured streams and springs. Thus, the estimated total average discharge of streams and springs from the water-budget area was about 500–525 cfs, or about 340 mgd (million gallons per day) for the 26-year period 1940–65. Of this total, about 50 mgd discharged from the northern part of the water-budget area and 290 mgd from the southern part of the water-budget area, which includes streamflow discharging into Peconic Bay from the water-budget area.

As shown in figure 24, the median of the average daily measured flows from the water-budget area for the period 1940–65 was about 440 cfs, which was slightly less than the average daily flow for this period. Furthermore, the average daily flow ranged from about 250 cfs to more than 1,000 cfs, which was considerably greater than the range in annual average flows.

A large amount of additional water undoubtedly seeps from the ground-water reservoir into the lower tidal reaches of the streams in the nearshore areas—particularly the southern nearshore area. Most of this water is derived from precipitation that recharges the ground-water reservoir in the nearshore areas—that is, it is not part of the deep circulating ground-water subsystem. The estimated average amount of this additional unmeasured streamflow is on the order of 40–80 mgd for the southern nearshore area and 10–15 mgd for the northern nearshore area. These very approximate estimates were developed as follows: The area of the "southern nearshore area" is about 80 square miles. If the average recharge rate in this area is about 1 mgd per sq mi (see section on "Summary of relations

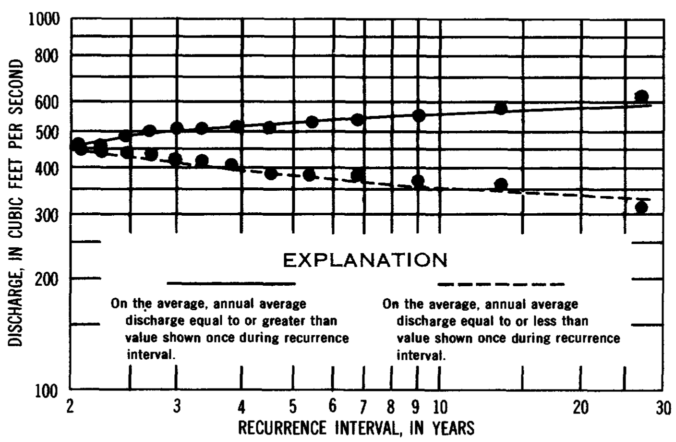


FIGURE 23.—Magnitude and frequency of annual average discharge of streams from the water-budget area D. E. Vaupel and A. G. Spinello (written commun., 1968).

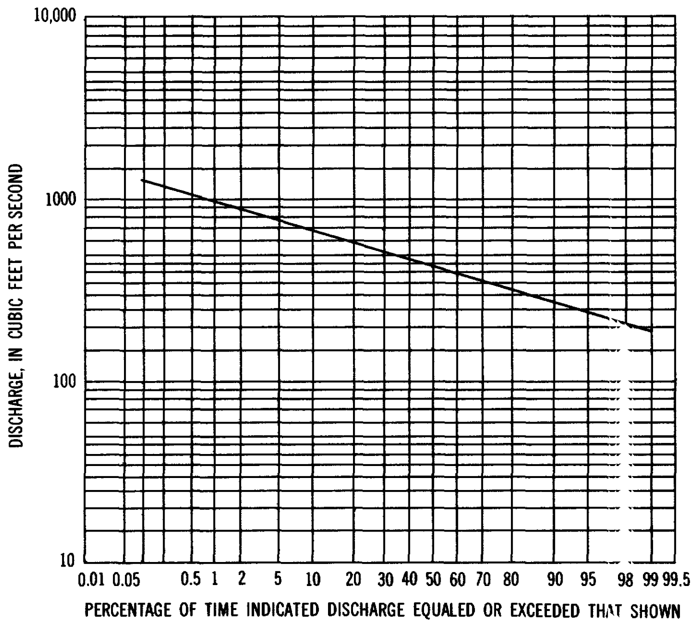


FIGURE 24.—Estimated duration curve of daily streamflow from the water-budget area. D. E. Vaupel and A. G. Spinello (written commun., 1968).

between components of the hydrologic system") and if all the recharge ultimately discharged into nearby tidal reaches of the streams, the resulting average increase in flow in tidal reaches of streams in the "southern nearshore area" would be about 80 mgd. However, a considerable amount of ground water probably is discharged by evapotranspiration (see next section of report) in this area because of the shallow depth to ground water and the high density of vegetation associated with the many swampy areas. Moreover, the average percentage of direct runoff in this area may be higher than the percentage in the water-budget area. Accordingly, an 80 mgd increase in streamflow is considered to be an upper limit, and the correct value is believed to lie between 40 and 80 mgd. The same lines of reasoning were applied to develop estimates of the increase in streamflow in the "northern nearshore area."

The close relation between streamflow and water levels in nearby water-table wells is shown in figures 25–27. The good correlation between the two hydrographs in figure 25 is evident. In figure 26 both sets of data from figure 25 were averaged for each month, which resulted again in two curves of very similar shape. Finally, the relation between the average monthly water-level data and the streamflow data in figure 26 is shown in figure 27. A straight line of best fit was estimated for the points representing October through March, which show an approximately linear relationship between stream discharge and ground-water-level altitude. The obviously different relationship between the two variables during the

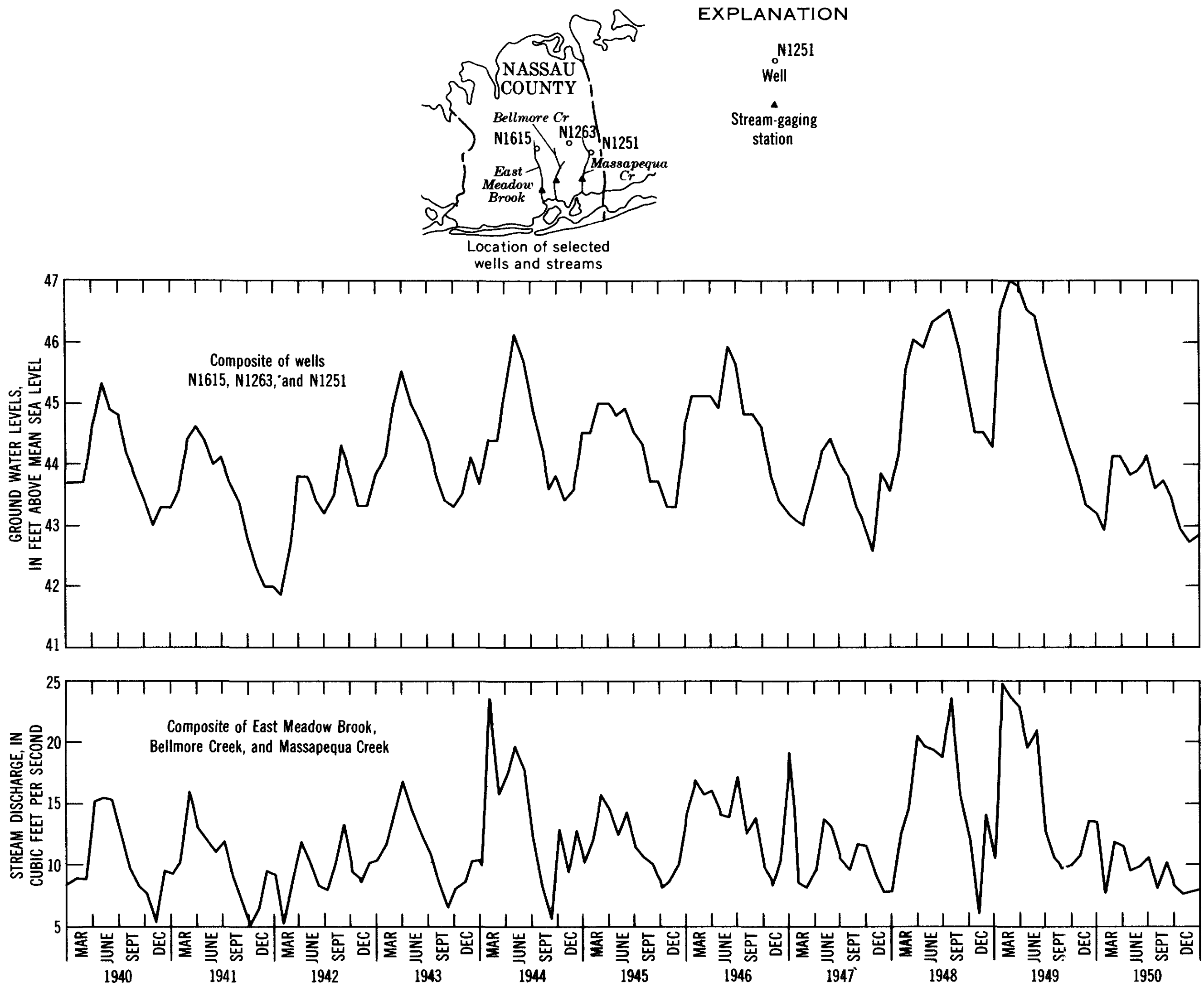


FIGURE 25.—Composite average monthly ground-water levels in selected wells and composite average monthly discharge of selected streams in Nassau County for the period 1940–50.

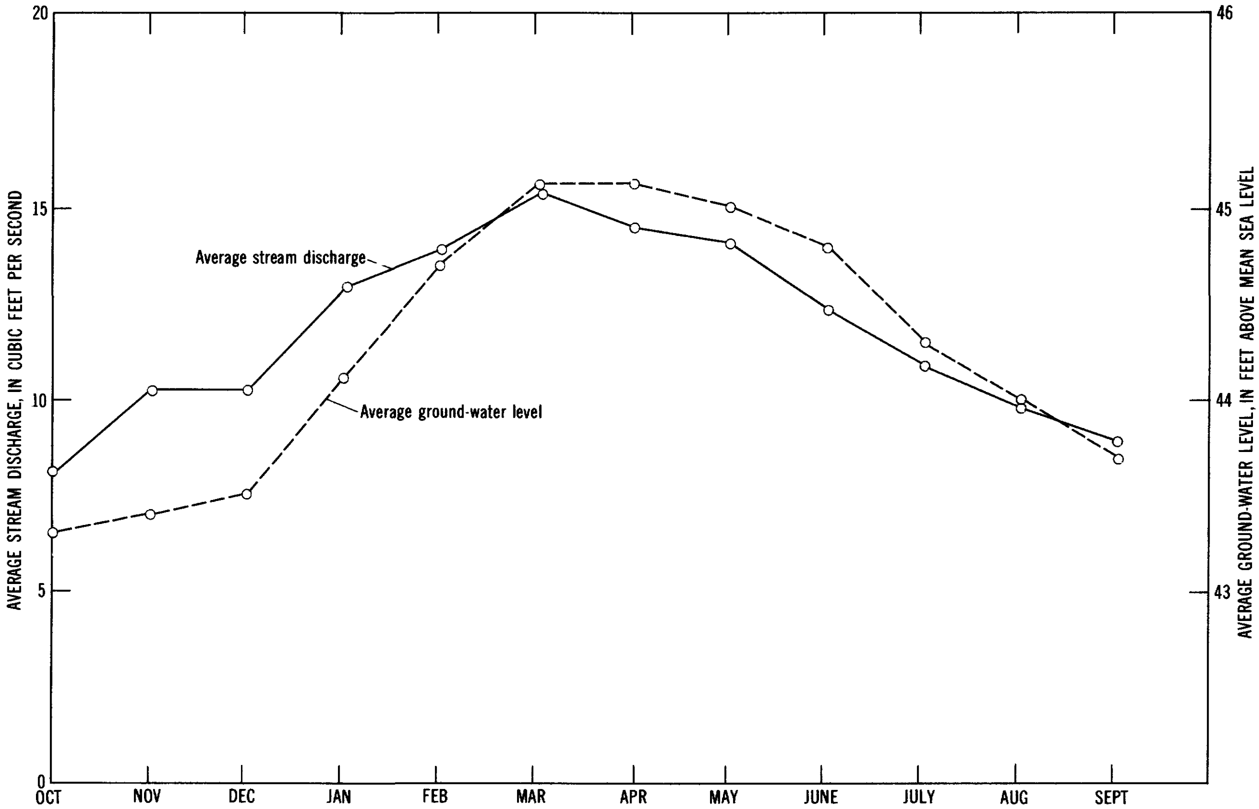


FIGURE 26.—Average monthly discharge of selected streams and average monthly ground-water levels in selected wells in Nassau County for the period 1940–50.

summer months (April–September) is undoubtedly due in part to ground-water evapotranspiration. (See next section of report.)

The regular seasonal variation in ground-water levels and streamflow, which is primarily the result of a seasonal variation in total evapotranspiration and ground-water recharge, is also shown in figures 25 and 26. In figure 26, ground-water levels and streamflow reach their maximums on the average in March or April and their minimums in September or October. The ratio of the maximum to minimum average monthly flows in figure 26 is slightly less than 2 to 1. Although this ratio varies from about 1.2 to 2 for individual streams on Long Island, this variation is small in comparison with many streams elsewhere and reflects the close relationship between the streams and the ground-water reservoir.

GROUND-WATER EVAPOTRANSPIRATION

The separation between the summer and winter recession curves for Carmans River (fig. 28) indicates that some factor that is not operative during the winter months reduces streamflow during the summer months or during periods without precipitation. In an unregulated stream under natural conditions such as Carmans River in the summer months, this factor probably is evapotranspiration of shallow ground water and evapotranspiration of soil moisture which, in turn, results in decreased recharge. In the absence of active evapotranspiration, this ground water would have seeped into the stream channel and increased streamflow. The separation between recession curves of other streams on Long Island (developed by D. E. Vaupel and A. G. Spinello, written commun., 1968) varies widely—some pairs of curves show more separation than Carmans River, and some show virtually no separation. The amount of separation in these curves seems to correlate very roughly with the size of the area adjacent to the stream whose altitude is almost the same as the stream and which is occupied by vegetation.

Pluhowski and Kantrowitz (1964) estimated the quantity of ground-water evapotranspiration in southwestern Suffolk County from observations of daily cyclic fluctuations in ground-water levels of a shallow well during the summer months. The well was located near Sampawams Creek in an area where the depth to ground water was less than 5 feet. From a hydro-

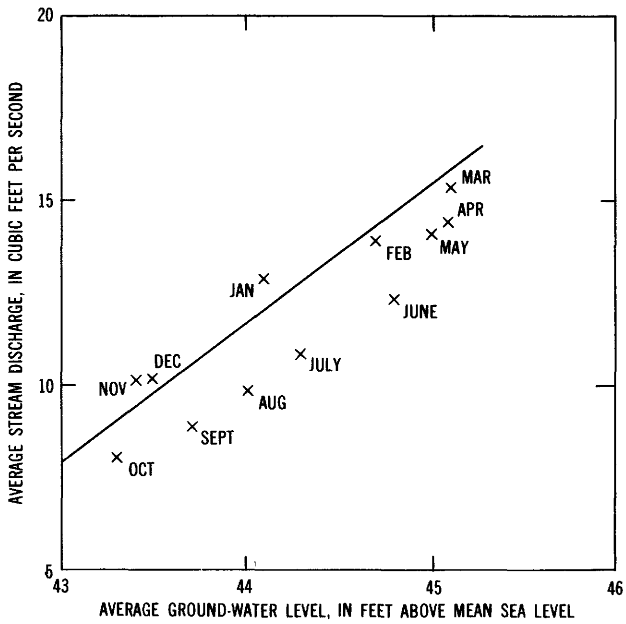


Figure 27.—Relation between average monthly discharge of selected streams and average monthly ground-water levels in selected wells in Nassau County for the period 1940–50.

graph of this well and a knowledge of the area in which the depth to ground water was less than 5 feet (about 30 sq mi), they estimated that the average ground-water evapotranspiration within their study area was about 11 mgd.

The depth to the water table is less than 10 feet in about 50 square miles and less than 5 feet in an estimated 30 square miles of the water-budget area. According to the previous estimate, therefore, the estimated average ground-water evapotranspiration from the water-budget area is on the order of 10–15 mgd. Most of the ground-water evapotranspiration on Long Island occurs in the low-lying nearshore areas north and south of the water-budget area—particularly south. No data are presently available to estimate the quantity of water consumed by ground-water evapotranspiration in these areas.

SUBSURFACE OUTFLOW OF GROUND WATER

Subsurface outflow of ground water is the second largest element of discharge from the water-budget area. To help estimate subsurface outflow, maps showing the transmissivity of the principal aquifers of Long Island (fig. 29) were developed in a report by McClymonds and Franke (1971). The Jameco aquifer was not included in figure 29 because it occurs, except for a small area in southwestern Nassau County, outside the water-budget area.

As the starting point in their investigation, McClymonds and Franke estimated the average hydraulic conductivity of the deposits opposite the screened interval of more than 2,000 wells by calculating modified specific-capacity numbers for each well, Q/sL, which is the specific capacity of the well (Q/s, or well discharge divided by drawdown in the well) divided by the screen length (L). The distribution of Q/sL numbers for the principal aquifers of Long Island (fig. 30) clearly differentiates the ability of the screened intervals in the three principal aquifers to transmit water to the wells. The estimated median hydraulic conductivities of the screened intervals in the wells from which data were used to construct the curves in figure 30 are 2,500, 1,000, and 600 gallons per day per square foot in the upper glacial, Magothy, and Lloyd aquifers, respectively.

By correlating the Q/sL numbers with the various observed lithologies in the screened intervals of many wells, estimated values of average hydraulic conductivity were assigned to each lithology in each aquifer. These average hydraulic conductivity values were then applied to each layer in the entire aquifer for individual wells, and the average hydraulic conductivity of the material penetrated by each well for which logs were available was computed. Although considerable variation was found between estimates of average hydraulic conductivity in nearby wells, a reasonable regional pattern of average hydraulic conductivity could be mapped where, on the average, one or more data points were available for every

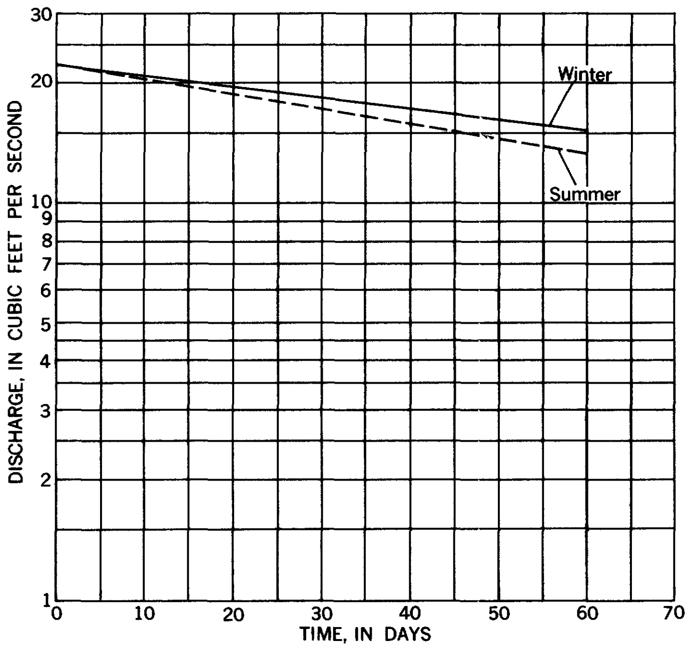


Figure 28.—Summer and winter recession curves for Carmans River. D. E. Vaupel and A. G. Spinello (written commun., 1968).

