Urbanization and Recharge in the Vicinity of East Meadow Brook, Nassau County, New York

Part 1—Streamflow and Water-Table Altitude, 1939-90

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U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 96-4187

Prepared in cooperation with the
NASSAU COUNTY DEPARTMENT OF PUBLIC WORKS

Coram, New York
1997

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CONVERSION FACTORS, ABBREVIATIONS AND VERTICAL DATUM

Multiply	By	To Obtain
	Length	
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	4,047	square meter
square mile (mi^2)	2.59	square kilometer
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second

Other abbreviations used

year (yr)
second (s)
minute (min)
inches per year (in/yr)
feet per day (ft/d)

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

Urbanization And Recharge In The Vicinity Of East Meadow Brook, Nassau County, New York

Part 1—Streamflow and Water-Table Altitude, 1939-90

By Michael P. Scorca

Abstract

Streamflow of East Meadow Brook and nearby ground-water levels were examined as part of a 1988-94 multidisciplinary study of the response of the hydrologic system near the stream to channel modification and to a large increase in the extent of the sanitary-sewer and storm-sewer systems since the 1940's. Sanitary sewers were installed to protect ground-water quality; Sewer District 2, in western Nassau County, and Sewer District 3, in eastern Nassau County, were completed in 1964 and 1988, respectively.

Analyses of precipitation data indicate that local precipitation was greater and more variable during the 1980's than previously. Water-level records from two wells near East Meadow Brook in Sewer District 3 were compared with those from two wells in an unsewered, sparsely developed part of Suffolk County. Water levels at well N1615, within East Meadow Brook's drainage area in the western part of Sewer District 3, have decreased 6 ft since 1954. Storm sewers and sanitary sewers in Sewer District 2 accounted for about half of this decline; the rest of the decline can be attributed to the effect of sewers in Sewer District 3 since 1974. Water levels at well N1197, near the center of Sewer District 3, showed little response to the operation of Sewer District 2 but have declined 7.5 ft since the early 1970's as a result of the completion of storm sewers and sanitary sewers in Sewer District 3.

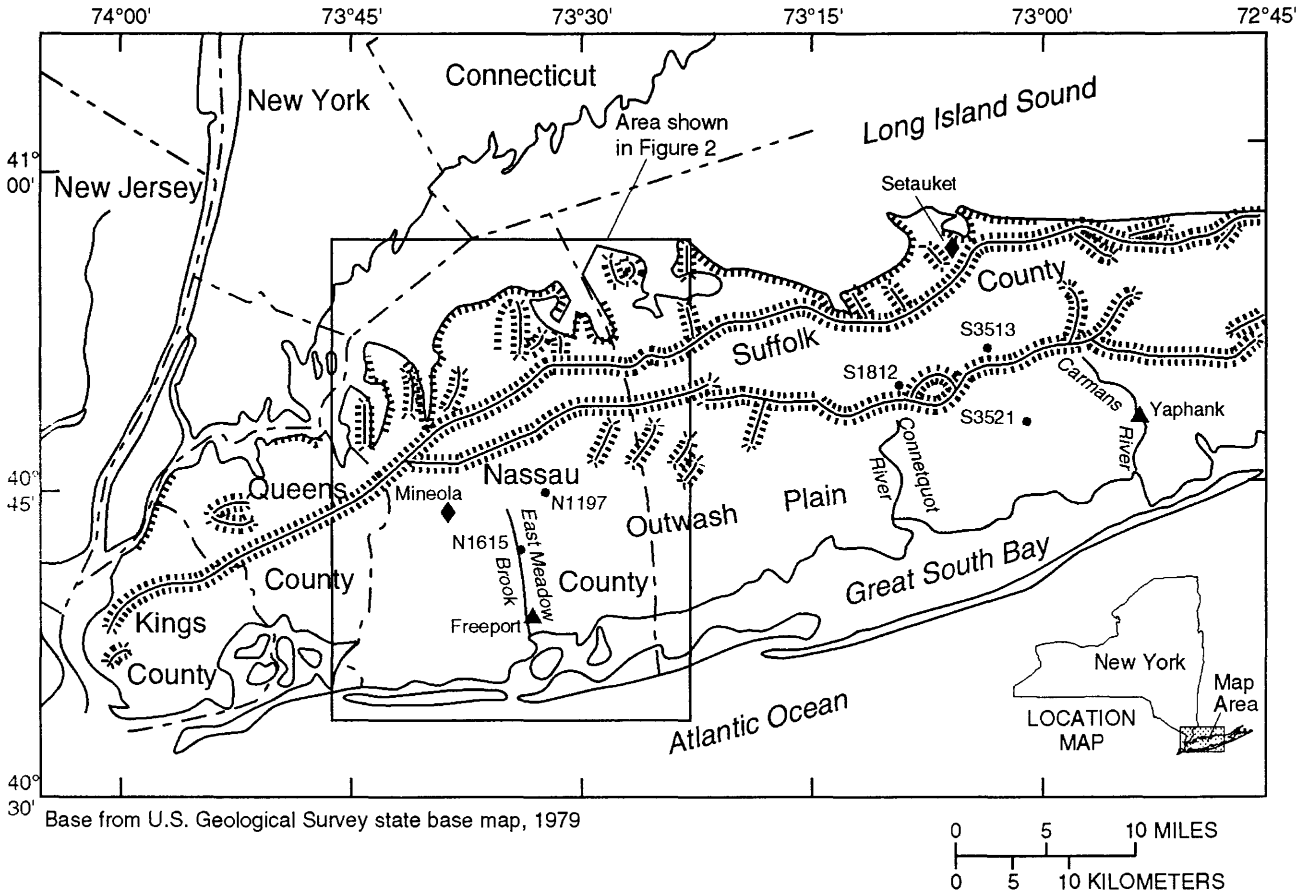
Lowered ground-water levels have shortened the continuous-flow reach of East Meadow Brook and decreased base-flow discharge by 65 to 70 percent since the predevelopment period, and have caused a reduction in total stream discharge. The percentage of streamflow contributed by base flow began to decrease in 1953 and, by the 1970's, had declined from its estimated predevelopment value (95 percent of total streamflow) to about 65 percent of total streamflow. An additional decline to 55 percent of total streamflow in the late 1970's and 1980's is attributed to the effects of Sewer District 3.

A water-budget analysis indicates that direct runoff to East Meadow Brook has increased 2.5-fold since the early 1940's as a result of the construction of roads with storm sewers that drain into the stream. The percentage of total streamflow that is derived from direct runoff has increased from its estimated predevelopment value of 5 percent to about 45 percent.

INTRODUCTION

Water supply for the 2.6 million inhabitants of Nassau and Suffolk Counties (fig. 1) is derived solely from the underlying aquifer system. The demand for water in these counties during the last 50 years has prompted extensive study of the aquifer system to enable the development of sound water-management programs. These studies have provided extensive hydrologic, geologic, and water-quality information that includes continuous streamflow data for selected streams since the early 1940's.

Nassau County's population nearly doubled from 673,000 to about 1.3 million during 1950-60 and reached a maximum of 1.43 million in 1970; it then declined to about 1.31 million in 1984 (Long Island Regional Planning Board and Long Island Lighting Company, 1987). Rapid urbanization of the county in the last 50 years has been accompanied by sharp increases in pumpage and in the use of storm sewers and sanitary sewers. Storm sewers channel surface runoff to streams, south-shore bays, and recharge basins



EXPLANATION

N1197 ● OBSERVATION WELL -- Numbers are assigned by New York State Department of Environmental Conservation. Prefix N denotes Nassau County; S denotes Suffolk County

▲ STREAMFLOW-GAGING STATION

◆ PRECIPITATION GAGE

GLACIAL MORAINE

Figure 1. Locations of selected geographic features and hydrologic data-collection sites on Long Island, N.Y. (Modified from McClymonds and Franke, 1972, fig. 2.)

(shallow, unlined pits that allow stormwater to percolate through unsaturated sediment to the water table for flood control and ground-water replenishment), and sanitary sewers transport wastewater to nearshore processing facilities that discharge the waste offshore after treatment to prevent the entry of sewage into the aquifer system. Storm sewers in some parts of Nassau County that are close to streams carry runoff from roads into the streams, from which it flows to tidewater, and storm sewers in inland areas without streams carry the runoff to recharge basins.

East Meadow Brook, a southward flowing stream near the border between Sewer Districts 2 and 3 (fig. 2), receives runoff from several storm sewers. Ground-water levels and base flow to East Meadow Brook declined substantially during 1953-74 as a result of sanitary sewering in Sewer District 2 (Franke, 1968; Pluhowski and Spinello, 1978); Sewer District 3 was completed during the 1980's, but the effects on East Meadow Brook have not been fully evaluated.

The U.S. Environmental Protection Agency and Nassau County Department of Public Works (NCDPW) studied the environmental effects of decreased streamflow (Lawler, Matusky & Skelly Engineers, 1982) and developed methods to augment streamflow at selected south-shore streams, thereby protecting the freshwater environment. During the

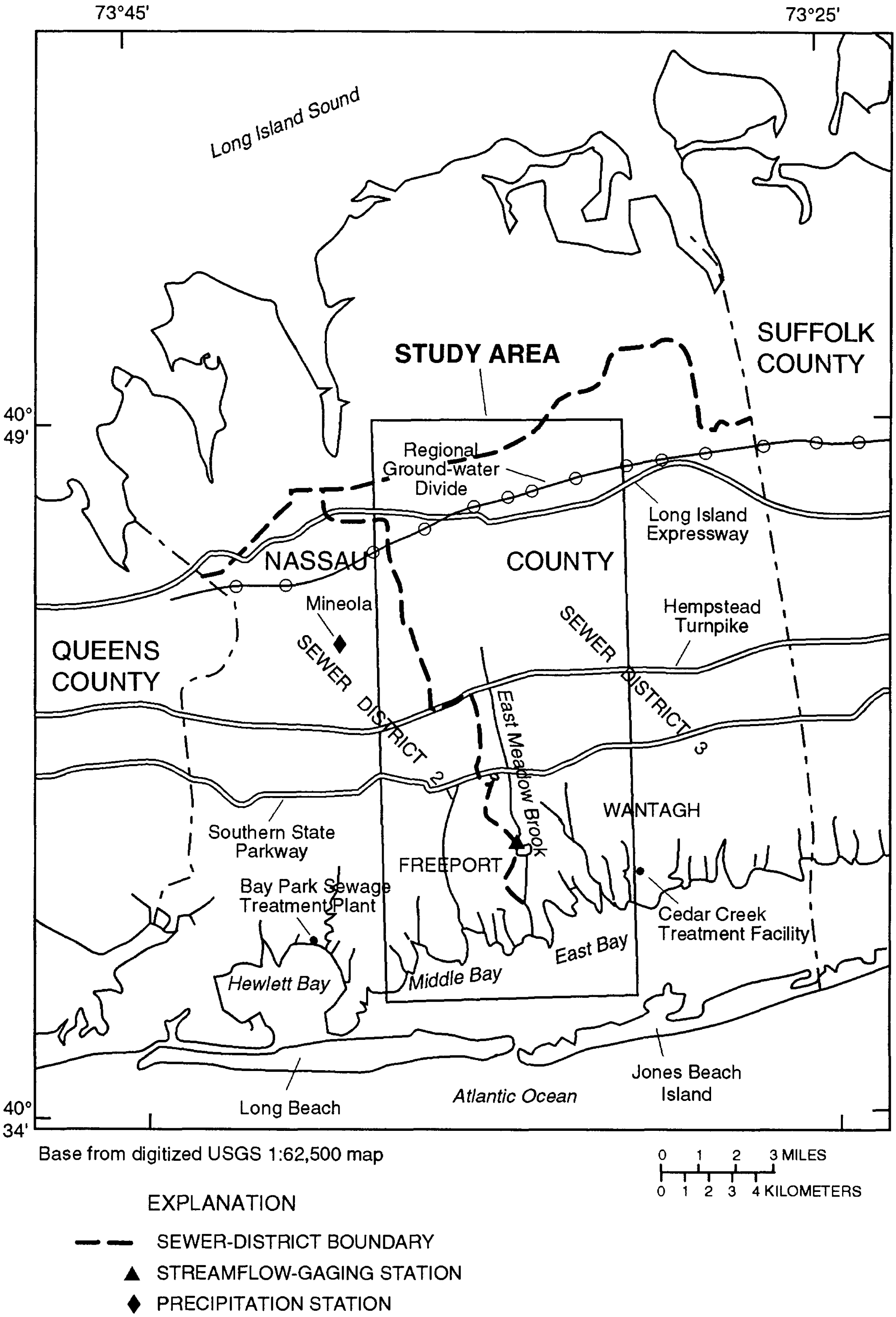


Figure 2. Locations of Sewer Districts 2 and 3, major roads, and selected hydrologic data-collection sites in Nassau County, N.Y. (Location is shown in fig. 1.)

mid-1980's, Nassau County began a stream-channel modification program that included the construction of dams and channel alterations to mitigate hydrologic effects of sewering on streams. As a component of this effort, the U.S. Geological Survey (USGS), in cooperation with the NCDPW, began a detailed investigation at the headwaters of East Meadow Brook in 1988 to evaluate the effects of stream-channel modification on recharge and water quality in the headwaters area. Channel modification at the headwaters and along the length of the stream was begun in 1992. This study provided an opportunity to assess the effects of storm sewers and sanitary sewers in Sewer District 3 on local ground-water levels and streamflow since the last detailed study of the stream in the 1960's (Seaburn, 1969).