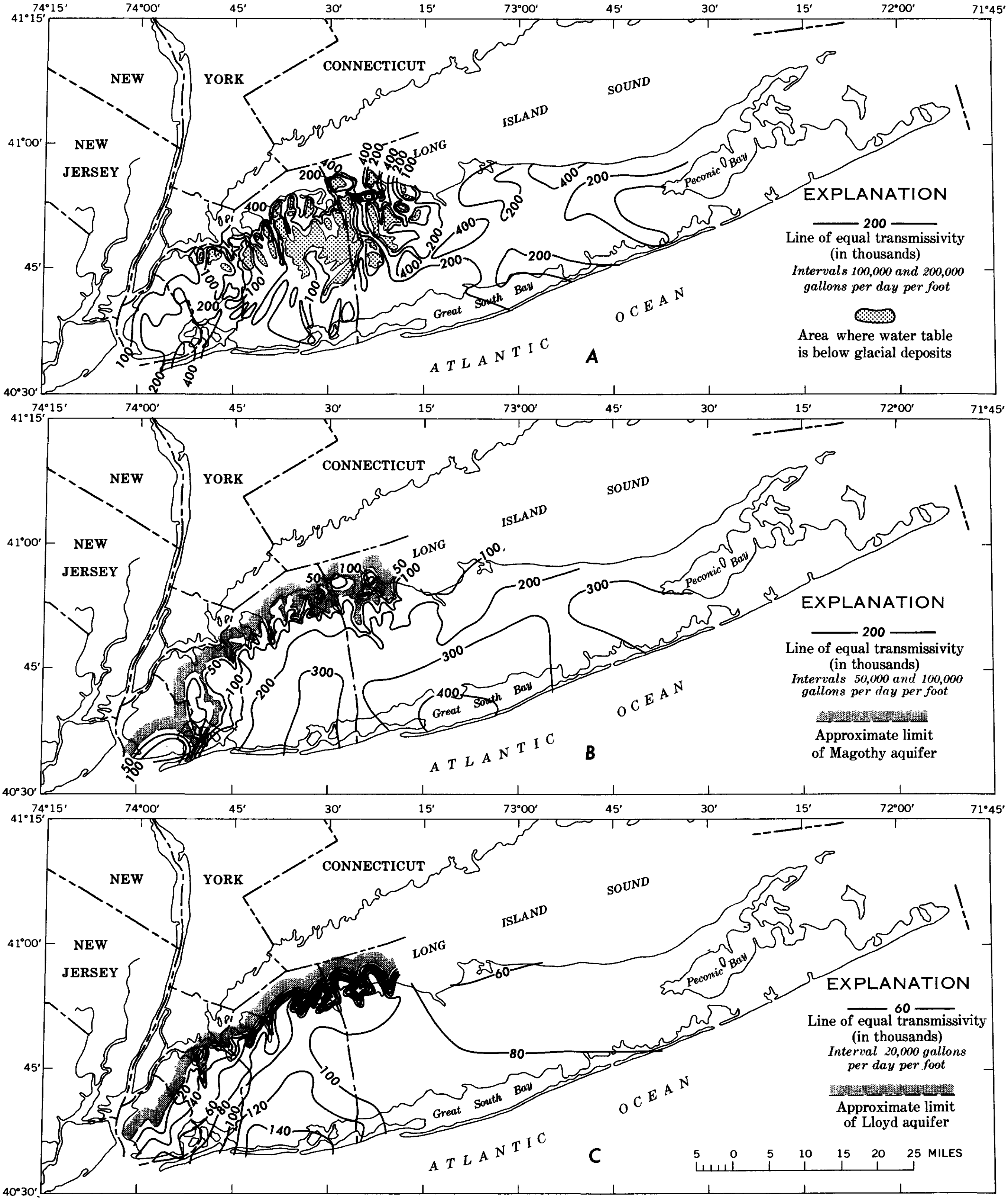


FIGURE 29.—Estimated transmissivity of (*A*) upper glacial aquifer, (*B*) Magothy aquifer, and (*C*) Lloyd aquifer. After McClymonds and Franke (1971). Transmissivity lines on these maps were developed by combining data from aquifer-thickness maps and maps of average hydraulic conductivity for the respective aquifers. (See McClymonds and Franke, 1971.) The high degree of detail shown for the transmissivity lines is not meant to imply a high degree of accuracy for transmissivity at any specific location. Rather, it largely reflects a fairly high degree of accuracy in the information shown on the aquifer-thickness maps and only a moderate degree of accuracy in the information shown on the maps of average hydraulic conductivity.

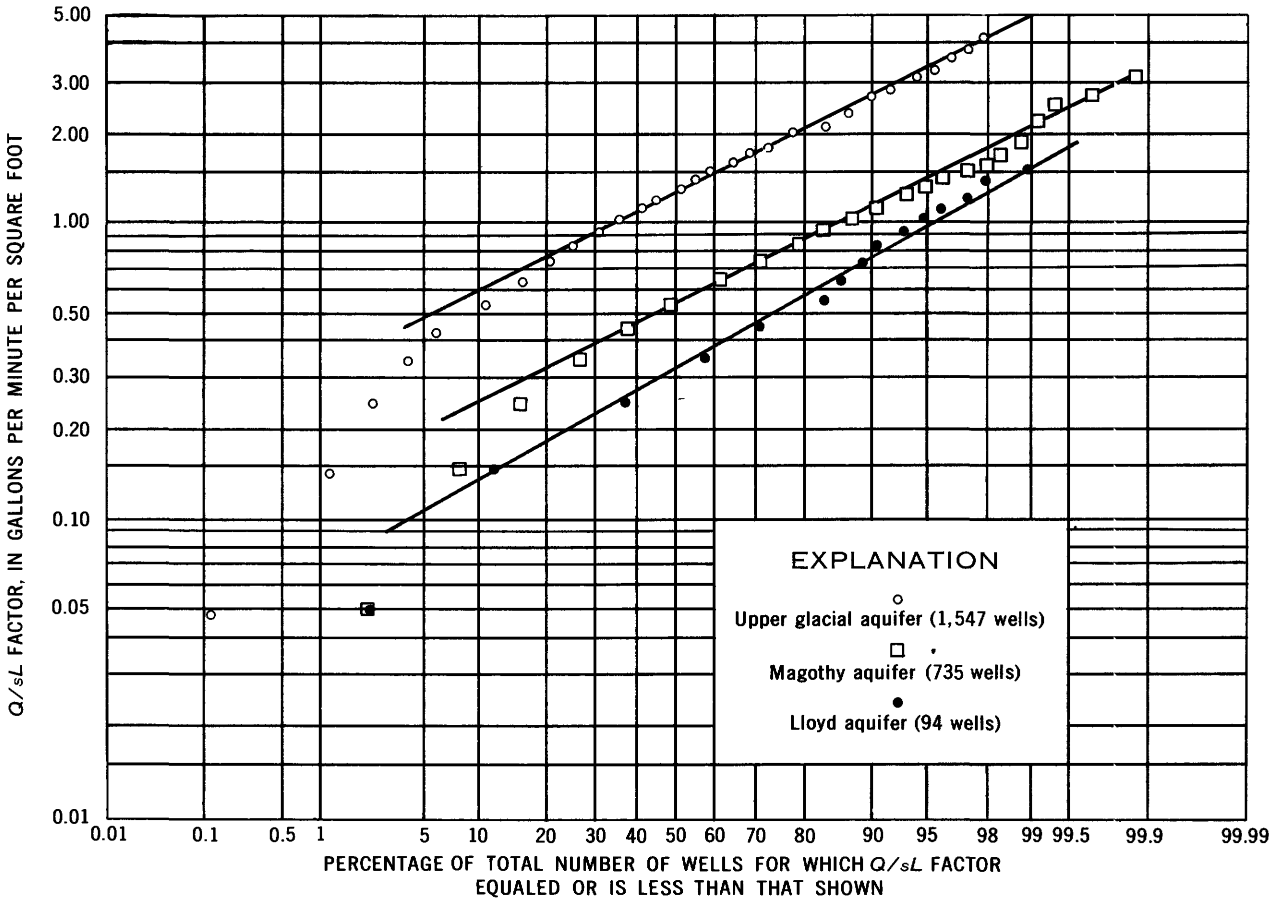


FIGURE 30.—Relation between a modified specific capacity factor (Q/sL) and percentage of total number of wells for the principal aquifers of Long Island, N.Y. After McClymonds and Franke (1971).

2 or 3 square miles. Average-hydraulic conductivity maps were prepared for each aquifer in the manner described above. The average-hydraulic conductivity maps and thickness maps of each aquifer were used to construct the transmissivity maps in figure 29. Average values of thickness, hydraulic conductivity, and transmissivity of the principal aquifers in the water-budget area, which were derived from figure 29 and from additional maps in the report by McClymonds and Franke, are given in table 9.

Estimated rates of subsurface outflow from the water-budget area and for each aquifer are given in

TABLE 9.—*Average transmissivity of the principal aquifers for the water-budget area, Long Island, N.Y.*

Aquifer	Average thickness (feet)	Average hydraulic conductivity (gallons per day per square foot)	Average transmissivity (gallons per day per foot)
Upper glacial	120	1, 800	210, 000
Magothy	620	400	250, 000
Lloyd	350	250	85, 000

table 10. These estimates were computed by applying Darcy's law, $Q=TIL$, to appropriate parts of each aquifer and by summing the flow from each part. In this formula, Q is the flow of ground water, in gallons per day; T is the transmissivity, in gallons per day per foot; I is the hydraulic gradient, in feet per foot; and L is the width, in feet, of the cross section through which the flow occurs. Appropriate T values were obtained from figure 29, and approximate values of the hydraulic gradient I were obtained from water-level contour maps.

Estimating the quantity of subsurface outflow from the upper glacial aquifer presented special difficulties because much of the water in the upper part of this aquifer discharges into streams. Thus, for the purpose of calculating subsurface outflow, it was assumed that ground water in the upper 40–50 feet of the upper glacial aquifer discharged to streams (see previous discussion on movement through the ground-water reservoir), and calculations of underflow were made only for the material below the upper 40–50 feet. In addition, the estimates of subsurface outflow from the northern part of the water-budget area were somewhat less certain than those from the southern part because water-level gradients are steeper and subject to wider variation along the north shore compared to the south shore, which makes the selection of average gradients subject to greater error.

TABLE 10.—*Estimated average subsurface outflow of ground water from the principal aquifers and total average subsurface outflow from the northern part, the southern part, and the entire water-budget area of Long Island, N.Y.*

[In millions of gallons per day]

Aquifer	Water-budget area, average subsurface outflow from—		
	Northern part	Southern part	Entire area
Upper glacial	130	40	170
Magothy	120	120	240
Lloyd	20	20	40
Total	270	180	450

Because of possible errors in the estimates of transmissivity and in the selection of average water-level gradients, the possible error in the estimated total subsurface outflow from the water-budget area in table 10 is probably on the order of plus or minus 25 percent. The possible error in the estimate of subsurface outflow from the northern part of the water-budget area and from the individual aquifers may be even larger.

SUMMARY OF RELATIONS BETWEEN COMPONENTS OF THE HYDROLOGIC SYSTEM

Water budgets for the northern and southern parts of the water-budget area and for the entire water-budget area are given in table 11. The values in table 11 are averages, and can be considered valid for the 26-year period water years 1940–65, although not all these averages have been calculated or estimated for exactly this period in this report. Although the amount of fresh ground water in storage locally in the water-budget area has decreased markedly in this period, the average decrease in storage is small. Moreover, in comparison with the total inflow and outflow, the decrease in storage is insignificant and, therefore, is disregarded in the water-budget analysis. If the additional simplifying assumption is made that, during the index period (water years 1940–65), changes in natural ground-water recharge and discharge were roughly compensated for by artificial recharge and discharge, the values in table 11 provide reasonable estimates for water-budget components in the water-budget area under natural conditions.

The most reliable estimates in table 11 are for precipitation and streamflow. The possible error in the budget figures for precipitation is probably not greater than 5–10 percent. The possible error in the estimates of average streamflow, on the other hand, is probably on the order of about plus or minus 15 percent. This possible error is primarily due to the uncertainty in estimating the flow of the ungaged streams from several miscellaneous measurements each year.

An indirect estimate of ground-water recharge under natural conditions can be developed from the data in table 11 if it is assumed that average annual ground-water recharge and discharge were approximately equal for the budget period 1940–65. Accordingly, the estimated average annual natural recharge is equal to the estimated average annual natural discharge—about 800 mgd (table 11). This value is equal to about 1.05 mgd of recharge per square mile for the water-budget area. This figure is very close to previous indirect estimates for average recharge of about 1 mgd per sq mi (Pluhowski and Kantrowitz, 1964, p. 38; Swarzenski, 1963, p. 35).

A comparison of the figures in table 11 shows a marked difference in the ratio of streamflow and subsurface outflow to precipitation in the two parts of the water-budget area. In the southern part, about 30 percent of total precipitation discharges as stream-

TABLE 11.—*Water budgets of the northern and southern parts of the water-budget area and the entire water-budget area of Long Island, N.Y., water years 1940–65* [1]

[In millions of gallons per day]

Type of water-budget element	No.	Water-budget element	Water-budget area		
			Northern part	Southern part	Entire
Inflow	1	Precipitation	650	950	1,600
Internal distribution.	2	Direct runoff	5	15	20
	3	Ground-water recharge [2]	320	465	785
	4	Ground-water discharge to streams.[3]	45	275	320
Outflow	5	Evapotranspiration of precipitation.[4]	325	470	795
	6	Subsurface outflow of ground water.	270	180	450
	7	Streamflow discharging to salt water.	50	290	340
	8	Evapotranspiration of ground water.[5]	5	10	15

[1] The quantities in this table were derived with the assumption that no significant change in ground-water storage occurred in the water-budget area during the period, water years 1940–65. Independent quantitative estimates were made for all components in the table unless otherwise noted. None of the values in this table are accurate to more than 2 significant figures, and many values are accurate to less. (See text discussion.) Where more than 2 significant figures are shown, the entry was derived from other entries in the table, and an additional significant figure was retained to balance inflow and outflow. (See footnotes below.)

[2] The estimate of ground-water recharge was obtained by adding components 4, 6, and 8.

[3] The estimate of ground-water discharge to streams was obtained by subtracting component 2 from component 7.

[4] The estimate of evapotranspiration of precipitation was obtained by adding components 6, 7, and 8 and subtracting the total from component 1. Therefore, the subtotal of components 5, 6, 7, and 8 (total outflow) equals component 1 (total inflow).

[5] These values may be in error by as much as 100 percent or more. Values are included mainly to indicate order of magnitude.

flow and 15 percent as subsurface outflow of ground water. The corresponding values for the northern part are about 10 and 35 percent, respectively. As discussed previously, estimates of subsurface outflow may be significantly in error, particularly the estimate from the northern part of the water-budget area. This large possible error may hide real differences in evapotranspiration and recharge in the two parts of the water-budget area, which might be caused by lower infiltration capacities in the surficial soils and greater evapotranspiration in the northern part compared to the southern part of the water-budget area. Unfortunately, however, presently available information is inadequate to evaluate this possibility.

WATER QUALITY

The general paths followed by liquid water through the hydrologic system of Long Island under natural conditions and related water-quality features are shown schematically in figure 31. As air moved across the bodies of salty water bordering Long Island, it picked up small quantities of salts from the ocean spray (fig. 31, item 1). Some of these substances were dissolved in the precipitation that fell on the island

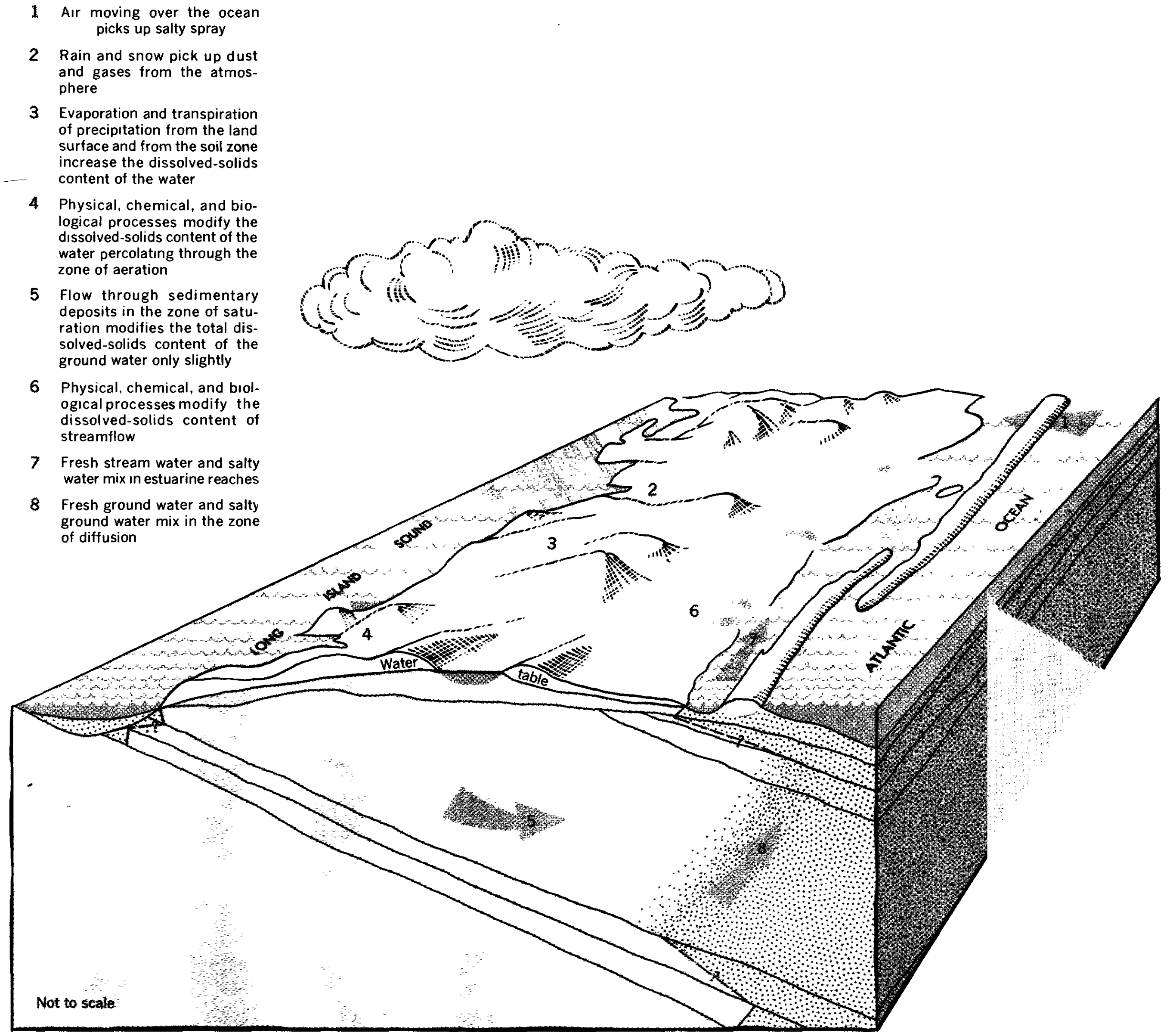


FIGURE 31.—Changes in the chemical quality of the water under natural conditions. After Cohen, Franke, and Foxworthy (1968, pl. 5A).

along with particles of dust and gases from the atmosphere (item 2).

Evaporation from the land surface and the soil zone, and transpiration by plants, increased the dissolved-solids content of the precipitation after it reached the ground (item 3). As the water that originated as precipitation moved through the uppermost part of the zone of aeration (item 4), it came into contact with, and partly dissolved, compounds that were formed in the biologically and chemically active soil zone. After passing through the soil zone, the water continued, but at a slower rate, to dissolve additional substances from the remainder of the less chemically active zone of aeration.

Most of the materials in the zone of saturation on Long Island are only slightly soluble in water. Accordingly, the dissolved-solids content of the ground water generally increased only slightly as it moved through this zone (item 5).

Some of the ground water ultimately discharged into the streams where it mixed with direct runoff. The dissolved-solids content of the water flowing in the streams increased, owing to biological activity and the solution of substances in the stream channels (item 6). The stream water underwent a marked further increase in dissolved-solids content (from less than 50 mg/l to hundreds and thousands of milligrams per liter) as the fresh water discharged into, and mixed with, the salty water in the estuarine reaches of the streams (item 7). Similarly, the dissolved-solids content of the ground water increased markedly (to thousands of milligrams per liter) as the fresh ground water mixed with salty ground water in the zone of diffusion (item 8).

Chemical analyses of waters representing various stages in the geochemical cycle shown in figure 31 are given in table 12. These analyses include one of precipitation (analysis 1), two each of samples from the three major aquifers (analyses 2–7), two of ground water near the fresh-salt water interface (analyses 8, 9), two of streams (analyses 10, 11), and two of lakes (analyses 12, 13). The salient features of the analyses in table 12 are summarized as follows:

1. The natural fresh water of Long Island had a remarkably low dissolved-solids content, which was always less than 50 mg/l and in some cases was as little as 20 mg/l.
2. Because the deposits of the Long Island ground-water reservoir were relatively inert chemically, the dissolved-solids content of the ground water changed very little as it moved through the reservoir.
3. Some of the fresh ground water (analyses 3, 4, 6, 7) had a high iron content, which was considerably above the 0.3 mg/l limit recommended for public-supply use (U.S. Public Health Service, 1962, p. 7). The source of the iron in the Magothy aquifer was probably pyrite nodules that occur locally.
4. The pH of Long Island ground water was generally low (commonly less than 6), which made the water very corrosive to metals.

Except for items 3 and 4, which may necessitate minor treatment of the water before use, the natural water of Long Island was suitable for most purposes.

Precipitation has the lowest dissolved-solids content (about 10 mg/l) of the analyses in table 12. Moreover, the surface-water samples have about the same dissolved-solids content as the ground water because most of the surface water is derived directly from the ground-water reservoir. The ground-water analyses in table 12 do not show a progressive increase in dissolved-solids content with increasing time of travel and length of flow path through the ground-water reservoir. On the contrary, the dissolved-solids content seems to decrease with depth, as shown, for example, by the analyses of water from the upper glacial aquifer and from the Magothy aquifer (table 12). Undoubtedly, at least a partial explanation of this apparent anomaly is that virtually no samples of completely uncontaminated water are available from the upper glacial aquifer. Furthermore, the data in table 12 represent a very limited sampling of water within the ground-water reservoir.

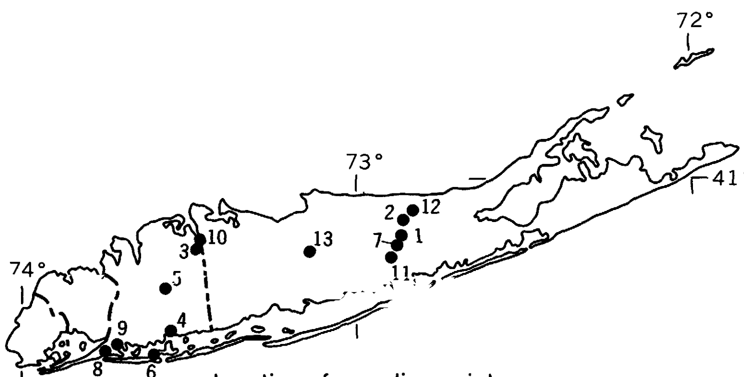
As noted in item 3 of figure 31, evapotranspiration increases the dissolved-solids content of the precipitation water as it moves through the upper part of the zone of aeration en route to the water table. Increases in the chloride content of the shallow ground water are almost entirely the result of this concentrating process because precipitation was virtually the only source of chloride in the waters of Long Island under natural conditions. Therefore, an indication of the ratio of precipitation to evapotranspiration is obtained by comparing the chloride content of rainfall and the shallow ground water. The chloride content of water from both these sources shows considerable variation in space and time. As is evident from analyses 1–3 in table 12, however, evapotranspiration has markedly increased the chloride content of water in the upper glacial aquifer compared to precipitation. These analyses indicate a ratio of precipitation to evapotranspiration ranging between approximately 2 to 1 and 1.5 to 1. This compares with a ratio of about 2 to 1

TABLE 12.—*Selected chemical analyses of natural* [1] *water on Long Island, N.Y.*

[Analyses made by U.S. Geological Survey and reported in milligrams per liter]

Sample	Source of water	Date collected	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Total dissolved solids (residue on evaporation at 180° C)	Specific conductance ($K\times10^6$)	pH	Temperature (° C)	Remarks
1	Precipitation				0.5	0.3	1.6	0.1	----------	3.8	2.7	--------	0.8	10	----------	4.5	----------	Average of 6 composite monthtly samples collected from rain gage a Brookhaven National Laboratory for the period Oct. 1965–Mar. 1966.
2	Ground water: Upper glacial aquifer (well S5518).	Oct. 15, 1948	6.0	0.01	1.5	1.3	3.2	.6	4	6.0	5.0	--------	.1	36	39	6.5	----------	Depth 54 ft; depth to water 32 ft; diameter 6 in. (De Laguna, 1964).
3	Upper glacial aquifer (well N1243).	Dec. 5, 1960	5.4	3.3	4.0	1.0	3.0	1.2	11	6.9	3.9	--------	1.9	35	56	6.1	14	Depth 16 ft; depth to water 6 ft. diameter 1¼ in.
4	Magothy aquifer (well N4149).	Sept. 30, 1953	6.5	.61	.5	.1	2.4	.3	3	1.6	2.5	--------	.1	15	22	5.8	13	Depth 500 ft; diameter 6 in.
5	Magothy aquifer (well N5655).	Mar. 26, 1957	7.5	.01	1.3	.1	2.7	.7	5	1.0	4.3	0.1	1.4	25	24	6.1	11	Depth 255 ft; diameter 12 in.
6	Lloyd aquifer (well N5227).	Nov. 14, 1961	--------	1.5	.9	.5	6.2	.5	4	14	2.0	--------	.1	36	50	5.3	----------	Depth 1,250 ft; diameter 8 in.
7	Lloyd aquifer (well S6409).	Nov. 8, 1948	7.5	1.3	1.5	1.6	4.4	2.2	16	3.5	4.1	.1	.1	32	50	6.4	----------	Sample from screen setting at 1,434 ft; diameter 8 in. (De Laguna, 1964).
8	Salty ground water: Magothy aquifer (well N4062).	Aug. 1, 1962	20	2.5	10	4.0	18	2.8	50	3.7	29	.1	.1	117	187	6.6	17	Depth 142 ft; diameter 4 in. (Luscyznski and Swarzenski, 1966).
9	Magothy aquifer (well N6707).	July 11, 1960	9.3	39	82	76	520	8.0	----------	76	1,150	.1	.4	2,180	3,760	4.4	16	Depth 506 ft; diameter 4 in. (Lusczynski and Swarzenski, 1966).
	Stream water:																	
10	Cold Spring Brook	May 6, 1966	--------	1.8	3.3	1.3	4.9	.5	14	3.2	7.2	.1	.8	37	56	6.8	14	Sample collected at gaging station; stream discharge 0.40 cfs.
11	Carmans River	Apr. 14, 1948	0	.03	5.2	2.1	4.8	.9	15	8.4	6.6	.0	2.2	49	72	6.5	----------	Sample collected at gaging station; estimated stream discharge 30 cfs (De Laguna, 1964).
12	Lake water: Lake Panamoka	Jan. 11, 1949	1.6	.01	1.9	1.0	3.8	1.3	5	5.6	5.4	.1	.2	24	46	6.5	----------	De Laguna (1964).
13	Lake Ronkonkoma	Apr. 29, 1948	1.5	.01	2.4	1.1	4.1	.8	5	8.2	5.8	.0	.5	28	47	7.1	----------	Do.

[1] The precipitation sample and the 2 samples of ground water from the upper glacial aquifer may be ghtly contaminated because of the activities of man. However, these samples are among the least contaminated that are presently available. See text for further discussion.



Location of sampling points

which was previously determined indirectly from the water-budget analysis.

HOW MAN HAS MODIFIED THE NATURAL HYDROLOGIC SYSTEM

The following discussion summarizes the effects of man's activities on the hydrologic system of Long Island. For the most part, the discussion is concerned with the effects of man's activities on the ground-water reservoir. An understanding of these effects provides valuable insight into the possible effects of future management alternatives on the hydrologic system.

In this section of the report the calendar year is generally used as the annual period of reference instead of the water year. In addition, succeeding quantitative estimates are generally made for all of Nassau and Suffolk Counties instead of only the water-budget area.

HISTORY AND PRESENT STAGE OF DEVELOPMENT

Ground-water development on Long Island has progressed through three major stages (Heath and others, 1966; Cohen and others, 1968). In the first stage of development, which began with the arrival of the first European settlers, almost every house had a shallow dug well from which water was withdrawn from the upper glacial deposits. Most of the domestic waste water was returned to the glacial deposits through individually owned cesspools. As the population increased, many individually owned wells were abandoned, and public-supply wells were installed in the upper glacial deposits; however, the disposal of waste water through individually owned cesspools continued. Although the quality of the water gradually deteriorated as a result of these practices, the amount of water permanently removed from the ground-water system (the "net withdrawal") was negligible.

Pollution of the shallow part of the ground-water reservoir by water from cesspools eventually forced the abandonment of many wells tapping the upper glacial deposits. In the second stage of development, these wells were replaced by deeper public-supply wells, mainly tapping the artesian Magothy and Jameco aquifers. Most of the domestic and industrial sewage, however, was still returned to the upper glacial deposits through cesspools and septic tanks. Accordingly, the net withdrawals from the entire ground-water reservoir remained negligible.

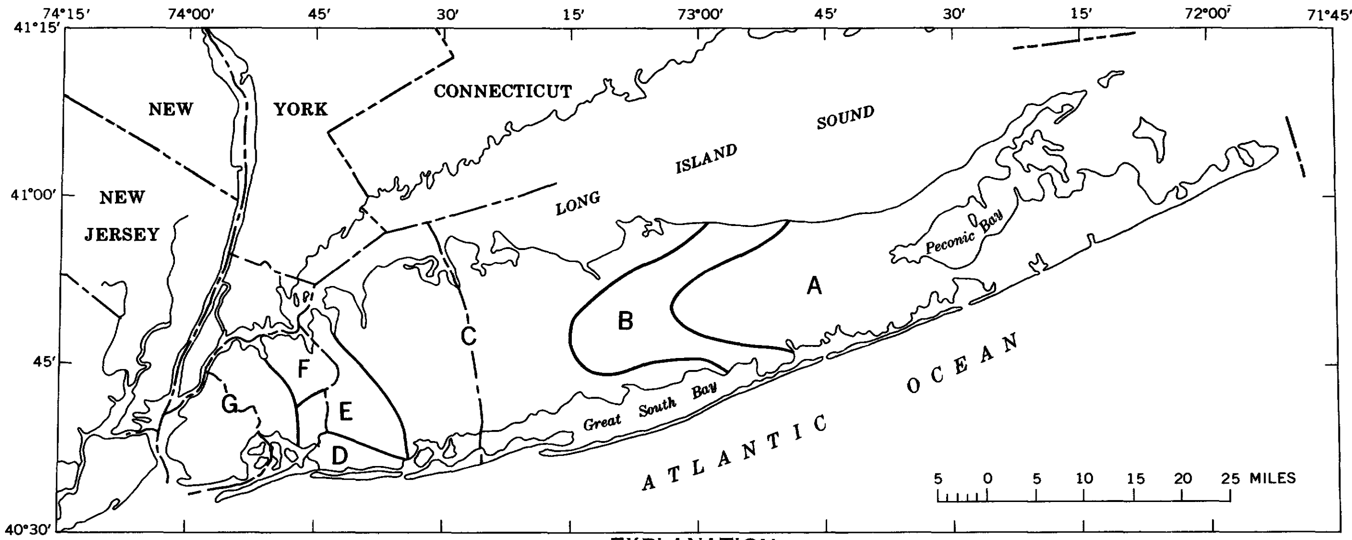
The third major stage of ground-water development was characterized mainly by the introduction of large-scale sewage systems—first in Kings and Queens Counties and then in the western one-third of Nassau County. After the sewers were installed, most of the once-used water that previously had been returned to the ground-water reservoir through cesspools and septic tanks was thereafter discharged to the sea, which represented a permanent loss of water from the system. The resulting disruption of the hydrologic balance caused large-scale salt-water encroachment, first in Kings County, then in Queens County, and most recently in the southwestern part of Nassau County.

The three major stages of development, as well as transitional stages, can presently be observed in different subareas of Long Island (fig. 32). Subarea A is largely rural and has the lowest population density on the island. In general, most of the subarea is in the first major stage of development. Subarea B is mainly in a stage of development intermediate between the first and second stages of development. Farms in this subarea are rapidly being replaced by housing developments, and the new homes are being supplied with water from large-capacity public-supply wells tapping the shallow glacial deposits. Most of the new homes have individual cesspools to dispose of domestic waste water. The ground-water system in this subarea also is still in a virtual state of dynamic equilibrium, although the quality of the shallow ground water undoubtedly is being degraded in the vicinity of the cesspools and septic tanks.

Because it is closer to New York City, subarea C experienced intensive suburban development earlier than subarea B. Most of the subarea is not sewered, and as a result, fairly large parts of the shallow upper glacial deposits have become polluted with cesspool effluent. This pollution, in turn, has forced the abandonment of many of the shallow wells, and most of the water supply for the subarea presently is obtained from deep wells tapping the Magothy aquifer. The subarea, therefore, is in the second stage of ground-water development.

Subarea D is in the third major stage of development. Public-supply water is derived mainly from large-capacity wells tapping the Magothy and Jameco aquifers, and most of the sewage water is discharged to the sea by way of large-capacity sewage-treatment plants. The ground-water system in the Magothy and Jameco deposits is no longer in quantitative equilibrium (inflow is less that outflow), and salty water from the ocean is invading these deposits.

Subarea E also is in the third major stage of development. It differs from subarea D mainly because the salty water has not yet invaded the aquifers in this subarea. If the trend continues, however, subarea D will expand at the expense of subarea E, and the



EXPLANATION

SUBAREA	CHARACTERISTICS
A	Hydrologic system mainly is in a state of virtual quantitative equilibrium.
B	Transitional in development between subareas A and C.
C	Hydrologic system is locally out of balance; local salt-water intrusion.
D	Hydrologic system is out of balance; widespread salt-water intrusion.
E	Hydrologic system is out of balance; may be subject to salt-water intrusion in the future.
F	Ground-water development is negligible, and the hydrologic system is in balance.
G	Large parts of the subarea are contaminated with salty ground water owing to former intensive ground-water development and related salt-water intrusion.

FIGURE 32.—Status of water development in 1966. After Heath, Foxworthy, and Cohen (1966, fig. 8).

aquifers in subarea E also will be contaminated with salty water.

Almost all the public-supply water for subarea F, which is in northeastern Queens County, is derived from surface-water supplies imported from upstate New York. The subarea is sewered, and because ground-water development is negligible, the ground-water system is still in balance.

All of subarea G, the most highly urbanized part of Long Island, is sewered. Presently, the subarea receives more than 85 percent of its public-supply water from the upstate surface-water reservoirs of the New York City municipal-supply system. As is described in a subsequent part of the report, large parts of the ground-water reservoir in the subarea have been contaminated with salty water because of substantial overdevelopment. Since the mid-1940's, when pumpage in the subarea had to be drastically reduced because of the salt-water contamination, ground-water levels in the subarea have recovered markedly.

EFFECTS OF MAN'S ACTIVITIES ON THE MOVEMENT AND DISCHARGE OF WATER

The following discussion of the effects of man's activities on the movement and discharge of water on Long Island is facilitated by reference to the flow diagram in figure 33. A comparison of this diagram and the diagram showing the flow system under natural conditions (fig. 13) indicates that a number of "boxes" have been added. These new boxes represent manmade structures, including recharge basins, cesspools and septic tanks, water pipes, diffusion and recharge wells, storm drains, and sewer drains. In addition, one of man's activities—namely, pumping of ground water—is also shown diagrammatically. As in figure 13, only flow paths that represent large quantities of water or those that are of particular significance are shown in figure 33.

In addition to the structures mentioned above, man has greatly modified the land surface of Long Island by large-scale construction of streets, parking lots, buildings, and other impervious surfaces. This construction has not only greatly reduced and modified the natural vegetative cover, but it also has necessitated the construction of adequate facilities for storm drainage. The methods of solving the problems of storm drainage on Long Island constitute one of the most important ways in which man's activities have modified the natural hydrologic system. The other major activities of man related to the hydrologic system of Long Island involve the development of ground water and the disposal of used water.