Purpose and Scope

This report (1) describes the hydrologic effects of sanitary sewers and stream-directed storm sewers on the flow of East Meadow Brook and ground-water levels in the surrounding area during 1939-90, and (2) quantifies the hydrologic effects of Sewer District 3 on ground-water levels at two selected sites and on base flow of East Meadow Brook. It also provides a basis for evaluation of the effects of stream-channel modification on ground-water levels and streamflow.

Data Presentation

Hydrologic data are commonly presented by water year rather than calendar year. (A water year extends from October 1 of the preceding year through September 30 of the named year.) In this report, annual values for average ground-water levels, precipitation, streamflow, base flow, and direct runoff are given by water year, but lengths of roads with storm sewers, sewage-plant outflows, and water-table hydrographs are presented by calendar year. All comparative hydrologic analyses herein use "water-year" data, and the "calendar year" data provide only an overview of general trends.

Acknowledgments

Thanks are extended to James Mulligan, Brian Schneider, and James Ahearn of the Nassau County Department of Public Works for providing comprehensive information on the storm-sewer network. Thanks are also extended to Dr. O.L. Franke of the U.S. Geological Survey and the City College of New York for his guidance and suggestions on methods of data analysis during this project.

HYDROGEOLOGIC SETTING

Long Island is underlain by unconsolidated sediments of Late Cretaceous to Quaternary age that rest on a southward-dipping bedrock surface. Nassau County's hydrogeologic setting has been described in detail by Suter and others (1949), Perlmutter and Geraghty (1963), and Ku and others (1975). A summary of principal hydrogeologic units is given in table 1; a generalized hydrogeologic section through Nassau County is presented in figure 3.

Pleistocene Deposits

The uppermost major stratigraphic unit on Long Island, which is the only unit of concern in this study, consists of glacial outwash, till, and glaciolacustrine sediments of upper Pleistocene age. Long Island was at the edge of the Wisconsinan continental ice sheet, which deposited two major terminal moraines (fig. 1). The area south of these moraines, which contains the study area, is an outwash plain that consists mostly of brown to tan quartzose sand and gravel deposits. The glacial deposits in the study area range from 50 to 200 ft in thickness.

The saturated upper Pleistocene deposits form the water-table (upper glacial) aquifer throughout most of Long Island. These deposits are highly permeable, as indicated by the estimated average hydraulic conductivity of 270 ft/d (Smolensky and others, 1989). The upper glacial aquifer underlies the entire study area and is the source of base flow in East Meadow Brook.

Table 1. Generalized description of hydrogeologic units underlying Nassau County, N.Y.

[Modified from Jensen and Soren, 1971, table 1; and Smolensky and others, 1989, table 1. Ft/d, feet per day]

Hydrogeologic unit	Geologic unit	Description and water-bearing character
Upper glacial aquifer	Upper Pleistocene deposits	Mainly brown and gray sand and gravel deposits of moderately high horizontal hydraulic conductivity (270 ft/d); may also include deposits of clayey till and lacustrine clay of low hydraulic conductivity. A major aquifer.
Gardiners Clay	Gardiners Clay	Green and gray clay, silt, clayey and silty sand, and some interbedded clayey and silty gravel. Unit has low vertical hydraulic conductivity (0.001 ft/d) and tends to confine water in underlying aquifer.
Magothy aquifer	Matawan Group and Magothy formation, undifferentiated	Gray and white fine to coarse sand of moderate horizontal hydraulic conductivity (50 ft/d). Generally contains sand and gravel beds of low to high conductivity in basal 100 to 200 ft. Contains much interstitial clay and silt, and lenses of clay of low hydraulic conductivity. A major aquifer.
Raritan confining unit	Unnamed clay member of the Raritan Formation	Gray, black, and multicolored clay and some silt and fine sand. Unit has low vertical hydraulic conductivity (0.001 ft/d) and confines water in underlying aquifer.
Lloyd aquifer	Lloyd Sand Member of the Raritan Formation	White and gray fine-to-coarse sand and gravel of moderate horizontal hydraulic conductivity (40 ft/d) and some clayey beds of low hydraulic conductivity.
Bedrock	Undifferentiated crystalline bedrock	Mainly metamorphic rocks of low hydraulic conductivity; considered to be the bottom of the ground-water reservoir.

Hydrologic Cycle

The hydrologic cycle on Long Island is discussed at length by Franke and McClymonds (1972), who evaluated the relations among major hydrologic factors such as rainfall, evapotranspiration, direct runoff, ground-water recharge, ground-water movement, and pumpage to develop an islandwide water budget. The hydrologic cycle can be thought of as beginning with precipitation, which has averaged 44.82 in/yr at Mineola, just west of East Meadow Brook (fig. 2), since 1938 (National Oceanic and Atmospheric Administration, 1938-90). Upon reaching the ground, precipitation either flows as surface runoff into a stream, infiltrates into the unsaturated zone, or evaporates. Part of the water that infiltrates the soil evaporates or is transpired by plants; the rest percolates downward to the water table.

Before water-supply pumpage and construction of storm sewers and sanitary sewers became extensive enough to affect hydrologic conditions severely, Long Island streams derived 95 percent of their total flow from ground water (Franke and McClymonds, 1972). Flow in these streams is still sustained almost entirely by base flow, but a further decline in ground-water levels could cause the upper reaches of some streams to become dry.

Precipitation

Precipitation is measured at several National Weather Service stations on Long Island. The stations at Mineola, west of East Meadow Brook (fig. 2), and at Setauket, near Carmans River in Suffolk County

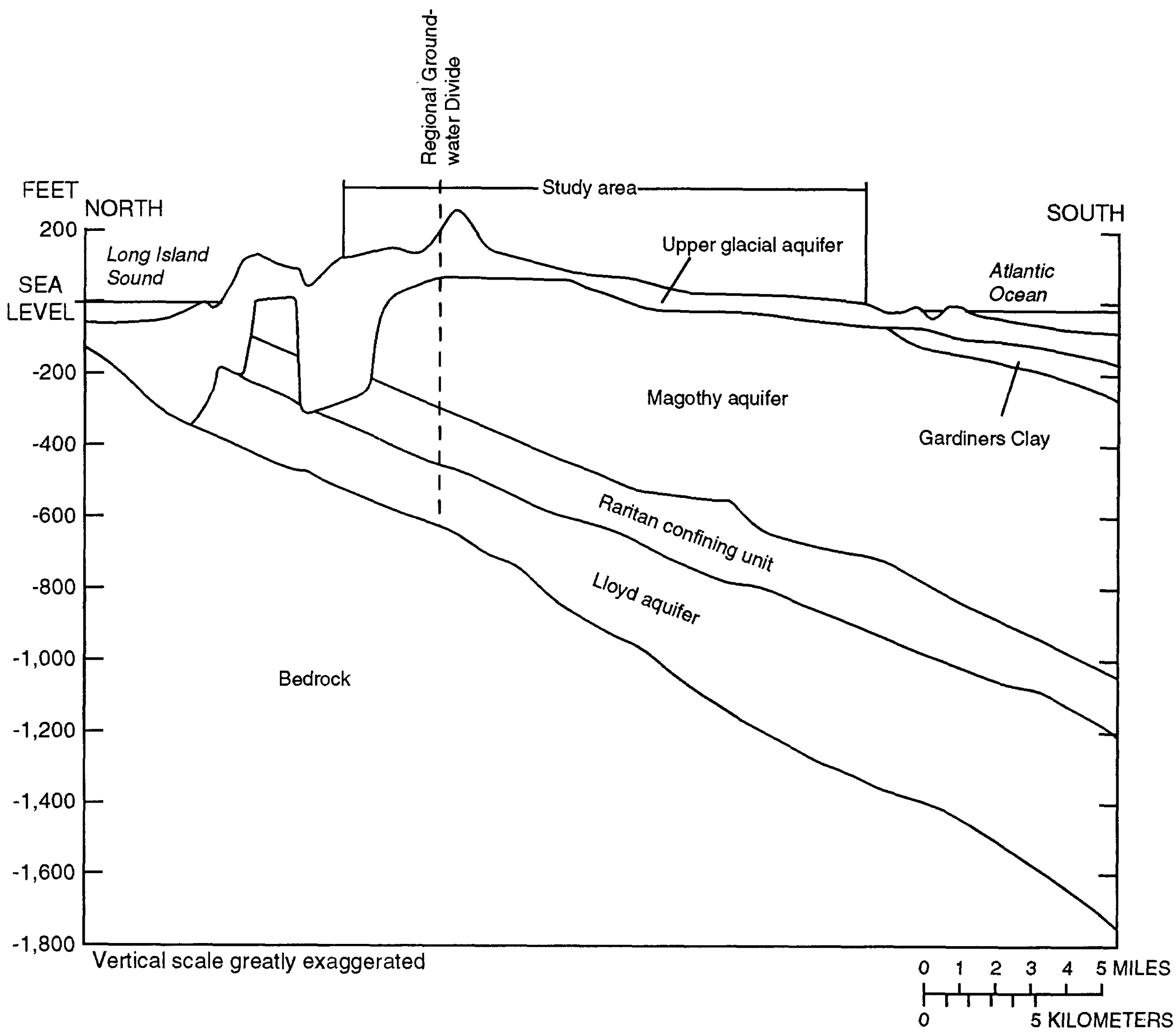


Figure 3. Generalized hydrogeologic section through Nassau County, N.Y. (Modified from Smolensky and others, 1989, sheet 1.)

(fig. 1), were selected for use in this study because they have long periods of continuous record and are near the two streams (East Meadow Brook and Carmans River), whose records were to be analyzed and compared.

Mineola.—Mean annual precipitation at Mineola for 1939-90 is 44.82 in/yr (fig. 4A). Annual precipitation has ranged from a maximum of 69.64 in/yr (1984) to a minimum of 27.27 in/yr (1965).

Although a thorough evaluation of Long Island's precipitation regime was beyond the scope of this study, a few general trends can be pointed out. The magnitude and range of annual precipitation measured before and during the 1962-66 drought (1939-66) differ from those measured after the drought (1967-90), as indicated by the 10-year-moving means of precipitation amounts and standard deviations (figs. 4B, 4C). The 10-year-moving mean of precipitation amounts peaked during 1975-84 but reached its second-highest level during 1981-90. The 10-year-moving mean of the standard deviation reached its highest level during 1980-89. These high moving averages indicate that