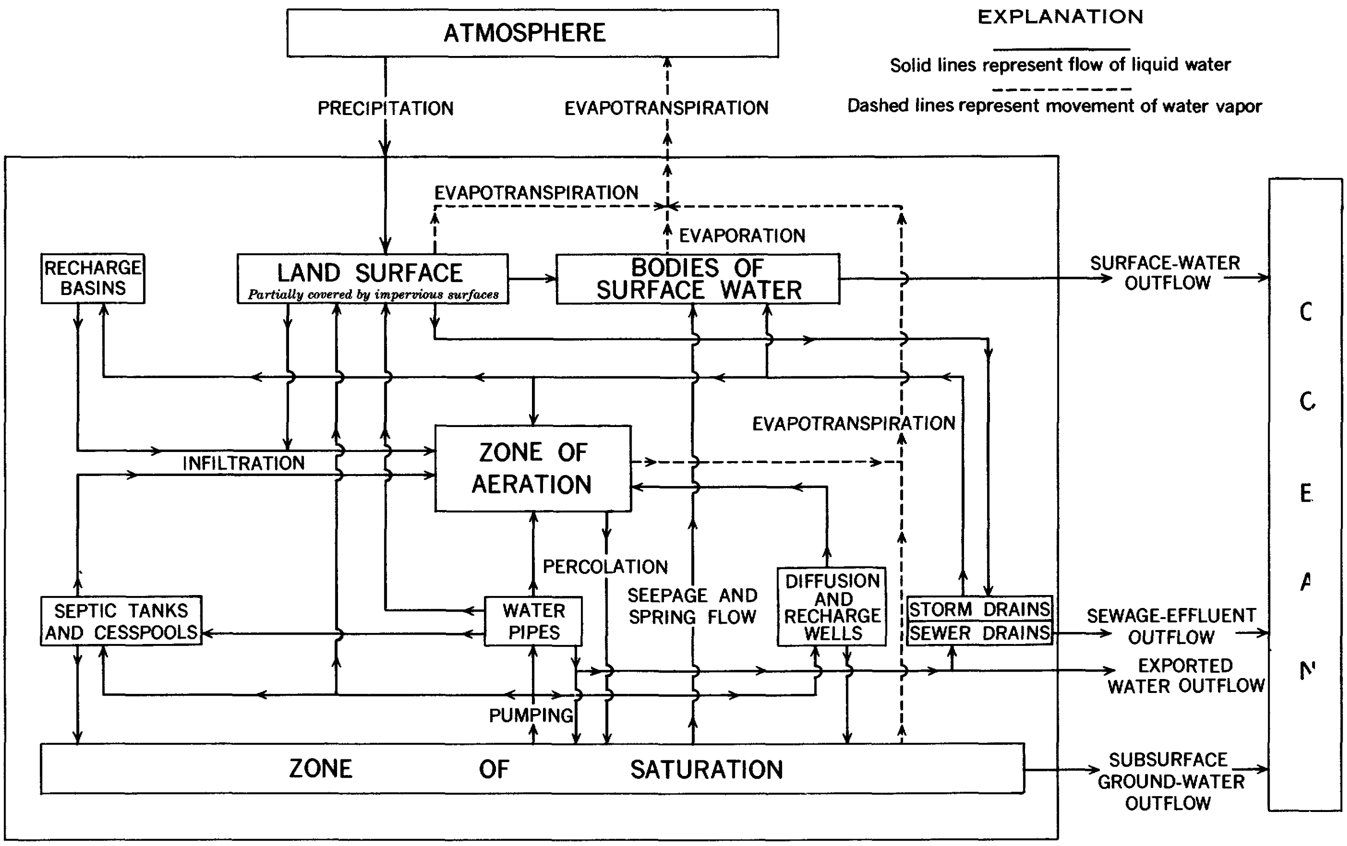


FIGURE 33.—Flow diagram of the hydrologic system, Nassau and Suffolk Counties, in the 1960's.

DISPOSAL OF DIRECT RUNOFF

Direct runoff from urban areas on Long Island flows by gravity through gutters and street inlets to storm sewers. The storm sewers generally transmit the runoff to either recharge basins or nearby streams (fig. 33).

RECHARGE BASINS

Recharge basins are unlined excavations in the glacial deposits; they range from about 10 to 20 feet in depth and from less than 1 to about 30 acres in area. In Nassau and Suffolk Counties there are more than 2,000 recharge basins, most of which are in the water-budget area. In the past two decades, most new housing and industrial developments in these counties have been required to include the construction of one or more basins, the size and number of which were related to the size of the drainage area. Moreover, most of the runoff from highways in these counties is collected in recharge basins. A recharge basin is generally used only where the water table is sufficiently deep to remain below the floor of the basin at least most of the time. Therefore, only a few recharge basins are located in nearshore areas where the water table is within a few feet of the land surface. In addition, on Long Island many street inlets are open bottomed and, therefore, function as small recharge basins.

Seaburn (1970) studied the inflow of two recharge basins in residential developments in Nassau County. From the rainfall-inflow relation for one of these basins (fig. 34), Seaburn estimated that, on the average, about 15 percent of the total precipitation falling on the drainage area of the basin discharged into the basin. In this particular drainage area (15 acres) about 11 percent of the total drainage area was streets, and the total impervious area, including streets, sidewalks, driveways, and roofs was about 32 percent.

The total drainage area of all the recharge basins in Nassau and Suffolk Counties is probably on the order of 250 square miles at present (1968). If it is assumed that 15 percent of total rainfall on this area enters recharge basins and that virtually all this water recharges the ground-water reservoir, average annual recharge to the ground-water reservoir from these basins is on the order of 80 mgd. The assumption that most of the water entering a recharge basin ultimately recharges the ground-water reservoir is based on the observation that water entering most basins percolates into the ground fairly rapidly (commonly within a day or so).

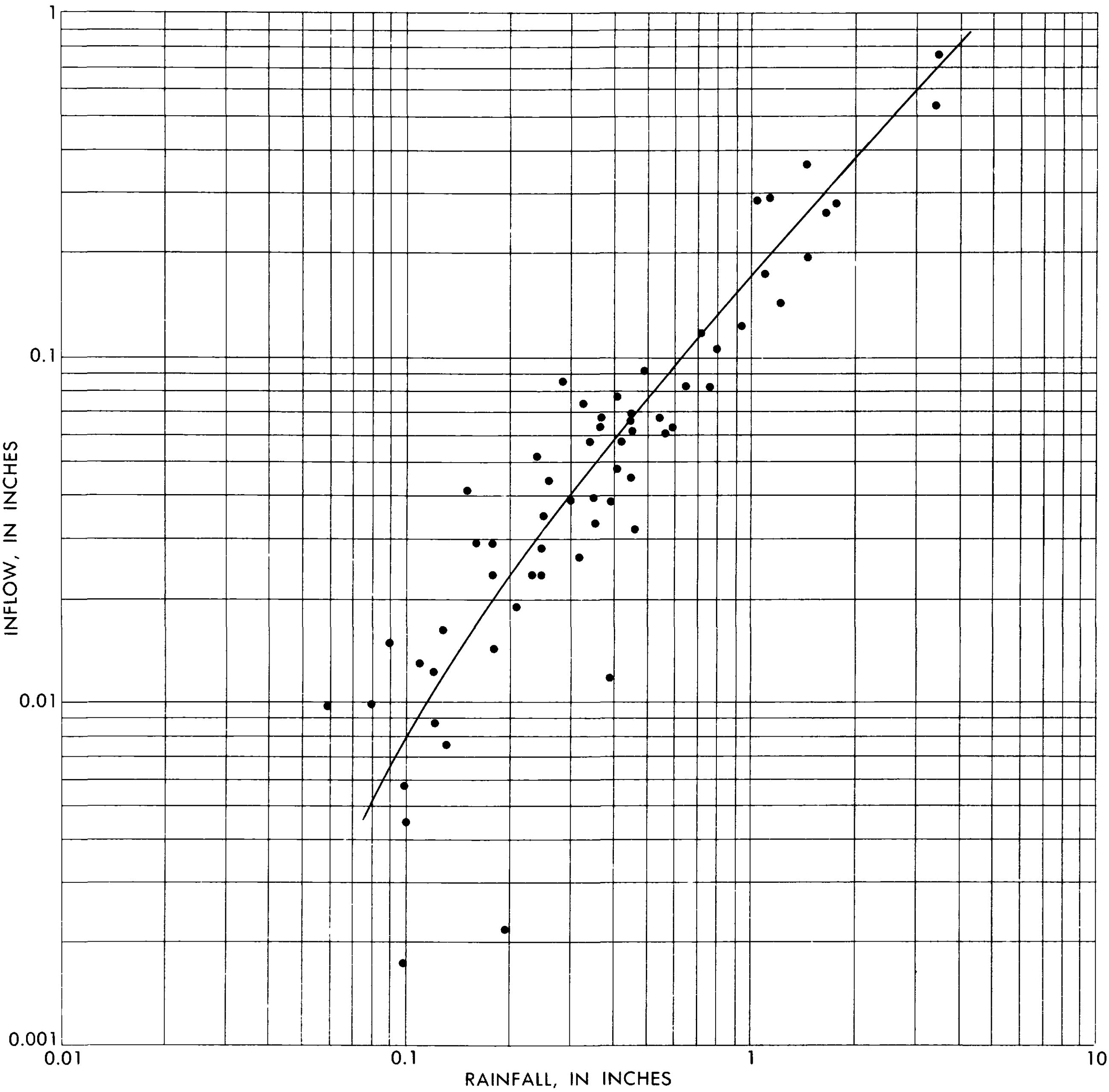


FIGURE 34.—Relation between rainfall and inflow to the Westbury recharge basin, Nassau County, 1966–67. After Seaburn (1970).

Insufficient information is available to determine whether present recharge in the drainage areas of recharge basins has increased, decreased, or remained the same as compared to recharge under natural conditions. According to the previous water-budget analysis, on the average about one-half the precipitation falling on any part of the recharge basin drainage area returned to the atmosphere as evapotranspiration and about one-half recharged the ground-water reservoir under natural conditions. Inflow to a recharge basin probably includes most of the precipitation that fell on the streets and some of the precipitation that fell on areas immediately adjacent to the streets. Thus, a larger proportion of the precipitation falling on this part of the drainage area of a recharge basin probably recharges the ground-water reservoir than under natural conditions. On the other hand, no information is presently available to compare the average recharge through lawns and other uncovered areas, which comprise more than one-half the drainage area of most recharge basins, to the recharge in these areas under natural conditions.

STREAMS

Direct runoff to some streams on Long Island has greatly increased because of increased direct runoff from urban areas. The values of direct runoff to streams as a percentage of total annual streamflow are given in table 13 (D. E. Vaupel and A. G. Spinello, written commun., 1968) for the gaged streams on Long Island in water years 1958 and 1964. These were years of relatively high and low precipitation, respectively. In general, values greater than 6–8 percent in table 13 indicate an increase in direct runoff compared to natural conditions, and these increases are related to urban development.

Seaburn (1969) studied the effects of urban development on direct runoff to East Meadow Brook in Nassau County for the period 1937–62. In 1937 the drainage area of East Meadow Brook was almost completely rural. After a period of intensive development in the 1950's, the southern part of the drainage area was almost completely occupied by housing developments. A cumulative plot of annual direct runoff to East Meadow Brook is shown in figure 35. The marked changes in the slope of the curve coincided with increases in annual direct runoff resulting from the construction of storm sewers draining to East Meadow Brook. The virtually straight curve of cumulative precipitation on the same graph implies that precipitation did not significantly cause the observed increases in direct runoff.

The relation between rainfall and runoff in East Meadow Brook for individual storms in the preurban (1937–43) and urban (1964–66) periods are shown in figure 36. Although the data points show considerable scatter, a marked difference is evident for the two periods—particularly for the larger storms. On the basis of figures 35 and 36 and an accurate delineation of the urbanized areas that were equipped with storm sewers that drain to East Meadow Brook, Seaburn estimated that between 10 and 15 percent of the total rainfall falling on that urbanized area appeared as direct runoff in the stream.

The total area of highly developed land in Nassau and Suffolk Counties from which direct runoff drains directly to streams or into the surrounding bodies of salty water is probably on the order of 200 square miles. If it is assumed that on the average about 15 percent of total rainfall dicharges from this area as

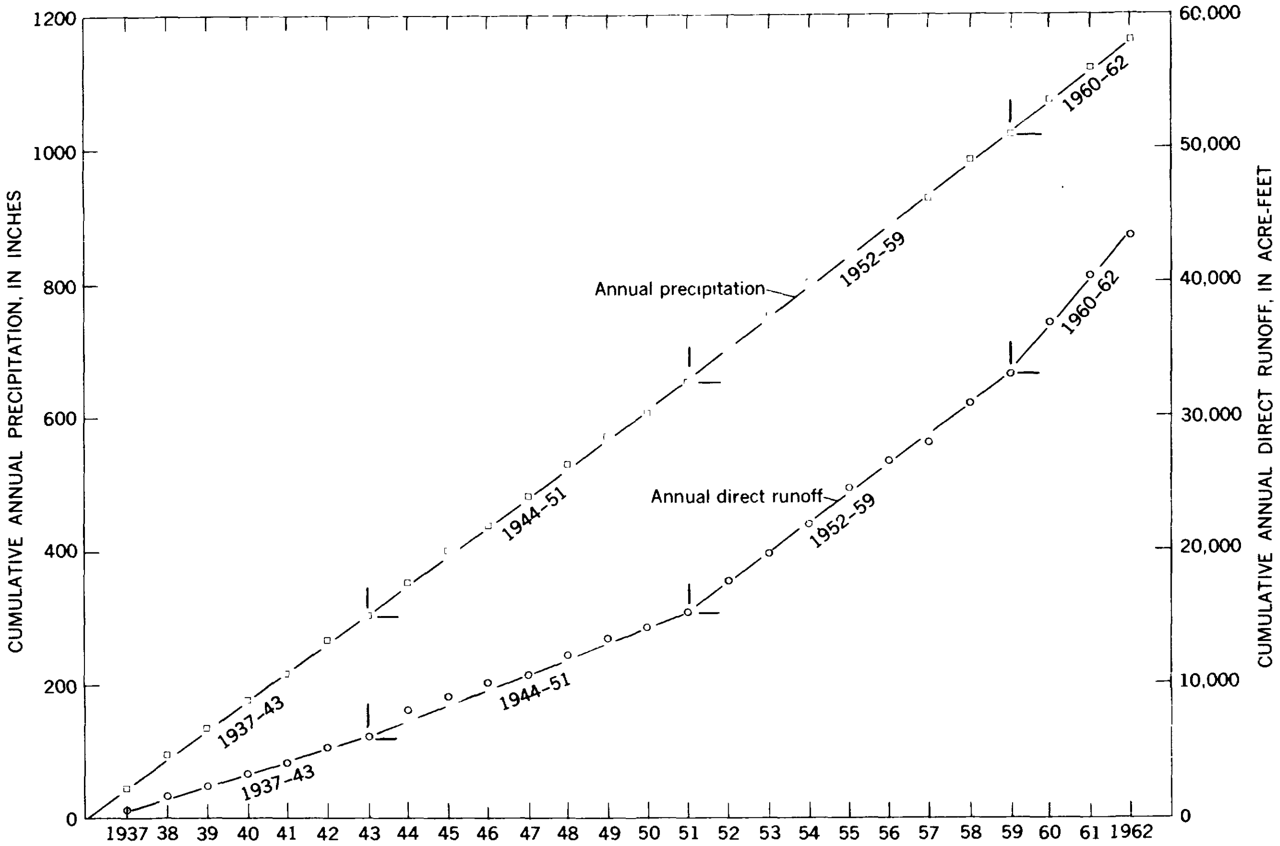


FIGURE 35.—Cumulative curves of annual direct runoff in East Meadow Brook and annual precipitation at Mineola. After Seaburn (1969).

TABLE 13.—*Annual direct runoff of the 19 continuously gaged streams on Long Island, N.Y., for water years 1958 and 1964*

[After D. E. Vaupel and A. G. Spinello, written commun., 1968]

Gaging station	Water year 1958		Water year 1964	
	Total discharge (cubic feet per second-days)	Total direct runoff (percentage of total discharge)	Total discharge (cubic feet per second-days)	Total direct runoff (percentage of total discharge)
Valley Stream	2, 600	32	340	52
Pines Brook	2, 400	26	460	49
East Meadow Brook	7, 700	19	[1] 3, 000	22
Bellmore Creek	5, 500	11	4, 400	11
Massapequa Creek	5, 500	12	3, 100	15
Santapogue Creek	1, 900	12	1, 100	11
Carlls River	11, 000	10	8, 600	8
Sampawams Creek	4, 700	10	3, 100	10
Penataquit Creek	2, 500	10	2, 400	9
Champlin Creek	3, 300	6	2, 200	5
Connetquot River	16, 000	6	12, 000	5
Patchogue Creek	9, 300	12	7, 100	7
Swan River	5, 600	5	4, 400	5
Carmans River	11, 000	3	7, 700	3
Cedar Swamp Creek	3, 200	24	1, 800	23
Mill Neck Creek	3, 900	10	2, 600	10
Cold Spring Brook	1, 800	9	1, 200	6
Nissequogue River	17, 000	7	14, 000	5
Peconic River	20, 000	8	11, 000	7

[1] Total for 9-month period January-September 1964.

direct runoff, the estimated average direct runoff from these areas is on the order of 60 mgd.

The significant feature of the increased direct runoff to streams resulting from urban development is that the direct runoff rapidly discharges into salty water and is therefore lost from the fresh-water system of Long Island. Some of the lost water would probably have been lost by evapotranspiration and direct runoff under natural conditions. However, much of this water undoubtedly represents a loss of recharge to the ground-water reservoir, and this loss causes ground-water levels to decline. In comparing average ground-water levels in urbanized and unurbanized areas by means of double-mass curves, Franke (1968) found evidence that the loss of recharge resulting from increased direct runoff caused average ground-water levels in an urbanized area in southeastern Nassau County to decline about 1–2 feet.

PUMPING AND DISTRIBUTION OF GROUND WATER

Two undesirable effects, both resulting from changes in the position of the two moveable boundaries of the ground-water reservoir (the water table and the salt-fresh water interface) are associated with large-scale pumping of ground water on Long Island. These effects are (1) a regional decline in ground-water levels and (2) an increase in the chloride content of the water in some wells. For these undesirable effects to occur, the pumped ground water must be permanently removed from the ground-water reservoir. Sanitary sewers are the major cause of a permanent loss of water from the ground-water reservoir of Long Island. Instead of returning used water to the ground-water reservoir through cesspools and septic tanks, the sanitary sewers dispose of the used water directly into salty water.

PUMPING OF GROUND WATER

Gross ground-water pumpage in Nassau and Suffolk Counties in selected years is given in table 14. Inasmuch as ground water has been practically the only source of water in these counties, gross pumpage has increased as the population has increased. In Nassau County, gross pumpage increased from about 75 mgd in 1940 to nearly 210 mgd in 1965. Similarly, gross pumpage in Suffolk County increased from about 30 mgd in 1940 to almost 120 mgd in 1965. During the same period, gross ground-water pumpage on all of Long Island increased from about 220 mgd to about 430 mgd. Furthermore, tabulations of pumpage and water use prepared by the New York State Water Resources Commission indicate that the average per capita use of ground water in Nassau and Suffolk Counties was about 140 gallons per day in 1965.

Not all the gross pumpage represents a loss of water from the hydrologic system of Long Island. As is discussed subsequently, much of the pumpage—particularly in Nassau and Suffolk Counties—is returned to the ground-water reservoir following its use. The proportion that actually is lost (net withdrawal) depends upon the type of water use and the method of waste-water disposal.