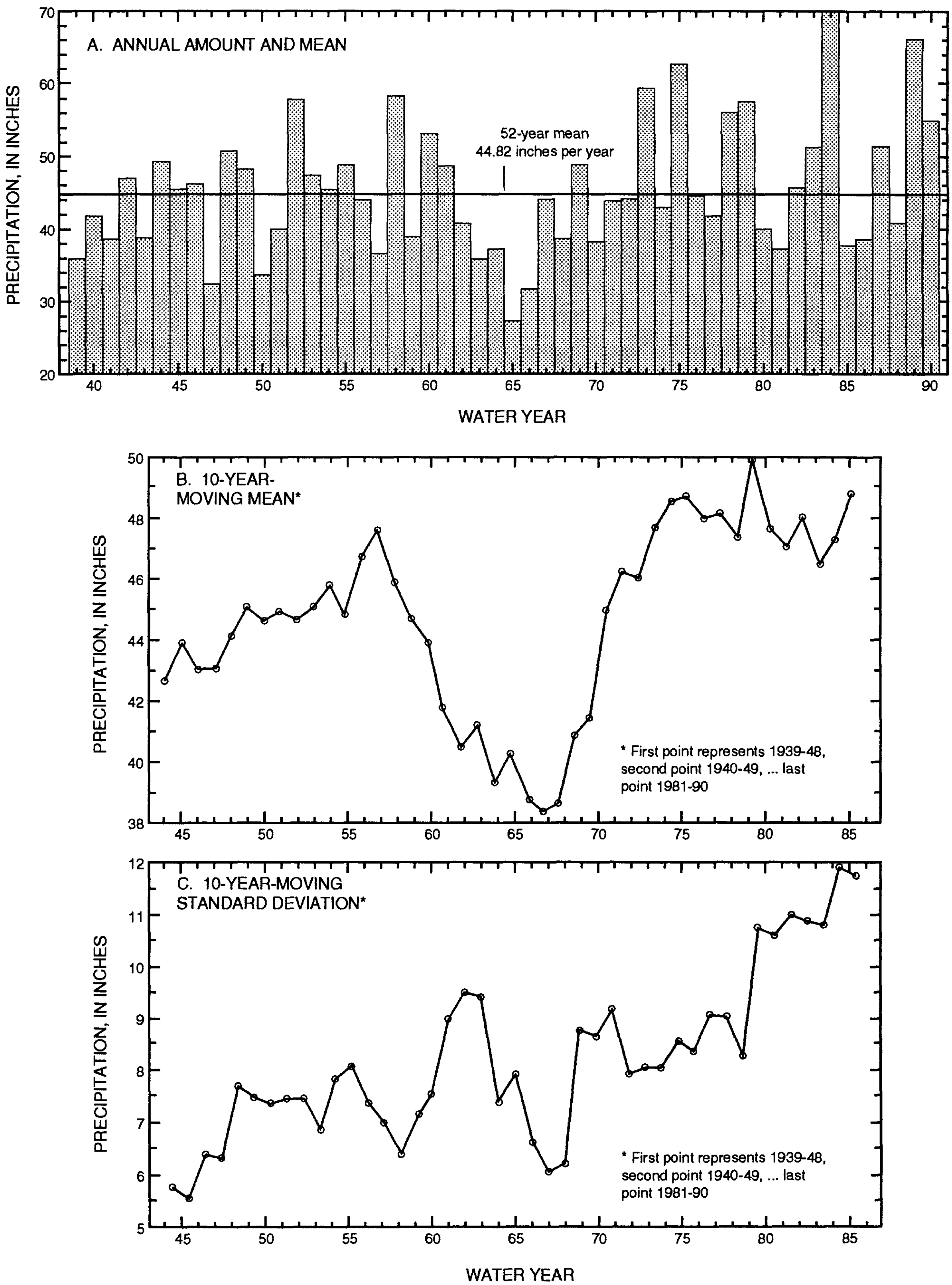


Figure 4. Precipitation at Mineola, N.Y. A. Annual amount and mean, 1939-90. B. 10-year-moving mean. C. 10-year-moving standard deviation.

annual precipitation was greater and more variable during the 1980's than previously.

Precipitation during 1939-66 exceeded 50 in/yr four times but never exceeded 60 in/yr. Precipitation during 1967-90 exceeded 50 in/yr nine times and exceeded 60 in/yr three times. Precipitation less than 40 in/yr was recorded 11 times during 1939-66 and only 6 times during 1967-90. Precipitation has not been less than 35 in/yr since 1966, although values below this amount were recorded four times during 1939-66.

Box plots (described by Chambers and others, 1983) illustrate the distribution of values within a data set by showing the median value, the interquartile range, the values within 1.5 times the interquartile range, and outliers. Box plots of precipitation at the Mineola station during four selected periods are shown in figure 5. These time periods were selected to represent significant events before and during urbanization. The first period, 1939-49, was a period of little road construction and no sanitary-sewer construction. The second period, 1950-64, was one with extensive road and storm-sewer construction and the construction of Sewer District 2. The third period, 1965-73, represents the time between the completion of Sewer District 2 and the start of Sewer District 3. The fourth period, 1974-90, spans the period of construction of Sewer District 3 and 2 years after its completion.

The median precipitation values for each time period in figure 5 are nearly equal, but the distribution of values differs. Values in the first and second periods are similar, and those in the third period are noticeably lower than those in the first and second. The last period shows the widest range and the highest values.

Setauket.—Records from the Setauket precipitation station, in Suffolk County (fig. 1), reflect rainfall amounts near Carmans River, whose drainage area is relatively undeveloped. This area is used herein as a basis for comparison with the urbanized, sewered East Meadow Brook drainage area described in this report.

The Setauket station has the longest continuous record of precipitation on Long Island; its record began in 1885.The records that were examined in this study represent 1939-90 (fig. 6) and encompass both the maximum and minimum annual precipitation ever recorded at Setauket. The minimum, 30.77 in/yr, was in 1966; the maximum, 63.0 in/yr, was in 1984.

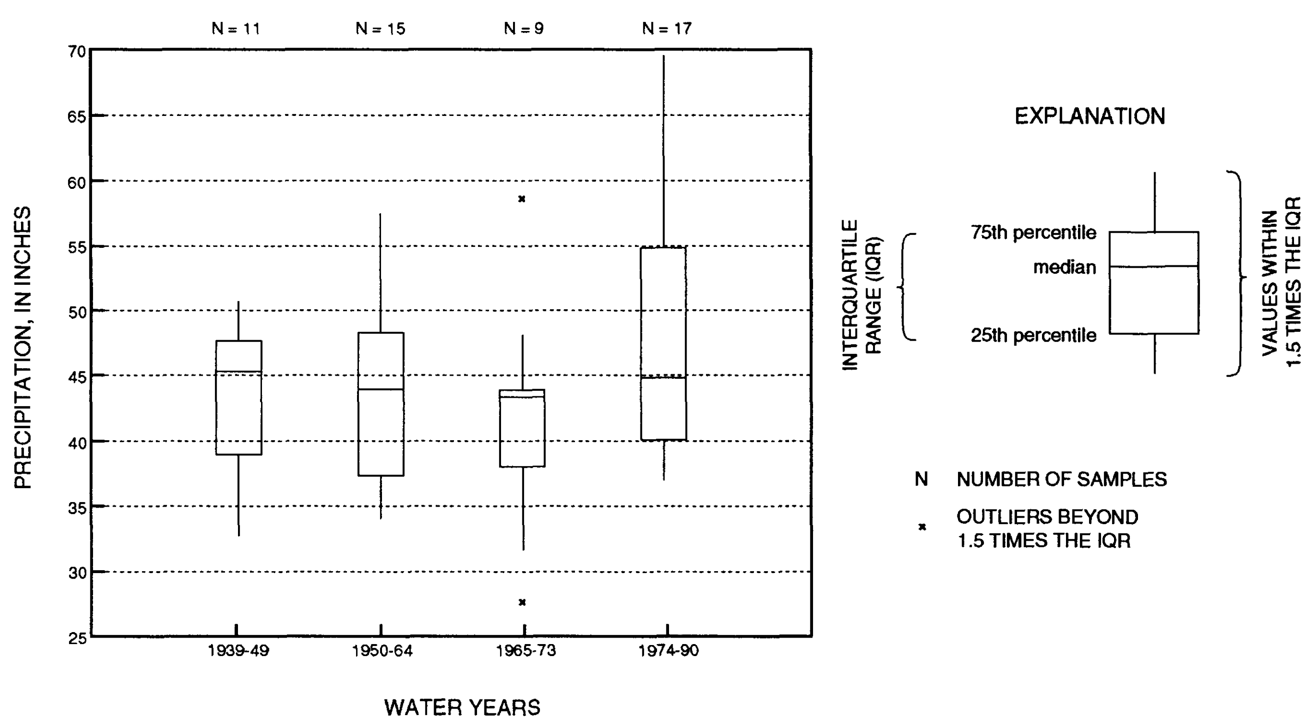


Figure 5. Precipitation at Mineola, N.Y., during four selected periods.