TABLE 14.—*Gross ground-water pumpage in Nassau and Suffolk Counties, Long Island, N.Y., 1940–65* [1]

[In millions of gallons per day]

Year	Nassau County	Suffolk County	Total (rounded)
1940	75	30	100
1945	63	31	94
1950	110	42	150
1955	130	67	200
1960	150	75	220
1965	210	120	330

[1] Based mainly on data obtained from the New York State Water Resources Commission.

LEAKY WATER PIPES

The two flow paths in figure 33—water pipes to zone of aeration and water pipes to zone of saturation—represent leakage from water-distribution systems. Except in areas of very shallow ground-water levels near the shorelines, most pipelines on Long Island are in the zone of aeration, and most of the leakage from them ultimately recharges the ground-water reservoir.

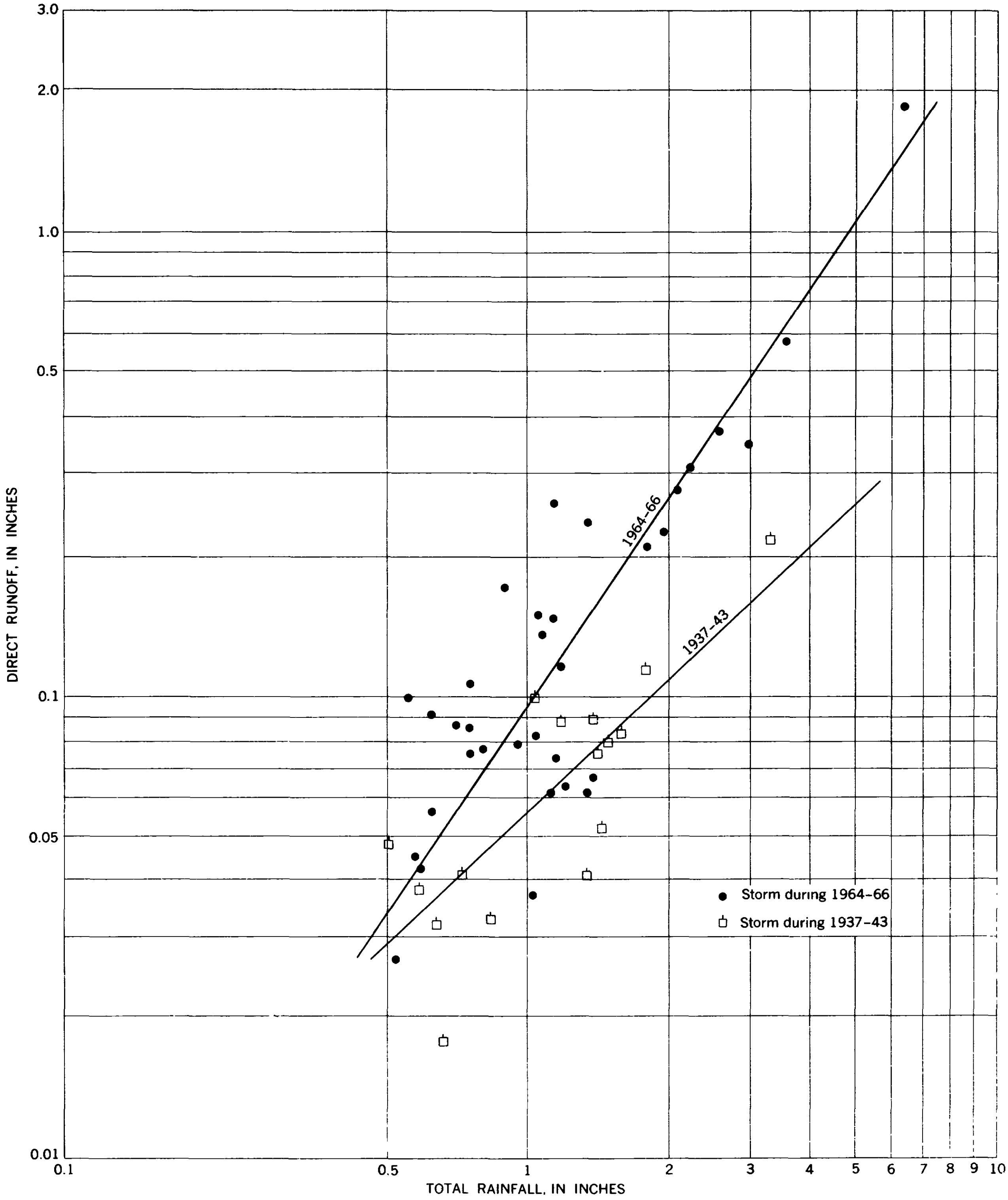


FIGURE 36.—Relation between rainfall and runoff for individual storms in the East Meadow Brook drainage area, Nassau County, for urban (1964–66) and preurban (1937–43) periods. After Seaburn (1969).

Informal discussions with some managers of water-supply companies on Long Island indicate that in well-maintained water-distribution systems the average quantity of leakage is about 10–15 percent of total water input to the systems. If it is assumed that about 15 percent of total public-supply pumpage leaks from the system before use and recharges the ground-water reservoir, the resulting leakage figure for Nassau and Suffolk Counties was about 35 mgd in 1965.

EXPORTED WATER

The flow path designated "exported water outflow" in figure 33 represents an element of discharge from Nassau and Suffolk Counties that is completely controlled by man. Since the beginning of this century, New York City has imported water to Kings and Queens Counties from several well fields near the south shore of Nassau County. Before 1920 the maximum annual-average withdrawals from this system were slightly more than 50 mgd. Since that time, withdrawals have decreased. In the decade 1940–49, the average withdrawal was less than 20 mgd, and since 1950, it was less than 5 mgd. Because the amount of exported water is small compared to natural discharge from the ground-water reservoir, the effect of exporting water on the ground-water reservoir in Nassau and Suffolk Counties is negligible at present.

LAWN SPRINKLING AND IRRIGATION

Two flow paths in figure 33, "water pipes to land surface" and "pumping to land surface," represent lawn sprinkling and other water used for irrigation. The amount of water used in this way is significant because a large part of it is lost from the hydrologic system by evapotranspiration.

A compilation of pumpage by all public water-supply companies in Nassau County for the years 1954–63 showed that, on the average, about 60 percent of the total withdrawals occurred during the summer months (April-September), and that 40 percent occurred in the winter months (October-March). Roughly, three-fourths of the 20 percent difference in seasonal pumpage, or 15 percent of total public-supply pumpage, is assumed to be related to lawn sprinkling. Because most people tend to overirrigate their lawns, it is further assumed that, on the average, about half the water used for lawn sprinkling is lost to evapotranspiration and that the remaining half eventually returns to the ground-water reservoir. Thus, the estimated total quantity of public-supply pumpage lost by evapotranspiration in Nassau and Suffolk Counties in 1965 is on the order of 20 mgd.

The flow path "pumping to land surface" represents several additional situations where ground water is pumped and used locally, including (1) pumping from private wells for lawn sprinkling by owners whose other water-supply needs are supplied by a water-supply company; (2) pumping from "backyard" wells for lawn sprinkling where all the other water supply needs are derived from that well; and (3) pumping for commercial purposes, such as golf-course sprinkling and irrigation of crops. The first two items listed above vary considerably from year to year and are difficult to estimate. There are probably about 60,000 private wells in Nassau and Suffolk Counties, most of which are small-diameter driven wells that extend a few feet into the glacial deposits. The estimated total average pumpage from these wells for lawn sprinkling and related uses is on the order of 10 mgd or less in most years. According to an unpublished estimate by the New York State Water Resources Commission, pumping for commercial purposes, as described above, was about 35 mgd in 1965. This included about 15 mgd for golf-course sprinkling and 20 mgd for farm and nursery irrigation. As is the case with lawn sprinkling, probably 25–50 percent of this water infiltrates into the zone of aeration and ultimately returns to the ground-water reservoir.

DISPOSAL OF USED WATER

Used water on Long Island is disposed of in three major ways—through recharge wells, cesspools and septic tanks, and sanitary sewers. Hydrologically, these methods differ in their effect on both the water balance and the quality of the water in the ground-water reservoir. The effect of these methods of waste-water disposal on the quality of the water is considered in a subsequent section of the report.

RECHARGE WELLS

In 1933 the New York State Legislature enacted a water-conservation law to protect the ground-water resources of Long Island. The law empowered the New York State Water Power and Control Commission (subsequently the New York Water Resources Commission) to regulate the construction of all wells on Long Island that withdraw more than 100,000 gpd (gallons per day) from the ground-water reservoir. In 1954 the law was modified to include all wells having capacities of 45 gpm (gallons per minute) or more (about 65,000 gpd).

The State regulatory agency established a policy in 1933 prohibiting, "the drilling of new industrial wells with capacities in excess of 69.4 gpm (100,000 gpd), unless the water pumped is returned in an uncontaminated condition into the ground through diffusion wells or other approved structures" (Johnson, 1948, p. 1160–1161). The term "diffusion well" as used on Long Island is virtually identical to the more widely used terms, "artificial-recharge well" or "injection well."

Presently, more than 1,000 recharge or diffusion wells return used ground water to the ground-water reservoir of Long Island. According to unpublished data supplied by the New York Water Resources Commission, an average of about 77 mgd was injected into recharge wells on Long Island in 1965, including about 45 mgd in Nassau and Suffolk Counties. Most of the water was used for air-conditioning (cooling), which caused its temperature to rise markedly before it was returned to the ground-water reservoir. Although the quality of the recharged water is changed, the use of ground water for air conditioning causes virtually no net loss to the ground-water reservoir. Because the pumping and recharge wells are usually very close to one another, the flow path in figure 33 designating this activity is drawn from "pumping" directly to "recharge wells." Although most recharge wells are screened in the zone of saturation (commonly at virtually the same depth as the supply well), some recharge wells are screened in the zone of aeration.

CESSPOOLS AND SEPTIC TANKS

In most of Nassau and Suffolk Counties, used household water is discharged into cesspools and septic tanks (flow paths "water pipes to cesspools and septic tanks" and "pumping to cesspools and septic tanks" in figure 33). Virtually all this water is derived from the ground-water reservoir. Because most cesspools and septic tanks are at least 3 feet below land surface, the used water discharging into them commonly percolates through the zone of aeration or enters the ground-water reservoir directly without appreciable losses by evapotranspiration (see flow paths "cesspools and septic tanks to zone of aeration" and "cesspools and septic tanks to zone of saturation" in figure 33). Therefore, discharge of used water to cesspools and septic tanks, although causing a marked change in the quality of the shallow ground water, does not appreciably disturb the quantitative balance in the ground-water reservoir.

In 1965, total public-supply pumpage in those parts of Nassau and Suffolk Counties where cesspools and septic tanks were used to dispose of used water was about 160 mgd. Based on pumping and sewage discharge tabulations in 1965 and 1966 for the sewered area (see section on "Sanitary Sewers") in southwest Nassau County, the estimated discharge into cesspools and septic tanks was about 70 percent of the total public-supply pumpage, or about 110 mgd. The remaining 30 percent was diverted between the pumping wells and the cesspools and septic tanks by pipe leakage and various uses of water such as lawn sprinkling.

Reportedly, about 260,000 people were not served by a public water-supply system in Suffolk County in 1965, but they obtained their water supply from privately owned wells. If the household use of water (excluding that used for lawn and garden sprinkling) is assumed to be about 50 gallons per day per person, the estimated additional discharge in 1965 to cesspools and septic tanks in Suffolk County from areas served by private wells was about 15 mgd. Therefore, the estimated total discharge in 1965 to cesspools and septic tanks in Nassau and Suffolk Counties was about 125 mgd.

SANITARY SEWERS

The flow paths "water pipes to sewer drains" and "sewer drains to ocean" (fig. 33) represent discharge from the fresh-water system to salty water—usually from a sewage-treatment plant. Some water leaks from the sewers to the zone of aeration where the sewers are above the water table (flow path not shown in fig. 33). If it is assumed that about 10–15 percent of the raw sewage entering the sewer-pipe network leaked from the system before reaching the sewage-treatment plant, the resulting leakage figure for Nassau and Suffolk Counties was about 10 mgd in 1965. In addition, water locally leaks from the sewers to the ground-water reservoir and from the ground-water reservoir into the sewers where the sewers are below the water table (flow paths not shown in fig. 33). However, it is virtually impossible to evaluate quantitatively the amounts of water involved. All the water that discharges to salt water from the sewage-treatment-plant system is ultimately derived, and represents a net loss from, the ground-water reservoir. The sewers are in a sense analogous to the streams in that they "short circuit" the flow of ground water from a point within the ground-water reservoir some distance inland to a point of discharge into salty water.

Total annual average discharge of treated sewage effluent to salty water in Nassau and Suffolk Counties for the period 1950–65 is shown in figure 37. The marked increase from 1950 to 1965 was mainly the result of the completion of the Nassau County Sewer District No. 2 secondary-treatment plant (locally referred to as the Bay Park sewage-treatment plant), which discharged an average of about 50 mgd in 1965. During this period the discharge of treated sewage effluent to salty water in Suffolk County was less than

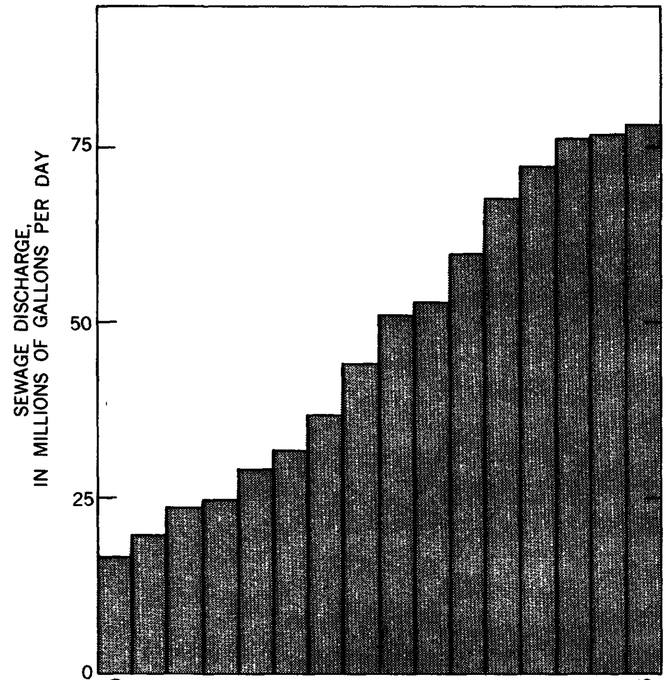


FIGURE 37.—Total treated sewage effluent discharged from Nassau and Suffolk Counties for the period 1950–65. Data from annual reports of the New York, New Jersey, and Connecticut Interstate Sanitation Commission and local agencies.

5 mgd. This low rate of discharge in Suffolk County mainly reflected the fact that most of the sewage in that county was disposed of through individually owned cesspools and septic tanks and the capacity of the sewage-treatment facilities in the county has not increased appreciably in the past 15 years.

The hydrologic consequences of the disposal of used water through sanitary sewers on Long Island are discussed in historical sequence in the following paragraphs.

In the past 60 years, intensive ground-water development accompanied by the disposal of used water through sanitary sewers has caused major changes in the altitude of the water table in Kings and Queens Counties. The 1903 water-table contour map shown in figure 38*A* is based on the earliest available water-level data. Nevertheless, these contours partly reflect the impact of ground-water development because net pumpage at the time already was substantial. In Kings County, for example, net pumpage at that time averaged about 28 mgd (Lusczynski, 1952, p. 4).

By the early 1930's, net ground-water withdrawals for public-supply and industrial use in Kings County exceeded 75 mgd. In addition, natural ground-water recharge had decreased substantially because much of the land surface had been covered with impermeable surfaces such as streets, highways, and buildings. These factors resulted in a marked imbalance in the ground-water system causing a net decrease in the amount of fresh ground water in storage as evidenced by declining ground-water levels.

By 1936 the water table in practically all of Kings County had declined below sea level (fig. 38*B*); locally it had declined about 50 feet to a depth of more than 35 feet below sea level. As a result, a landward hydraulic gradient had developed, and salty ground water invaded the fresh ground-water reservoir.

As wells in Kings County became contaminated with salty water, more and more of the county was supplied with water obtained from upstate New York sources through the New York City public-supply system. In 1946 all pumping of ground water in Kings County for public-supply use was discontinued. In addition the mandatory use of recharge wells, which returned water used for air conditioning and other purposes to the ground-water reservoir, resulted in the conservation of large amounts of ground water. Accordingly ground-water levels in Kings County began to recover substantially in the latter 1940's. By 1965, when gross pumpage was about 24 mgd and net pumpage probably was about 10 mgd, the water table in all but the northern part of Kings County had recovered to a position above sea level (fig. 38*C*).

Ground-water pumpage continued to increase in Queens County during the period in which it decreased in Kings County (from the late 1930's to the present). As a result, the water table in Queens County in 1965 locally declined to a level more than 10 feet below sea level (fig. 38*C*), and salty water began to invade the ground-water reservoir in the southwestern part of the county.

Contamination of well water by salty ground water in southwestern Nassau and southeastern Queens Counties has been the cause of considerable concern and, therefore, the subject of intensive study (Perlmutter and Geraghty, 1963; Lusczynski and Swarzenski, 1966). As noted previously (fig. 10), three major tongues or wedges of salty ground water are found in the area: (1) A shallow unconfined wedge in the upper glacial aquifer, (2) an intermediate confined wedge in the Jameco aquifer and in the upper part of the Magothy aquifer, and (3) a deep confined wedge in the Magothy aquifer and in the Raritan clay.