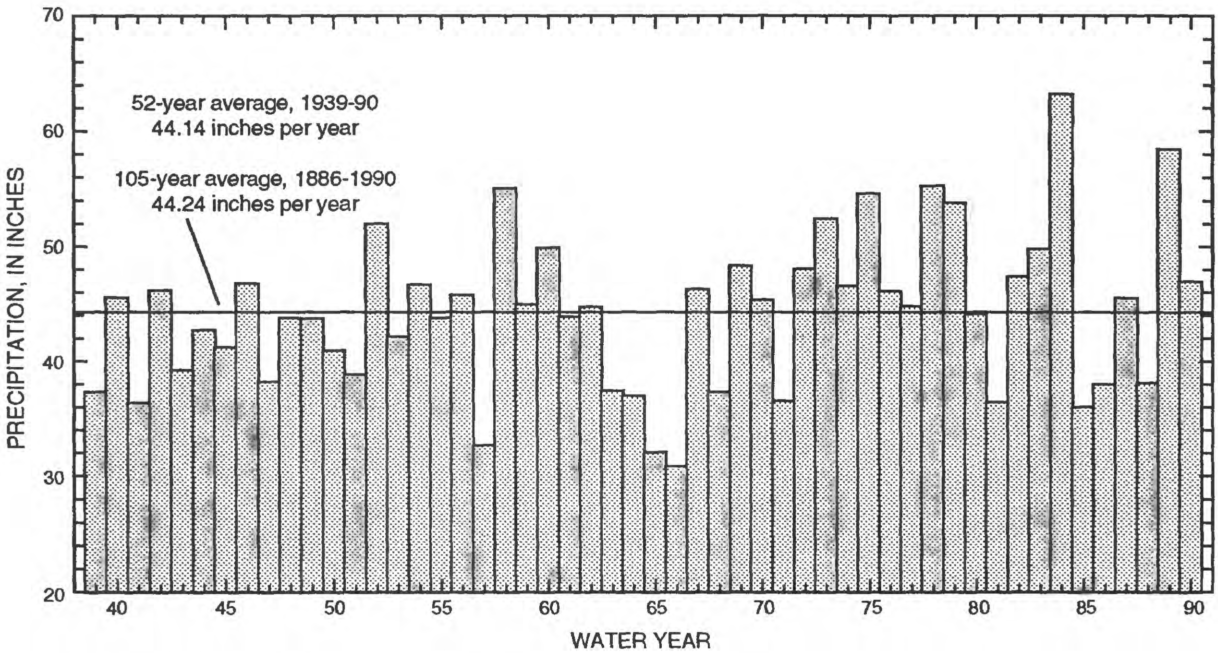


Figure 6. Annual precipitation at Setauket, N.Y., 1939-90.

Ground-Water Flow

The Long Island ground-water system consists of two components—the regional flow system and the shallow flow system associated with streams (fig. 7). Ground water enters the regional flow system along the main ground-water divide (fig. 2), where it moves downward through the water-table aquifer into the underlying aquifers and eventually moves seaward. Water that enters the regional flow system south of the divide flows southward and discharges to tidewater beneath the south-shore bays or the Atlantic Ocean; water that infiltrates north of the divide flows northward and discharges to tidewater beneath Long Island Sound. All precipitation that infiltrates upgradient of each stream's shallow flow system becomes part of the regional flow system; precipitation that infiltrates within the ground-water contributing area of a stream becomes part of that stream's shallow flow system (fig. 7).

Recharge and Discharge

Recharge to the water table on Long Island can vary widely from year to year as a function of precipitation; recharge also fluctuates seasonally because plants capture and transpire most of the water in the unsaturated zone during the growing season (May through October), so virtually all recharge occurs during the nongrowing season (November through April) in most years (Warren and others, 1968). The water table rises in response to recharge and typically exhibits a net rise in years when precipitation is notably higher than in the preceding year. This rise, in turn, results in increased ground-water discharge to streams, to the south-shore bays, and to the ocean.

Before extensive urbanization, about 50 percent of the annual precipitation in undeveloped areas of Long Island was lost as evapotranspiration and direct runoff; the other 50 percent infiltrated the soils and recharged the ground-water system (Aronson and Seaburn, 1974; Franke and McClymonds, 1972). These percentages could vary considerably from wet to dry years and from place to place, but are adequate for purposes of this study. After precipitation has entered the ground-water system, it flows seaward and discharges directly to tidewater or, if within the contributing area of a stream, seeps into the stream and becomes base flow.

EAST MEADOW BROOK STUDY AREA

The following sections describe the hydrologic changes that have occurred in the drainage area of East Meadow Brook above the gaging station at Freeport

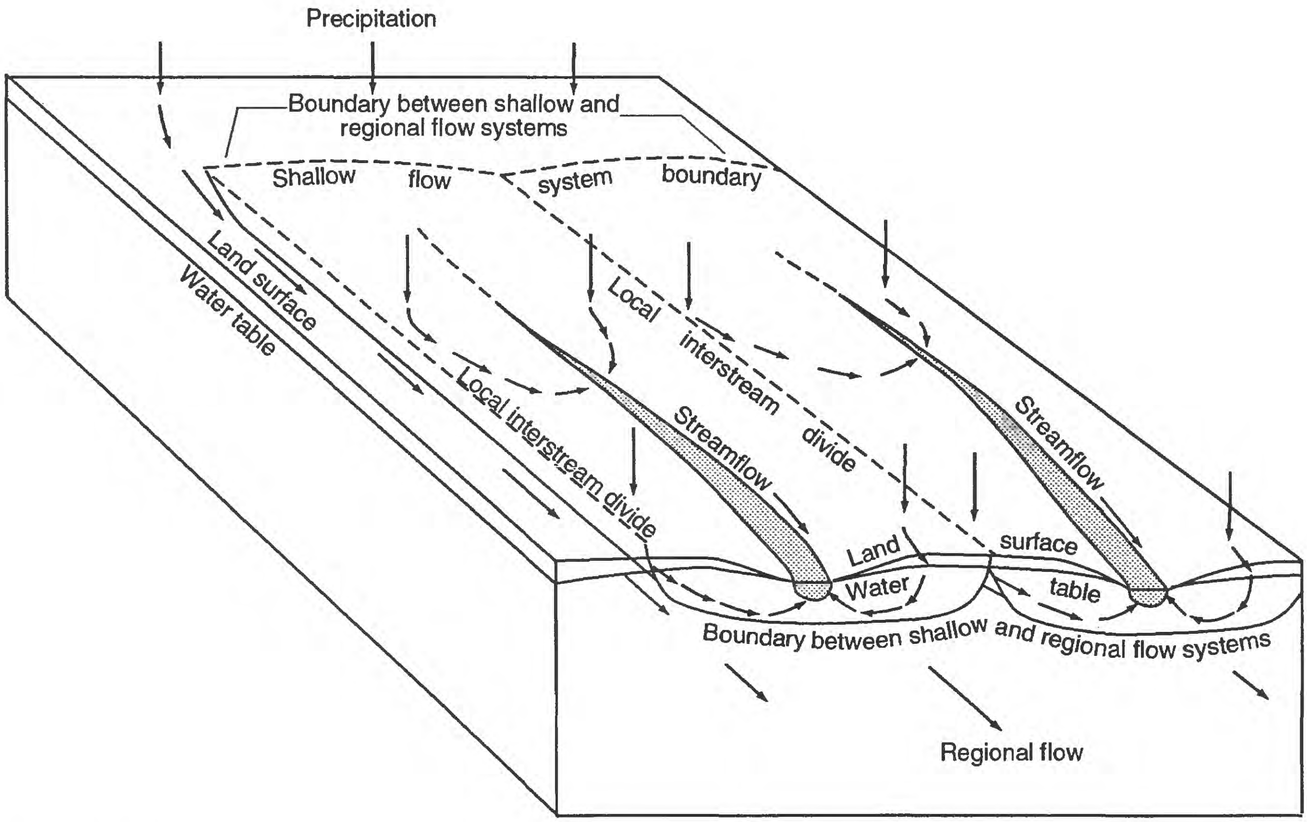


Figure 7. Shallow ground-water system near two typical streams on Long Island, N.Y. (From Prince and others, 1988, fig. 4.)

(fig. 8) since 1939. The boundaries of the drainage area are difficult to delineate because they shift with the water-table altitude and also have changed historically, as discussed further on.

The topographic drainage area of East Meadow Brook encompasses 31 mi^2 and extends into northeast Nassau County (fig. 8). As at other Long Island streams, this topographic drainage area is not closely related to present-day streamflow because it is a relict of streams that drained meltwater from the glaciers at the end of the Pleistocene Epoch. Rather, the area that contributes ground water to a stream ("ground-water contributing area") constitutes the effective drainage area of that stream. East Meadow Brook's ground-water-contributing area is discussed in detail further on.

Location and Hydrologic Characteristics

East Meadow Brook is the largest stream in Nassau County; it flows from near the center of the county southward across the outwash plain and discharges into a saltwater channel between Middle Bay and East Bay (fig. 8) (Seaburn, 1969). It has a maximum length of 7.5 mi and had an annual-mean discharge of 13.9 ft^3/s during 1938-90. East Meadow Brook is in Sewer District 3, near the eastern border of Sewer District 2 (fig. 2). The continuous-record gaging station at Freeport is just north of East Meadow Pond (fig. 8), about 0.5 mi north of the mouth and upstream of the area of tidal influence. East Meadow Brook is mostly less than 5 ft deep and has a gentle gradient of about 12 ft/mi (Seaburn, 1969). The channel generally is 10 to 20 ft across except at the few ponds along its length.

The area around East Meadow Brook has been suburban-residential since the 1940's, and its population density ranges from 5 to 20 persons per acre. The construction of storm sewers that divert runoff from roads has affected the flow characteristics of the stream and altered it physically. The stream channel begins at the convergence of three stormwater culverts 4,500 ft north of Hempstead Tpke (fig. 9). Construction of roads and parking lots north of this point has

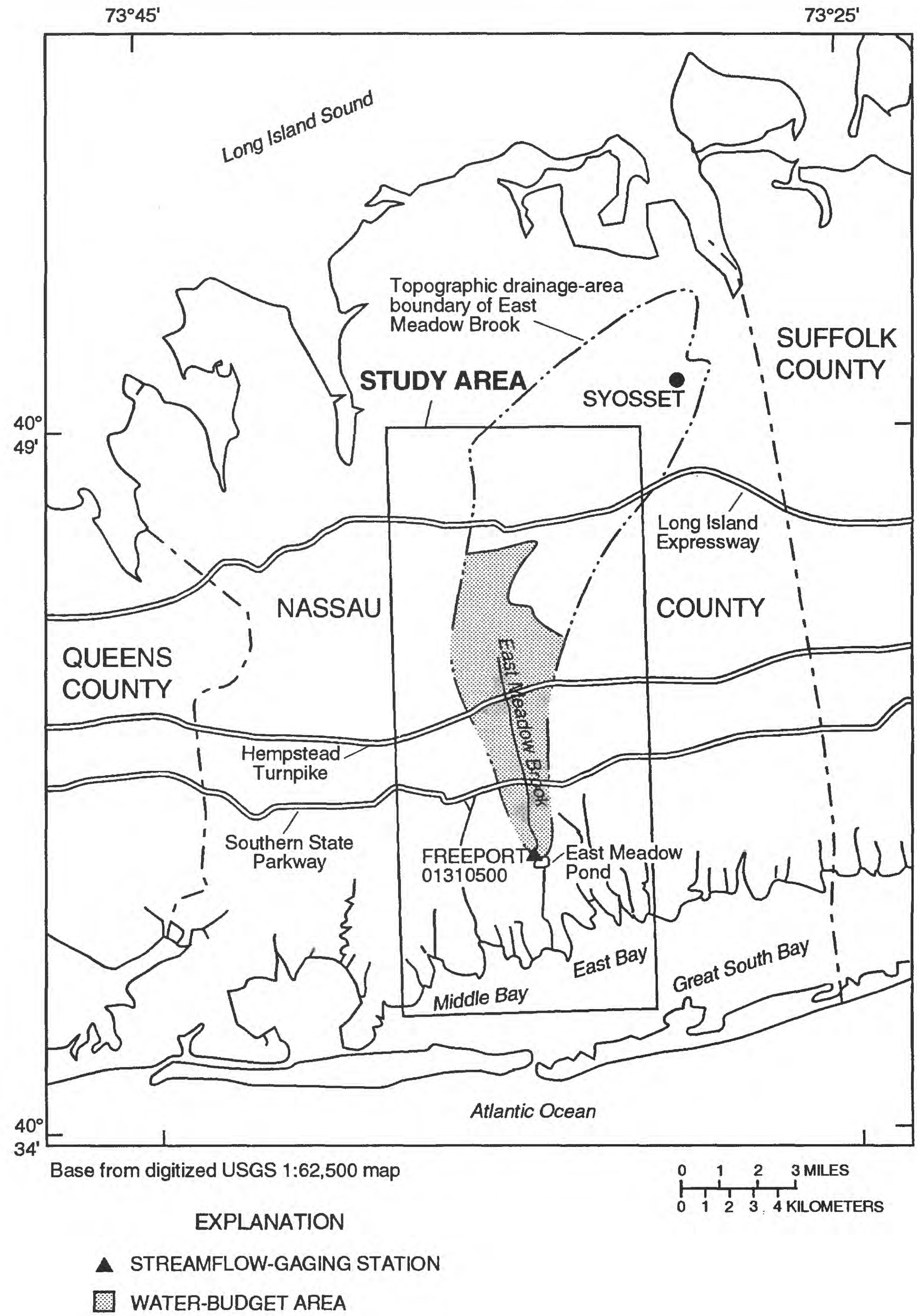
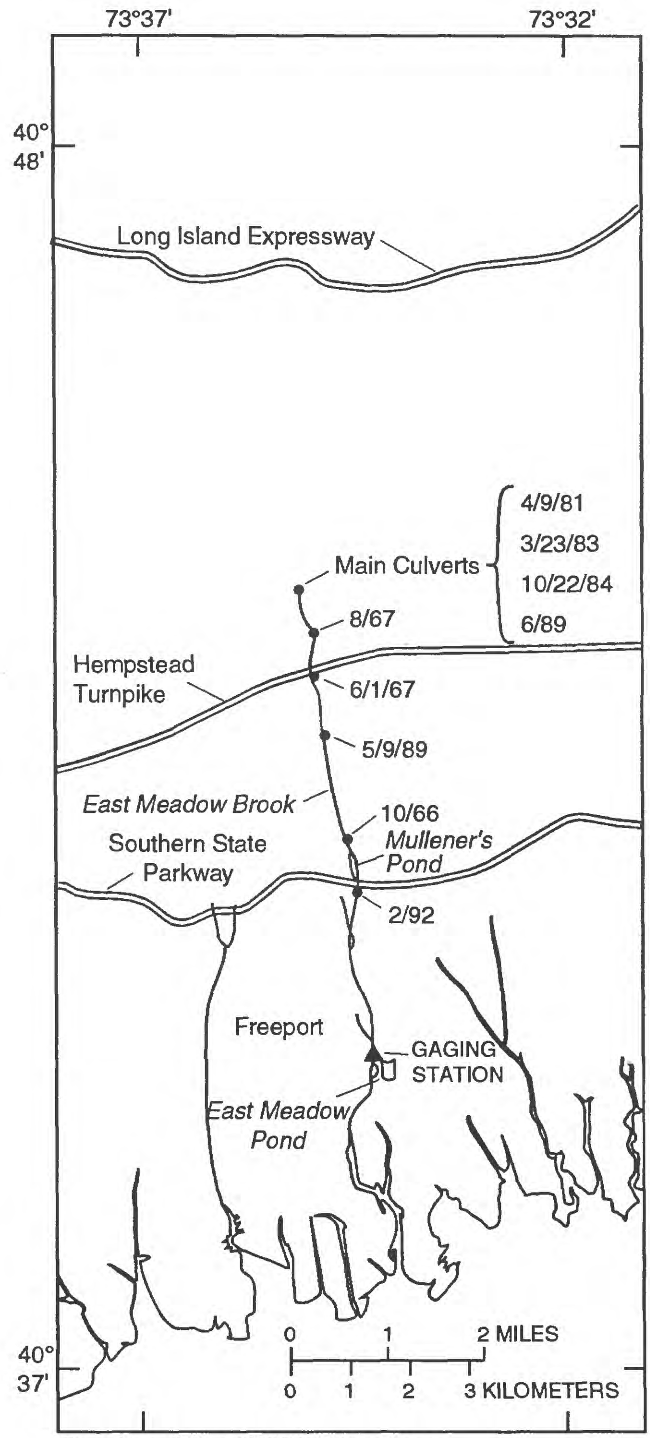