For the most part, the position of the shallow wedge of salty water has not changed significantly during historic time. However, locally, especially in and near

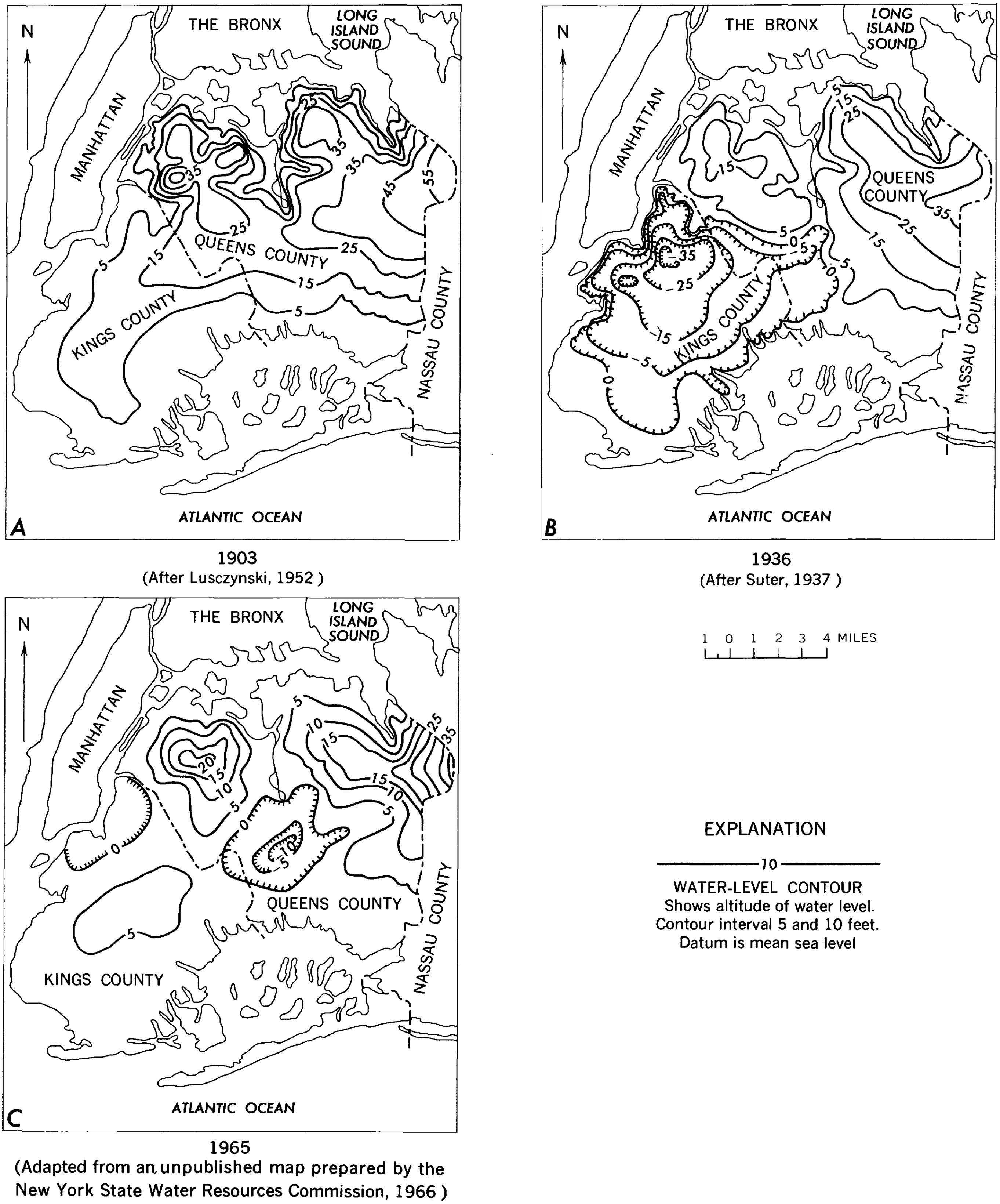


FIGURE 38.—Ground-water levels in Kings and Queens Counties in (A) 1903, (B) 1936, and (C) 1965. After Cohen, Franke, and Foxworthy (1968, pl. 8B).

several areas of intensive pumping, the deep body seems to be actively moving landward. Pumpage from the Jameco aquifer and the Magothy aquifer in southwestern Nassau and southeastern Queens Counties is presently more than 100 mgd, and much of this pumpage is ultimately discharged to the sea through sewage-treatment plants. As a result, the amount of fresh ground water in storage in the area is decreasing and thereby causing the salty ground water to move inland.

Lusczynski and Swarzenski (1966, p. 50–52) estimated that the deep salty-water wedge in the Magothy aquifer has moved inland an average of about 1,000 feet (at rates ranging from 10 to 50 ft per yr) since the early 1900's; locally, however, in the vicinity of some well fields, it has moved more than 1 mile inland since 1952, at a rate of about 300–400 feet per year. Lusczynski and Swarzenski (1966, p. 55) also noted that, on the average, the intermediate salty-water wedge in the Jameco aquifer has moved inland less than 1,000 feet since the early 1900's.

Waste water has been disposed of through sewers in southwestern Nassau County since 1951. In 1966 the total sewered area was about 70 square miles, and the annual average discharge of treated-sewage effluent from this area to the sea was about 50 mgd. The estimated average decline of ground-water levels in a 50-square-mile area in southwestern Nassau County due to sewering was about 7 feet in 1966 (Franke, 1968, p. 209).

In summary, although water of relatively poor quality from cesspools and septic tanks is no longer contaminating the ground-water reservoir in sewered areas, the net loss of water to the ground-water reservoir due to sewering can and has caused extensive lowering of ground-water levels, which, in turn, is accelerating the encroachment of salty water into the aquifers of Long Island.

SUMMARY OF EFFECTS OF MAN'S ACTIVITIES ON THE MOVEMENT AND DISCHARGE OF WATER

In this section of the report the effects of man's activities are considered from two points of view—artificial ground-water recharge and losses of water from the hydrologic system.

SUMMARY OF ARTIFICIAL RECHARGE

Most of the artificial ground-water recharge on Long Island results from cesspools and septic tanks, recharge basins, injection wells, and leaking water and sewer pipes. The estimated artificial recharge in Nassau and Suffolk Counties in 1965 from these sources is as follows:

Source	*Million gallons per day*
Cesspools and septic tanks	125
Recharge basins:	
Direct runoff	60
Waste water	25
Injection wells	55
Leaking water and sewer pipes	45
Total	310

The large amount of artificial ground-water recharge in Nassau and Suffolk Counties significantly affects the hydrologic regimen, and a large decrease in this recharge, which, for example, would result from discontinued use of cesspools and septic tanks, would materially alter the quantitative balance of the ground-water system. The imbalance would, as has been discussed previously, cause a decline in ground-water levels and the landward movement of salty ground water, at least locally, into the fresh-water aquifers.

LOSS OF WATER FROM THE HYDROLOGIC SYSTEM AS A RESULT OF MAN'S ACTIVITIES

The activities of man which result in a loss of water from the hydrologic system in Nassau and Suffolk Counties are (1) watering of vegetation (lawn and golf-course sprinkling and irrigation), (2) disposal of direct runoff from urban areas to streams and subsequent outflow to the sea, (3) disposal of sewage effluent to salty water, and (4) export of water to New York City. The estimated total amount of water lost from the hydrologic system of Long Island as a result of these activities for selected years are shown in figure 39. The largest single loss, about 60 percent of the total in 1965 (about 75 mgd), was the discharge of sewage effluent to salty water. In 1940 and 1945, New York City imported about 26 and 10 mgd of ground water, respectively, from Nassau County. These large exports of water from Nassau County caused the trend anomaly that is evident for those years in figure 39.

The estimated total loss from the hydrologic system in Nassau and Suffolk Counties in 1965 resulting from the activities of man, about 125 mgd (fig. 39), is less than 10 percent of the estimated average annual input of water to the hydrologic system within the water-budget area, and less than 20 percent of the estimated total discharge from the ground-water reservoir under natural conditions (table 11). However, much of this loss is concentrated in the 70-square-mile area in southwestern Nassau County that is sewered, and its effect in this area on ground-water levels and streamflow has been marked.

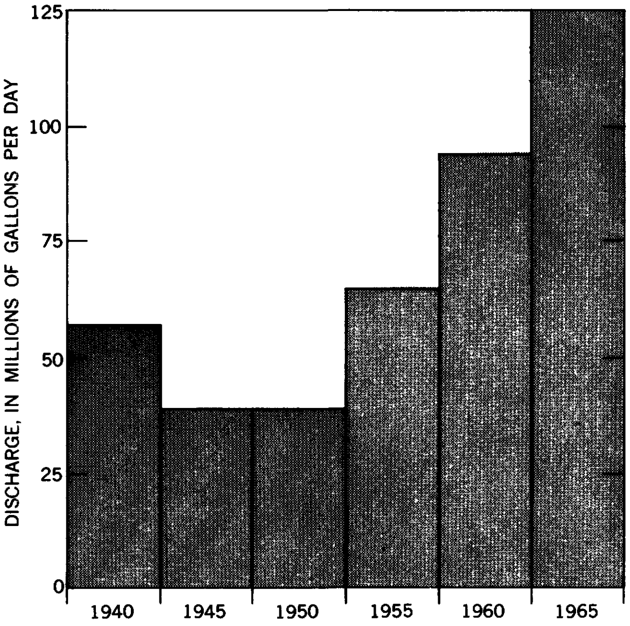


FIGURE 39.—Estimated discharge of water from Nassau and Suffolk Counties, as a result of man's activities, 1940–65.

EFFECTS OF MAN'S ACTIVITIES ON THE QUALITY OF THE WATER

Man has affected the quality of the water on Long Island primarily through the disposal of wastes, including (1) the discharge of smoke and other particulate matter into the atmosphere, (2) the discharge of household waste waters into the ground-water reservoir through cesspools and septic tanks, and (3) the discharge of industrial wastes directly into streams or into the ground-water reservoir through recharge basins. In addition, the dissolved-solids content of the ground water in many areas has increased markedly because of leaching of fertilizers. Selected chemical analyses of water that has been polluted by these various means are given in table 15. In the following discussion the analyses in table 15 are compared to the analyses of natural water in table 12.

Sample 1 of precipitation in table 15 has a high sulfate content (SO_4), which is undoubtedly due in part to contamination of the air as a result of burning fuels. Although in different proportions, samples 2 and 3 of shallow ground water show a particularly high content of calcium, sodium, chloride, sulfate, and nitrate, and the increase in these constituents prob-
content of calcium, sodium, chloride, sulfide, and cesspool effluent, respectively (De Laguna, 1964).

Sample 4 represents water that is contaminated with industrial plating wastes (cadmium and hexavalent chromium) and cesspool effluent. This specific occurrence of pollution by industrial wastes has been studied in considerable detail (Davids and Lieber, 1951; Lieber and Welsch, 1954; Welsch, 1955; Perlmutter and others, 1963). The chromium and cadmium content in sample 4 is considerably in excess of the limits recommended by the U.S. Public Health Service (1962) for these metallic ions (0.05 and 0.01 ppm, respectively).

Sample 5 is characterized by a high nitrate content, which results from the disposal of duck-farm wastes directly into the stream. De Laguna (1964) showed a marked contrast in the amount of dissolved nitrate in water from streams located adjacent to duck farms and those distant from duck farms. The introduction of stream water into Great South Bay which is rich in nitrate and phosphate has caused extensive algal blooms and a resulting upset in the chemical and nutrient balance of this brackish-water body; efforts are being made at present to alleviate this source of pollution.

Sample 6 is representative of ground-water seepage to a stream in a highly urbanized area. In this area, household wastes are discharged into the ground-water reservoir through cesspools and septic tanks. Other streams that derive ground-water seepage from similar areas commonly have a total dissolved-solids content ranging between 150 and 200 mg/l. This range is particularly significant because it represents an approximate average dissolved-solids content of the shallow ground water beneath the highly urbanized areas on Long Island which are not sewered. Locally, of course, the shallow ground water may have a considerably higher dissolved-solids content.

Locally, salt-water encroachment has also adversely affected the quality of the ground water. However, this type of contamination of the fresh ground-water reservoir differs from those just mentioned in that man's activities have not added dissolved constituents to the water, but these activities have changed the location of the naturally occurring salty ground water. Selected analyses of salty ground water in the zone of diffusion are given in table 12.

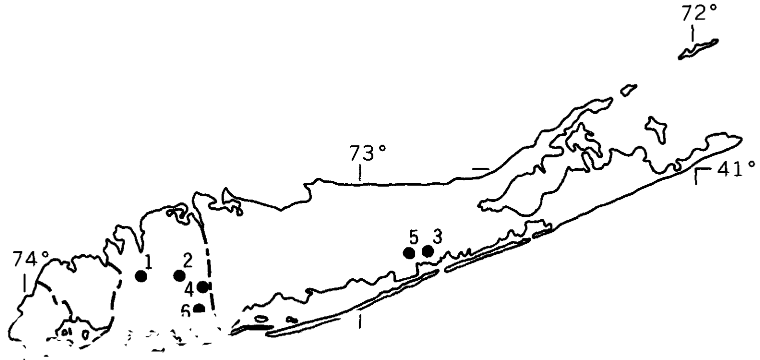
Man has also affected the temperature of the ground water locally. Brashears (1941) described a case history of thermal pollution resulting from recharge of cooling water used in the manufacture of ice in Kings County. Similar situations, although not common, have occurred in other areas where water used for cooling was returned to the ground-water reservoir through recharge wells. In addition, Pluhowski and Kantrowitz (1964, p. 65–66) noted small increases in the temperature of the shallow ground water in the vicinity of housing developments.

TABLE 15.—*Selected chemical analyses of water contaminated by the activities of man on Long Island, N.Y.*

[Analyses made by U.S. Geological Survey and reported in milligrams per liter]

Sample	Source of water	Date collected	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Additional constituents	Total dissolved solids (residue on evaporation at 180° C)	Specific conductance ($K \times 10^5$)	pH	Remarks
1	Precipitation	Feb. 1, 1967	-------	-------	4.4	1.7	3.9	0.4	4	16	3.4	-------	3.6	-------	-------	76	6.4	Partial analysis; composite sample, collected from rain gage at Mineola, N.Y., for period Jan. 3–Feb. 1 1967.
	Ground water, upper glacial aquifer:																	
2	Well N2403	Jan. 21, 1952	9.1	0.04	45	7.3	15	2.6	9	96	22	0.0	46	-------	247	389	6.8	Depth 84 ft; diameter 12 in.; water probably contaminated by fertilizer (De Laguna, 1964).
3	Well S7144	Feb. 13, 1950	8.4	2.0	18	5.7	29	4.4	3	20	50	.1	52	-------	208	360	4.9	Depth 40 ft; depth to water about 20 ft; diameter 2 in.; water probably contaminated by cesspool effluent (De Laguna, 1964).
4	Well N8194	Nov. 7, 1962	13	.22	4.8	1.1	39	5.7	19	57	16	1	16	Hexavalent chromium, 6.2; Cd, 0.4; ABS, 0.26 [1].	173	270	6.2	Water contaminated by metal-plating wastes (hexavalent chromium and cadmium) and cesspool effluent (Perlmutter, and others, 1963).
	Stream water:																	
5	Forge River, West Branch.	Apr. 29, 1948	9.9	.02	8.1	2.6	6.3	4.2	13	7.0	8.8	.3	22	-------	93	114	6.0	Sample collected at Route 27; water probably contaminated by duck-farm wastes (De Luguna, 1964).
6	Massapequa Creek.	May 11, 1966	6.8	.36	13	4.3	16	2.6	12	32	20	.1	12	MBAS, 0.4 [2].	146	211	6.2	Sample collected at gaging station; stream discharge 3.1 cfs.

[1] ABS (alkylbenzensulfonate).
[2] MBAS (methylene blue active substance).



Location of sampling points

WATER-MANAGEMENT IMPLICATIONS OF THE HYDROLOGIC ANALYSIS

The goal of water-resources planning on Long Island is to provide sufficient water of suitable quality to meet the present needs of the residents of Long Island and to meet their needs for a reasonable period of years in the future. This section of the report relates the hydrologic analysis in the previous sections to the planning and development of the local water resources of the area, with special emphasis on Nassau and Suffolk Counties.

THE PRESENT DILEMMA

Future water-resources planning in Nassau and Suffolk Counties must build on the existing state of water-resources development in the area, and it must take into account many complex hydrologic, economic, and political factors. The major features of present water-resources development in the area are (1) withdrawal of ground water from both the shallow unconfined aquifers and from the deeper confined aquifers (2) artificial recharge of polluted waste water through cesspools and septic tanks, (3) injection of relatively uncontaminated waste water through diffusion wells, (4) artificial recharge of direct-runoff water through shallow basins, and (5) discharge of treated sewage water, which was initially derived from the ground-water reservoir, into the sea.

At present (1968), as a result of these water-management practices, total fresh-water outflow from the ground-water reservoir within the water-budget area is greater than total fresh-water inflow, and the amount of fresh ground water in storage is decreasing. This decrease is indicated by declining ground-water levels and the encroachment of salty ground water into the fresh ground-water reservoir. If the present management practices continue, it is likely that, within the water-budget area, (1) the hydrologic imbalance will increase, (2) ground-water levels will continue to decline, and (3) salty ground water will continue to move inland. Accordingly, the present management practices, including particularly the seaward discharge of sanitary sewers, is equivalent to a method of planned overdevelopment.

The complex economic, sociologic, and political factors associated with water-resources development are partly related to the sometimes conflicting interests and desires of the citizens in Nassau and Suffolk Counties. Many citizens are interested in maintaining the size and chemical purity of the lakes and streams for recreation. Others are concerned with maintaining the ecologic balance in the salty bays along the south shore of Long Island to preserve the fauna, flora, and natural beauty of the area. County and State health officials strive to fulfill their responsibilities of assuring a water supply that is completely without hazard to health. All the citizens are, of course, concerned about the cost of future water-resources development.

The present controversy of whether or not to construct sanitary sewers in parts of Nassau and Suffolk Counties is an example of largely valid but conflicting points of view. The present method of disposing of household waste through cesspools and septic tanks in most of Nassau and Suffolk Counties helps maintain the quantity of water in the ground-water reservoir, but causes a deterioration of the quality of the water in the shallow aquifers, which poses a possible health hazard. The construction of sanitary sewers will help preserve the chemical quality of the shallow aquifers, but this construction will result in an increase in the net loss of water from the ground-water reservoir if other conservation procedures are not adopted.

SOME CONCEPTS RELATED TO WATER MANAGEMENT

PRINCIPLE OF CONTINUITY

As a consequence of the principle of continuity, the quantities of water entering and leaving any arbitrary volume (for example, the Long Island ground-water reservoir) within a given time are related by the so-called hydrologic equation:

$$\text{Inflow} = \text{Outflow} \pm \text{Change in storage.}$$

If the change in storage is positive (denoting an increase in the quantity of water in storage), it is added to the right side of the equation; if it is negative (denoting a decrease in the quantity of water in storage), it is subtracted.

The hydrologic system of Long Island must respond to any water-management program in a way that is consistent with the hydrologic equation. If one of the management objectives is to use the water in a way that will not result in a continued decrease in the amount of fresh ground water in storage, it follows from the equation that a balance between total ground-water inflow (recharge) and outflow must be attained. That is, increased consumptive use of ground water must be balanced by increased inflow (such as artificial recharge) or by a reduction of natural outflow (such as ground-water discharge to streams) to avoid a continued decrease in the amount of fresh ground water in storage.

A management program that causes a continual hydrologic imbalance in which the total inflow to the ground-water reservoir is less than the total net outflow (the total quantity permanently lost from the system by evapotranspiration or by discharge to the sea) necessarily will result in the eventual depletion of the fresh ground water in storage. However, if the concept of temporary overdraft of fresh water from the ground-water reservoir is incorporated into a management program, the number of management choices increases markedly. For example, increased net ground-water withdrawals from the water-budget area could be accomplished if the decision is made to tolerate (1) declining ground-water levels, (2) the landward movement of salty ground water, (3) decreased streamflow, or (4) a combination of these factors.

YIELD OF THE SYSTEM

Discussions on the development of the water resources of Long Island often focus on the "yield" or the "safe yield" of the ground-water system. Probably, the most commonly cited definition of safe yield is that given by Meinzer (1923, p. 55); he defined safe yield as, "the rate at which water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is no longer economically feasible." Todd (1959, p. 200–214) reviewed the concept of safe yield in considerable detail and redefined the term as follows: "The safe yield of a ground-water basin is the amount of ground water which can be withdrawn from it annually without producing an undesired result." Todd's definition is a somewhat more general statement of the concept of safe yield than the definition by Meinzer and, therefore, expands its applicability and enhances its usefulness. Accordingly, the definition of safe yield developed by Todd (1959, p. 200) is adopted in this report.

One of the most significant aspects of the concept of the safe yield of any hydrologic system, including the ground-water system of Long Island, is that a quantitative value for safe yield must be determined within the framework of (1) the hydrologic equation and (2) a precise definition of the extent to which certain undesirable results will be tolerated. Accordingly, the safe yield of any ground-water system is not a single, fixed value, but is a variable that depends upon many complexly interrelated factors.

Safe yield is a useful concept in evaluating the possible alternatives of managing a hydrologic system. However, in practice, the concept has been greatly misused—usually, because an attempt is made to develop a single value for the safe yield of an area. This misuse of the concept of safe yield is detrimental to constructive and intelligent water-resources planning, and under these circumstances effective planning might be facilitated by abandoning the concept altogether.

CONSERVATION OF GROUND WATER

Conservation is usually defined as the careful preservation and protection of a resource—especially the planned management of a natural resource to prevent its exploitation, destruction, or neglect. Management of the water resources of Long Island involves many complex cause-and-effect relationships, particularly within the ground-water reservoir. Therefore, a diversity of opinion exists regarding which factors involve exploitation of the water resources, and what is desirable and undesirable with regard to developing and managing the water resources. Some people believe that it is highly desirable to preserve the present size of the ground-water reservoir—that is not to decrease the amount of fresh ground water in storage. Others believe that conservation of water involves the most effective use of the available water by man, which may or may not be compatible with preserving the present size of the ground-water reservoir. Despite the fact that they also may share these different points of view, most engineers and scientists would probably agree that the best procedure in planning the water-resources development of Long Island is to evaluate the various water-management alternatives from as many valid points of view as possible and then to select the alternative or combination of alternatives which produces the most desirable, or least undesirable, results in accordance with the wishes of the citizens of Long Island.

WATER-MANAGEMENT ALTERNATIVES

The following alternatives for developing the water resources of Long Island are classified according to the terms of the hydrologic equation which are most affected by the alternatives. Pertinent information developed for each alternative includes (1) changes in the volumes of fresh water flowing into and out of the hydrologic system, (2) changes in storage within the system, (3) changes in internal routing of the water in the hydrologic system (fig. 33), and (4) changes in the quality of the water.

INCREASE INFLOW TO THE HYDROLOGIC SYSTEM

Inasmuch as precipitation was the only source of fresh water on Long Island under natural conditions, increased precipitation and the importation of fresh water from sources other than those on the island are the only methods of increasing the total amount of fresh water on and beneath Long Island. The potential outside sources of fresh water include mainland sources, desalination of sea water or salty ground water, and perhaps the construction of a fresh-water reservoir in Long Island Sound (Gerard, 1966; A. J.

Pansini, written commun., 1967). However, because the present study was concerned mainly with the development of the local water resources, a detailed discussion of these possibilities is beyond the scope of this report.

SALVAGE OUTFLOW FROM THE HYDROLOGIC SYSTEM

The estimated average rate at which ground water discharges into streams and thence into the bodies of salty surface water bordering the island is about 320 mgd in the water-budget area of Long Island (table 11). Much of this water could probably be salvaged by means of a network of carefully spaced shallow wells and pumping galleries adjacent to the streams, particularly near the south shore of Long Island. Such shallow wells are commonly referred to as "skimming wells" because they skim fresh water from very near the top of the ground-water reservoir. With careful spacing of the wells, a large volume of water could probably be withdrawn with only small and local decreases in ground-water levels resulting therefrom. Thus, this method of development would be accompanied by only a minimal decrease in the total volume of ground water in storage.

Salvaging natural ground-water discharge by the use of skimming wells would be largely at the expense of streamflow. The resulting decrease in streamflow to the sea would change the salinity of the bays and estuaries, and thus might alter the plant and animal life therein. The resulting possible harmful effects and the loss of some of the esthetic features associated with the streams would therefore have to be considered carefully when evaluating the possible application of skimming wells.

Because the chemical quality of much of the shallow ground water has been affected adversely by cesspools and septic tanks, the quality of the water withdrawn from the skimming wells might be less than optimum, and, therefore, the water might require some treatment prior to use. Nevertheless, skimming wells, galleries, or collectors seemingly could increase the yield of the Long Island ground-water reservoir substantially compared to the present program of development.

If the total ground-water inflow remains unchanged, the only possibility of significantly decreasing ground-water outflow from the hydrologic system of Long Island without a concurrent decrease of ground water in storage is to decrease evapotranspiration losses. As discussed previously, the quantity of ground water consumed by evapotranspiration in the water-budget area is small. Moreover, the likelihood of salvaging large amounts of precipitation and surface water that are lost by evapotranspiration on Long Island seems remote at present. Accordingly, an attempt to salvage evapotranspiration losses on Long Island does not seem to be a significant water-management alternative at present.

PERMIT A PLANNED DECREASE OF FRESH GROUND WATER IN STORAGE

The ultimate stable positions of the wedges of salty ground water are dependent upon water-level altitudes in the fresh ground-water reservoir. When fresh ground-water levels rise, the wedges of salty ground water move seaward, and, at the same time, subsurface outflow of fresh ground water increases. When ground-water levels decline, the reverse occurs.

Experiments have shown that the landward extent or length of a wedge of salty water in a given aquifer is about inversely proportional to the rate at which ground water is discharging from the aquifer into the ocean (Todd, 1959, p. 281). It follows, therefore, that if a management decision is made to maintain the positions of the interfaces between fresh and salty ground water that existed under natural conditions, then roughly, 400 mgd of fresh ground water (table 11) must be allowed to discharge by subsurface outflow from the water-budget area toward the sea. On the other hand, if the salt-water wedges are permitted to move inland, an additional quantity of fresh ground water could be withdrawn from the aquifers and used consumptively.

If the goal of water-resources planning were to salvage as much outflow from the ground-water reservoir as possible and at the same time the decision was made to tolerate a large decrease in the volume of ground water in storage, it might be possible to salvage as much as half the total subsurface outflow of fresh ground water, or about 200 mgd (table 11). Moreover, much of the base flow of the streams that discharges into the sea could be salvaged. It probably would not be feasible to salvage all the base flow of the streams (an average of about 320 mgd), but at least 200 mgd probably could readily be salvaged. Under conditions of intensive development, therefore, extensive and carefully planned lowering of ground-water levels could result in salvaging on the order of 400 mgd—200 mgd of subsurface outflow plus 200 mgd of streamflow.

Ground-water development that results in salvaging large amounts of subsurface outflow and streamflow will result in a decrease of ground water in storage beneath the water-budget area and beneath the bordering bays and the ocean. Sustained regional drawdowns in the ground-water reservoir beneath the water-budget area on the order of tens of feet would ultimately result in the landward movement of the fresh-salt water interfaces of several thousands of feet or more. The change in storage of fresh ground water beneath the water-budget area would be many times smaller than the change in storage of fresh ground water beneath the bordering bays and ocean.

The amount of fresh ground water in storage beneath the bays and the ocean can only be roughly estimated (table 4). However, even if this quantity of fresh water in storage was accurately known, the amount that could be salvaged as the fresh-salt water interfaces moved landward would be uncertain. Wide variations in hydraulic conductivity in adjacent and overlying layers in the ground-water reservoir could cause an uneven or fingering pattern of salt-water encroachment, which could result in local bodies of fresh ground water being isolated and rendered virtually unrecoverable.

The principle of permitting the salt-water wedges to move inland to new stable positions that require less subsurface outflow of fresh ground water to the sea is, in effect, a method of planned overdevelopment. This method could be employed, to whatever extent deemed desirable, in conjunction with any one of the several other alternative methods of development. In summary, the safe yield of the ground-water reservoir of Long Island could be increased substantially if it were deemed tolerable to permit the salt-water wedges to move inland, and thereby allow some of the present wells to become contaminated with salty water.

MAINTAIN APPROXIMATE BALANCE BETWEEN INFLOW AND OUTFLOW BY MEANS OF ARTIFICIAL RECHARGE

According to the principle of continuity, if outflow exceeds inflow the volume of water in storage in the ground-water reservoir must decrease. In the previous section of this report, the advantages of decreasing outflow from the ground-water reservoir accompanied by a planned decrease in the volume of ground water in storage were discussed. At some time in the future, however, the water managers may deem it desirable to maintain the salt-water wedges at approximately constant positions. When this point has been reached, a balance between total fresh ground-water inflow and outflow must be maintained.

Various proposals are now under consideration on Long Island to maintain the balance between fresh ground-water outflow and inflow by artificially recharging treated waste water into the ground-water reservoir. These proposals include (1) injecting renovated water into the deeper aquifers through a line of barrier-injection wells near the south shore (and perhaps also near the north shore at a later date) of Long Island and (2) recharging renovated water into the shallow aquifers through basins that would be located near the center of the island.

Water injected into the deeper aquifers will increase the artesian pressure in the vicinity of each injection well in proportion to the quantity of injected water, and the injected water will move radially away from the well. The seaward hydraulic gradient from the injection well will increase, and a landward hydraulic gradient also will be established. If the wells are properly spaced, the individual mounds of artesian pressure around each well will coalesce, and a pressure ridge will form parallel to the coast. The extent to which the pressure ridge will be effective in preventing the landward movement of salty water will depend upon many complexly interrelated factors, especially (1) the magnitude of the increase in artesian pressure in both the horizontal and vertical directions and (2) the location and magnitude of nearby ground-water withdrawals.

Irrespective of the size and shape of the pressure ridge formed by injecting a given quantity of water into a network of barrier injection wells, theoretically, the yield of the system will be increased by the amount of additional fresh-water recharge to the ground-water system. In practice, however, not all the injected water will be recovered, but a large proportion probably could be salvaged under a careful program of development.

Some of the injected water will move inland toward wells that are withdrawing public-supply water; eventually, diluted treated effluent, and under some circumstances undiluted treated effluent, might be withdrawn from nearby pumping wells. For this reason, the sewage-plant effluent that is injected will receive tertiary treatment to upgrade the quality of the water so that it meets or exceeds virtually all the commonly accepted standards for drinking water.

Shallow basins provide an additional significant option to the water manager as a means of recharging renovated water into the ground-water reservoir—either used alone or in conjunction with injection wells. In Suffolk County a regulation recently established by the Suffolk County Health Department requires that all new housing developments in the county having 100 or more individual homes must be equipped with communal sewage-treatment and disposal facilities. As a result, several housing developments in Suffolk County presently are discharging treated sewage-plant effluent into recharge basins, and the total quantity of such artificial recharge probably will increase markedly in the future.

Shallow basins have the advantage that they are easy to construct and maintain. Furthermore, experience with storm-runoff and disposal basins on Long Island has shown that most such basins can readily dispose of large quantities of treated waste water. A major disadvantage of basins, however, is the large land area that they require.

Theoretically, if after it is used, all the water pumped from the ground-water reservoir is returned by means of injection wells, recharge basins, or other methods, the yield of the system would be almost limitless were it not for water-quality considerations and for the differences between horizontal and vertical hydraulic conductivities. Each time that the water is recirculated (pumped from the ground, used, treated, and returned underground) the quality of the water would deteriorate unless certain demineralizing treatment methods were used. Such methods are possible, but are at present relatively expensive. Even if demineralization is not employed, tertiary treatment of waste water and subsequent recharging of the ground-water reservoir could increase the safe yield of the system manyfold, and might extend the usefulness of the ground-water reservoir of Long Island over hundreds of years.

If most of the future pumpage is from the deeper artesian aquifers and if the pumped water is returned to the shallow aquifers after use, a local imbalance might result in the deeper aquifers. Because vertical hydraulic conductivities ordinarily are much less than horizontal hydraulic conductivities, water returned to the shallow aquifers may not move downward into the deeper aquifers as rapidly as it is pumped from these aquifers, with the result that some water pumped from the deeper aquifers will be replaced instead by laterally encroaching salty water.

CONCLUDING COMMENTS ON WATER-MANAGEMENT ALTERNATIVES

Several major questions must be answered in order to develop a rational and comprehensive plan for managing the water resources of Long Island. Two of the most significant questions that have been considered thus far in the report are (1) should salty ground water be permitted to move inland, and if so, how far inland? and (2) what role should renovated water play in water-resources planning? A third major question and a question that could materially affect the planning process, relates to the length of time for which comprehensive plans should be designed—for 25, 50, or 100 years, or longer. None of these major questions can be answered independently, but each must be answered in the context of the answers to the other questions.

The advantages and disadvantages of permitting planned salt-water encroachment are considered in previous sections of the report. However, an additional word regarding the effect of planned salt-water encroachment on the optimum use of water by man is appropriate. A decrease in the subsurface outflow of ground water from the deeper aquifers on Long Island will be accompanied by a decrease in the volume of water in storage within these aquifers. Over a period of many years the amount of water salvaged as a result of reduced outflow will undoubtedly be greater than the net decrease of ground water removed from storage. Under these circumstances, the argument can be made that, to achieve the optimum use of water by man, some encroachment of salty water would be beneficial.

Several of the apparently most feasible water-management alternatives involve the use of renovated water. From the hydrologic point of view, these alternatives are mainly concerned with achieving the optimum pattern of ground-water withdrawals and artificial recharge of ground water. Another important consideration, however, is the reaction of the citizens of Long Island to the use of renovated water. Instead of recharging renovated water into the ground-water reservoir and allowing it to mix there with unused water before possible withdrawal again by pumping, the same degree of dilution could be obtained by mixing renovated water and unused water in the water mains. This procedure would avoid the cost of recharging much of the renovated water. This course of action, however, may not be acceptable to the citizens of Long Island at present for psychological or other reasons.

The significance of the time factor in water-resources planning cannot be over emphasized. Within the next 25 or 50 years, for example, the technical ability to economically convert salty water to fresh water may be greatly improved. Also, many other water-management alternatives may become technically and economically feasible. In the meantime, the citizens and water planners of Long Island are fortunate because of the large size of the fresh ground-water reservoir. This large volume of high-quality fresh water in storage lends time, which, in turn, provides the opportunity for a careful consideration of the available alternatives and considerable flexibility to the water manager.

This report has shown the close interrelations between the various components of the hydrologic system.

Although the fresh ground-water reservoir of Long Island is very large, the activities of man in one part of the reservoir ultimately will also affect other parts of the reservoir. For this reason, the most efficient planning to utilize and manage the ground-water reservoir can be achieved if the reservoir is developed and managed as a unit without regard for political boundaries.

An adequate evaluation of the various alternatives for developing and managing the water resources of Long Island will require the combined efforts of many specialists including hydrologists, engineers, geologists, ecologists, economists, sociologists, and regional planners. The complexity of the problems involved and the possibly great impact of a final overall plan on the lives of the citizens of Long Island requires such a multidisciplinary approach. Moreover, because of the great cost involved in implementing some of the alternatives, a substantial effort in the planning phase is warranted. As stated previously, because of the great size of the fresh ground-water reservoir, adequate time is available for such careful planning.

A continuing program of hydrologic studies is mandatory to provide the necessary input of hydrologic information to an overall planning effort. The present data-collection activities on Long Island, which provide a continuous record of the state of the hydrologic system, should be continued and further refined. In particular, a more intensive study and monitoring of water quality in various parts of the island would be helpful. Previous efforts to define the shape and areal extent of the various aquifers should also be continued. This is particularly true in eastern Suffolk County where many deep public-supply wells are being drilled in areas where very few deep wells previously existed. The data from these wells will provide much valuable lithologic, water quality, and test information.

As shown in this report, man has already altered both the internal routing within and outflow from the hydrologic system and the quality of the water therein. Man's future role in causing further changes will undoubtedly be even greater. As a result, an increasing amount and intensity of hydrologic study will be necessary to keep abreast of these continual changes.

Finally, the present intensity of water-resources development on Long Island and the projected future development of these resources warrant the use of the most sophisticated tools now available to the hydrologist. An electric-analog model study of most of the Long Island ground-water reservoir is now underway. Studies with this model should help define and evaluate the hydrologic results of some of the management alternatives considered in this report. These studies should be followed by other types of analog studies. Furthermore, it is now possible to simulate at least some problems associated with the Long Island ground-water reservoir on a digital computer. All these tools will aid the water manager in formulating a rational and comprehensive plan for developing the water resources of Long Island.

SELECTED REFERENCES

Baffa, J. J., and others, 1958, Developments in artificial ground-water recharge: Am. Water Works Assoc. Jour., v. 50, no. 7, p. 812–871.

Brashears, M. L., Jr., 1941, Ground-water temperatures on Long Island, New York, as affected by recharge of warm water: Econ. Geology v. 36, no. 8, p. 811–828.

Burr, W. H., Hering, Rudolph, and Freeman, J. R., 1904, Report of the Commission on additional water supply for the City of New York: New York, Martin B. Brown Co., 980 p.

Cohen, Philip, and Durfor, C. N., 1967, Artificial-recharge experiments utilizing renovated sewage-plant effluent—a feasibility study at Bay Park, New York, U.S.A.: Internat. Assoc. Sci. Hydrology Pub. 72, p. 194–199.

Cohen, Philip, Franke, O. L., and Foxworthy, B. L., 1968, An atlas of Long Island's water resources: New York State Water Resources Comm. Bull. 62, 117 p.

Cohen, Philip, Franke, O. L., and McClymonds, N. E., 1969, Hydrologic effects of the 1962–66 drought on Long Island, New York: U.S. Geol. Survey Water-Supply Paper 1879–F, 18 p.

Cooper, H. H., Jr., 1964, A hypothesis concerning the dynamic balance of fresh water and salt water in a coastal aquifer, *in* Sea water in coastal aquifers: U.S. Geol. Survey Water-Supply Paper 1613–C, p. C1–C11.

Davids, H. W., and Lieber, Maxim, 1951, Underground water contamination by chromium wastes: Water and Sewage Works, v. 98, no. 12, p. 528–534.

de Laguna, Wallace, 1963, Geology of Brookhaven National Laboratory and vicinity, Suffolk County, New York: U.S. Geol. Survey Bull. 1156–A, 35 p.

——— 1964, Chemical quality of water, Brookhaven National Laboratory and vicinity, Suffolk County, New York: U.S. Geol. Survey Bull. 1156–D, 73 p.

de Laguna, Wallace, and Brashears, M. L., Jr., 1948, The configuration of the rock floor in western Long Island, New York: New York State Water Power and Control Comm. Bull. GW–13, 32 p.

Faust, G. T., 1963, Physical properties and mineralogy of selected samples of the sediments from the vicinity of the Brookhaven National Laboratory, Long Island, New York: U.S. Geol. Survey Bull. 1156–B, 34 p.

Fleming, W. L., 1935, Glacial geology of central Long Island: Am. Jour. Sci., v. 30, p. 216–238.

Flynn, J. M., and others, 1958, Study of synthetic detergents in ground water: Am. Water Works Assoc. Jour., v. 50, no. 12, p. 1551–1562.

Franke, O. L., 1968, Double-mass-curve analysis of the effects of sewering on ground-water levels on Long Island, New York, *in* Geological Survey research 1968: U.S. Geol. Survey Prof. Paper 600–B, p. B205–B209.

Fuller, M. L., 1914, The geology of Long Island, New York: U.S. Geol. Survey Prof. Paper 82, 231 p.

Gerard, R. D., 1966, Potential freshwater reservoir in the New York area: Science, v. 153, no. 3738, p. 870–871.

Harder, J. A., Simpson, T. R., Lau, L. K., Hotes, F. L., and McGawhey, P. H., 1953, Laboratory research on sea-water intrusion into fresh ground-water sources and methods of its prevention—final report: Univ. Calif., Berkeley, Sanitary Eng. Research Lab., 68 p.

Heath, R. C., Foxworthy, B. L., and Cohen, Philip, 1966, The changing pattern of ground-water development on Long Island, New York: U.S. Geol. Survey Circ. 524, 10 p.

Isbister, John, 1966, Geology and hydrology of northeastern Nassau County, Long Island, New York: U.S. Geol. Survey Water-Supply Paper 1825, 89 p.

Jacob, C. E., 1945a, The water table in the western and central parts of Long Island, New York: New York State Water Power and Control Comm. Bull. GW–12, 24 p.

——— 1945b, Correlation of ground-water levels and precipitation on Long Island, New York: New York State Water Power and Control Comm. Bull. GW–14, 20 p.

Johnson, A. H., 1948, Ground-water recharge on Long Island: Am. Water Works Assoc. Jour., v. 49, no. 11, p. 1159–1166.

——— 1955, Conservation of ground water on Long Island: Am. Water Works Assoc. Jour., v. 47, no. 4, p. 348–354.

Kohout, F. A., 1964, The flow of fresh water and salt water in the Biscayne aquifer of the Miami area, Florida, *in* Sea water in coastal aquifers: U.S. Geol. Survey Water-Supply Paper 1613–C, p. 12–32.

Leggette, R. M., 1936, Long-time records of ground-water levels on Long Island, New York: Am. Geophys. Union Trans., v. 17, p. 341–344.

——— 1937, The mutual interference of artesian wells on Long Island, New York: Am. Geophys. Union Trans., 18th Ann. Mtg., pt. 2, p. 490–494.

Leggette, R. M., and Brashears, M. L., Jr., 1938, Ground water for air-conditioning on Long Island, New York: Am. Geophys. Union Trans., 19th Ann. Mtg., pt. 1, p. 412–418.

Lieber, Maxim, Perlmutter, N. M., and Frauenthal, H. L., 1964, Cadmium and hexavalent chromium in Nassau County ground water: Am. Water Works Assoc. Jour., v. 56, no. 6, p. 739–747.

Lieber, Maxim, and Welsch, F. W., 1954, Contamination of ground water by cadmium: Am. Water Works Assoc. Jour., v. 46, no. 6, p. 541–547.

Lounsbury, Clarence, and others, 1928, Soil survey of Suffolk and Nassau Counties, New York: U.S. Dept. Agriculture, Bur. Chemistry and Soils, ser. 1928, no. 28, 46 p.

Lubke, E. R., 1964, Hydrogeology of the Huntington-Smithtown area, Suffolk County, New York: U.S. Geol. Survey Water-Supply Paper 1669–D, 68 p.

Lusczynski N. J., 1952, The recovery of ground-water levels in Brooklyn, New York, from 1947 to 1950: U.S. Geol. Survey Circ. 167, 29 p.

——— 1961, Head and flow of ground water of variable density: Jour. Geophys. Research, v. 66, no. 12, p. 4247–4256.

Lusczynski, N. J., and Johnson, A. H., 1951, The water table in Long Island, New York, in January 1951: New York State Water Power and Control Comm. Bull. GW–27, 28 p.

Lusczynski, N. J., and Swarzenski, W. V., 1960, Position of the salt-water body in the Magothy(?) Formation in the Cedarhurst-Woodmere area of southwestern Nassau County, Long Island, New York: Econ. Geology v. 55, no. 8, p. 1739–1750.

——— 1962, Fresh and salty ground water in Long Island, New York: Am. Soc. Civil Engineers Proc., v. 88, no. 3207, p. 173–194.

——— 1966, Salt-water encroachment in southern Nassau and southeastern Queens Counties, Long Island, New York: U.S. Geol. Survey Water-Supply Paper 1613–F, 76 p.

McClymonds, N. E., and Franke, O. L., 1971, Water-transmitting properties of Long Island's aquifers: U.S. Geol. Survey Prof. Paper 627–E (in press).

Meinzer, O. E., 1923, Outline of ground-water hydrology with definitions: U.S. Geol. Survey Water-Supply Paper 494, 71 p.

Meyer, A. F., 1928, The elements of hydrology: New York, John Wiley & Sons, 522 p.

Miller, J. F., and Frederick, R. H., 1969, The precipitation regime of Long Island, New York: U.S. Geol. Survey Prof. Paper 627–A, 21 p.

Nassau County Planning Commission, 1959, Planning Nassau County—A compilation of land uses: Mineola, Nassau County Planning Comm., 17 p.

New York City Department of Planning, 1962, Land use in New York City: New York, Newsletter Dept. City Planning, April 1962.

New York State Water Pollution Control Board, 1960, Effect of synthetic detergents on the ground waters of Long Island, New York: New York State Water Pollution Control Board Research Rept. 6, 17 p.

Perlmutter, N. M., and Crandell, H. C., 1959, Geology and ground-water supplies of the south-shore beaches of Long Island, New York: New York Acad. Sci. Annals, v. 80, p. 1060–1076.

Perlmutter, N. M., and DeLuca, F. A., 1963, Availability of fresh ground water, Montauk Point area, Suffolk County, Long Island, New York: U.S. Geol. Survey Water-Supply Paper 1613–B, 39 p.

Perlmutter, N. M., and Geraghty, J. J., 1963, Geology and ground-water conditions in southern Nassau and southeastern Queens Counties, Long Island, New York: U.S. Geol. Survey Water-Supply Paper 1613–A, 205 p.

Perlmutter, N. M., Geraghty, J. J., and Upson, J. E., 1959, The relation between fresh and salty ground water in southern Nassau and southeastern Queens Counties, Long Island, New York: Econ. Geology, v. 54, no. 3, p. 416–435.

Perlmutter, N. M., Lieber, Maxim, and Frauenthal, H. L., 1963, Movement of waterborne cadmium and hexavalent chromium wastes in South Farmingdale, Nassau County, Long Island, New York, *in* Short papers in geology and hydrology: U.S. Geol. Survey Prof. Paper 475–C, p. C179–C184.

——— 1964, Contamination of ground water by detergents in a suburban environment—South Farmingdale area, Long Island, New York, *in* Geological Survey research 1964: U.S. Geol. Survey Prof. Paper 501–C, p. C170–C175.

Perlmutter, N. M., and Soren, Julian, 1962, Effects of major water-table changes in Kings and Queens Counties, New York City, *in* Short papers in geology, hydrology, and topography: U.S. Geol. Survey Prof. Paper 450–E, p. E136–E139.

Pluhowski, E. J., 1961, Variation in temperature of two streams on Long Island, New York, *in* Geological Survey research 1961: U.S. Geol. Survey Prof. Paper 424–D, p. D55–D58.

Pluhowski, E. J., and Kantrowitz, I. H., 1962, Source of ground-water runoff at Champlin Creek, Long Island, New York, *in* Short papers in geology, hydrology, and topography: U.S. Geol. Survey Prof. Paper 450–B, p. B95–B97.

——— 1963, Influence of land-surface conditions on ground-water temperatures in southwestern Suffolk County, Long Island, New York, *in* Short papers in geology and hydrology: U.S. Geol. Survey Prof. Paper 475–B, p. B186–B188.

——— 1964, Hydrology of the Babylon-Islip area, Suffolk County, Long Island, New York: U.S. Geol. Survey Water-Supply Paper 1768, 119 p.

Reiners, W. A., and Woodwell, G. M., 1966, Water budget of a forest damaged by ionizing radiation: Ecology, v. 47, no. 2, p. 303–306.

Sanford, J. H., 1938, Report on the geology and hydrology of Kings and Queens Counties, Long Island: New York State Water Power and Control Comm. Bull. GW–7, 68 p.

Sawyer, R. M., 1963, Effect of urbanization on storm discharge and ground-water recharge in Nassau County, New York, *in* Short papers in geology and hydrology: U.S. Geol. Survey Prof. Paper 475–C, p. C185–C187.

Seaburn, G. E., 1969, Effects of urban development on direct runoff to East Meadow Brook, Long Island, New York: U.S. Geol. Survey Prof. Paper 627–B, 14 p.

——— 1970, Preliminary results of hydrologic studies at two recharge basins on Long Island, New York: U.S. Geol. Survey Prof. Paper 627–C, 17 p.

Spear, W. E., 1912, Long Island sources—an additional supply of water for the City of New York: New York City Board Water Supply, 708 p.

Suffolk County Planning Commission, 1962, Existing land use: Hauppauge, Suffolk County Dept. Planning, 42 p.

Suter, Russell, 1937, Engineering report on the water supplies of Long Island, New York: New York State Water Power and Control Comm. Bull. GW–2, 64 p.

Suter, Russell, de Laguna, Wallace, and Perlmutter, N. M., 1949, Mapping of geologic formations and aquifers of Long Island, New York: New York State Water Power and Control Comm. Bull. GW–18, 212 p.

Swarzenski, W. V., 1963, Hydrology of northwestern Nassau and northeastern Queens Counties, Long Island, New York: U.S. Geol. Survey Water-Supply Paper 1657, 90 p.

Thornthwaite, C. W., and Mather, J. R., 1955, The water balance: Drexel Inst. Technology Pubs. in Climatology, v. 8, no. 1, p. 1–86.

——— 1957, Instructions and tables for computing potential evapotranspiration and the water balance: Drexel Inst. Technology Pubs. in Climatology, v. 10, no. 3, p. 185–311.

Todd, D. K., 1959, Ground water hydrology: New York, John Wiley & Sons, 336 p.

Upson, J. E., 1955, Ground-water sources on Long Island: Am. Water Works Assoc. Jour., v. 47, no. 4, p. 341–347.

——— 1959a, Relation of Long Island ground-water resources to regional needs: Am. Water Works Assoc. Jour., v. 51, no. 2, p. 286–300.

——— 1959b, Ground-water problems in New York and New England: Am. Soc. Civil Engineers Proc., v. 85, no. HY 6, 12 p.

U.S. Public Health Service, 1962, Public Health Service drinking water standards—1962: Public Health Service Pub. 956, U.S. Govt. Printing Office, 61 p.

Veatch, A. C., and others, 1906, Underground water resources of Long Island, New York: U.S. Geol. Survey Prof. Paper 44, 394 p.

Welsch, F. W., 1955, Ground-water pollution from industrial wastes in Nassau County, New York: Sewage and Industrial Wastes, v. 27, no. 9, p. 1065–1069.

——— 1956, Conservation of ground water practices on Long Island: Water and Sewage Works v. 103, no. 10, p. 468–473.

——— 1960, Conservation in Nassau County, New York: Am. Water Works Assoc. Jour., v. 52, no. 12, p. 1494–1498.

White, W. N., 1932, A method of estimating ground-water supplies based on discharge by plants and evaporation from soil: U.S. Geol. Survey Water-Supply Paper 659–A, 105 p.

Wyckoff, R. D., and Reed, D. W., 1935, Electrical conduction models for the solution of waste seepage problems: Physics, v. 6, p. 395–401.

TENTATIVE WATER BUDGETS

Tentative water budgets for subareas of the water-budget area are given in tables 16–19. The areas of the subareas are about 100, 210, 125, and 325 square miles, respectively, and the locations of the subareas are shown in figure 2. These water budgets are consistent with the budgets in table 11. For example, the sum of the same budget items in tables 16 and 17 are equal to the corresponding budget item relating to the northern part of the water-budget area in table 11. To achieve this consistency and at the same time subdivide the values in table 11 in proportions most consistent with available hydrologic information, the number of significant figures in many entries in tables 16–19 is greater than the accuracy of these entries warrants.

A possible inconsistency in these data is evident from calculating the recharge per square mile in the four parts of the water-budget area. This inconsistency is due in part to errors in the estimates of individual entries and in part to some deviation from the underlying assumption made in this analysis—especially the assumption that no appreciable change in storage has occurred in these areas during the water-budget period, 1940–65. This assumption is least vaild for southern Nassau County.

TABLE 16.—*Water budget of the northern part of the water-budget area within Nassau County, Long Island, N.Y., water years 1940–65* [1]

Type of water-budget element	No.	Water-budget element	Estimated value of water-budget element (millions of gallons per day)
Inflow	1	Precipitation	210
Internal distribution.	2	Direct runoff	2
	3	Ground water recharge [2]	100
	4	Ground-water discharge to streams [3]	14
Outflow	5	Evapotranspiration of precipitation [4]	108
	6	Subsurface outflow of ground water	85
	7	Streamflow discharging to salt water	16
	8	Evapotranspiration of ground water [5]	1

[1] The quantities in this table were derived with the assumption that no significant change in ground-water storage occurred in the water-budget area during the period, water years 1940–65. Independent quantitative estimates were made for all components in the table unless otherwise noted. None of the values in this table are accurate to more than 2 significant figures, and many values are accurate to less. Where more than 2 significant figures are shown, the entry was derived from other entries in the table, and an additional significant figure was retained to balance inflow and outflow.
[2] The estimate of ground-water recharge was obtained by adding components 4, 6, and 8.
[3] The estimate of ground-water discharge to streams was obtained by subtracting component 2 from component 7.
[4] The estimate of evapotranspiration of precipitation was obtained by adding components 6, 7, and 8 and subtracting the total from component 1. Therefore, the subtotal of components 5, 6, 7, and 8 (total outflow) equals component 1 (total inflow).
[5] These values may be in error by as much as 100 percent or more. Values are included mainly to indicate order of magnitude.

TABLE 17.—*Water budget of the northern part of the water-budget area within Suffolk County, Long Island, N.Y., water years 1940–65* [1]

Type of water-budget element	No.	Water-budget element	Estimated value of water-budget element (millions of gallons per day)
Inflow	1	Precipitation	440
Internal distribution.	2	Direct runoff	3
	3	Ground water recharge [2]	220
	4	Ground-water discharge to streams [3]	31
Outflow	5	Evapotranspiration of precipitation [4]	217
	6	Subsurface outflow of ground water	185
	7	Streamflow discharging to salt water	34
	8	Evapotranspiration of ground water [5]	4

[1] The quantities in this table were derived with the assumption that no significant change in ground-water storage occurred in the water-budget area during the period, water years 1940–65. Independent quantitative estimates were made for all components in the table unless otherwise noted. None of the values in this table are accurate to more than 2 significant figures, and many values are accurate to less. Where more than 2 significant figures are shown, the entry was derived from other entries in the table, and an additional significant figure was retained to balance inflow and outflow.
[2] The estimate of ground-water recharge was obtained by adding components 4, 6, and 8.
[3] The estimate of ground-water discharge to streams was obtained by subtracting component 2 from component 7.
[4] The estimate of evapotranspiration of precipitation was obtained by adding components 6, 7, and 8 and subtracting the total from component 1. Therefore, the subtotal of components 5, 6, 7, and 8 (total outflow) equals component 1 (total inflow).
[5] These values may be in error by as much as 100 percent or more. Values are included mainly to indicate order of magnitude.

TABLE 18.—*Water budget of the southern part of the water-budget area within Nassau County, Long Island, N.Y., water years 1940–65* [1]

Type of water-budget element	No.	Water-budget element	Estimated value of water-budget element (millions of gallons per day)
Inflow	1	Precipitation	260
Internal distribution.	2	Direct runoff	5
	3	Ground water recharge [2]	113
	4	Ground-water discharge to streams [3]	50
Outflow	5	Evapotranspiration of precipitation [4]	142
	6	Subsurface outflow of ground water	60
	7	Streamflow discharging to salt water	55
	8	Evapotranspiration of ground water [5]	3

[1] The quantities in this table were derived with the assumption that no significant change in ground-water storage occurred in the water-budget area during the period, water years 1940–65. Independent quantitative estimates were made for all components in the table unless otherwise noted. None of the values in this table are accurate to more than 2 significant figures, and many values are accurate to less. Where more than 2 significant figures are shown, the entry was derived from other entries in the table, and an additional significant figure was retained to balance inflow and outflow.
[2] The estimate of ground-water recharge was obtained by adding components 4, 6, and 8.
[3] The estimate of ground-water discharge to streams was obtained by subtracting component 2 from component 7.
[4] The estimate of evapotranspiration of precipitation was obtained by adding components 6, 7, and 8 and subtracting the total from component 1. Therefore, the subtotal of components 5, 6, 7, and 8 (total outflow) equals component 1 (total inflow).
[5] These values may be in error by as much as 100 percent or more. Values are included mainly to indicate order of magnitude.

TABLE 19.—*Water budget of the southern part of the water-budget area within Suffolk County, Long Island, N.Y., water years 1940–65* [1]

Type of water-budget element	No.	Water-budget element	Estimated value of water-budget element (millions of gallons per day)
Inflow	1	Precipitation	690
Internal distribution.	2	Direct runoff	10
	3	Ground water recharge [2]	352
	4	Ground-water discharge to streams [3]	225
Outflow	5	Evapotranspiration of precipitation [4]	328
	6	Subsurface outflow of ground water	120
	7	Streamflow discharging to salt water	235
	8	Evapotranspiration of ground water [5]	7

[1] The quantities in this table were derived with the assumption that no significant change in ground-water storage occurred in the water-budget area during the period, water years 1940–65. Independent quantitative estimates were made for all components in the table unless otherwise noted. None of the values in this table are accurate to more than 2 significant figures, and many values are accurate to less. Where more than 2 significant figures are shown, the entry was derived from other entries in the table, and an additional significant figure was retained to balance inflow and outflow.
[2] The estimate of ground-water recharge was obtained by adding components 4, 6, and 8.
[3] The estimate of ground-water discharge to streams was obtained by subtracting component 2 from component 7.
[4] The estimate of evapotranspiration of precipitation was obtained by adding components 6, 7, and 8 and subtracting the total from component 1. Therefore, the subtotal of components 5, 6, 7, and 8 (total outflow) equals component 1 (total inflow).
[5] These values may be in error by as much as 100 percent or more. Values are included mainly to indicate order of magnitude.

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