Figure 8. Boundary of topographic drainage area above East Meadow Brook gaging station, Nassau County, N.Y.



EXPLANATION

4/9/81 Date of start-of-flow measurement

Figure 9. Observed locations of start-of-flow in East Meadow Brook, Nassau County, N.Y.

altered the land surface and modified the channel; therefore, the three culverts are the maximum upper limit of the stream, 7.5 mi from the southern shore. The point at which flow begins ("start-of-flow") in the channel shifts with the rise or fall of ground-water levels; therefore the length of the flowing stream also fluctuates.

The northern part of East Meadow Brook's drainage area is not heavily urbanized, and the relatively large amounts of open space and unpaved land surface allow infiltration of larger volumes of storm runoff than in the southern part, which is more highly developed and has a larger percentage of impermeable land surface. The primary method of storm-runoff disposal in the northern part of the drainage area is recharge basins, which transmit stormwater to the underlying aquifer system, whereas the southern part has few recharge basins because the land-surface is close to the water table; here most storm runoff is diverted to the stream by storm sewers and does not recharge the aquifer.

Stream Length and Start-of-Flow

Stream discharge on Long Island consists of base flow (ground-water seepage) and direct runoff (stormwater). Under predevelopment conditions, before ground-water levels were lowered by pumping and by the diversion of wastewater to sewers, 95 percent of the total streamflow was derived from base flow, and the flow of most streams began farther north than in subsequent years.

During intervals between storms, streamflow begins at the point at which the water table intersects the channel. This point (the start-of-flow) reflects the surrounding water-table altitude, and its position shifts in response to water-table fluctuations. The first measurement of start-of-flow in East Meadow Brook was made in October 1966; that and the few subsequent measurements are plotted in figure 9. Because ground-water levels were higher during the early 1900's than in recent years, as illustrated by comparison of water-table maps by Donaldson and Koszalka (1983) and Doriski (1987) with the 1903 water-table map of Veatch and others (1906), flow in East Meadow Brook in the early 1900's probably started north of the three stormwater culverts.

The start-of-flow moves southward during periods of declining ground-water levels, and the length of the flowing stream decreases; conversely, the start-of-flow moves northward when the water table rises, and length of the flowing stream increases. During periods of high ground-water levels, base flow enters the channel at the storm culverts (fig. 9), and the true start-of-flow is not observable. In October 1966, at the end of the 1962-66 drought, the start-of-flow was just north of Mullener's Pond (fig. 9), but as water levels recovered in 1967, it moved northward. In February 1992, the start-of-flow was just south of the Southern State Parkway and the flowing reach was about 3,000 ft shorter than in 1966. Although this measurement was made after 6 months of below-average precipitation, the effect of recent sanitary sewering probably was a major contributing factor.

STREAMFLOW AND WATER-TABLE ALTITUDE

This study entailed compilation of data on streamflow, base flow, and direct runoff at East Meadow Brook for each water year since 1939, and these data are grouped to represent the period of light urbanization (1939-43), and the period of urbanization (1944-90). Comparison of data from the two periods indicates the effects of sanitary and storm sewers on base flow, direct runoff, and total annual stream discharge.

Period of Light Urbanization (1939-43)

Nassau County has become increasingly urbanized throughout the 20th century, but hydrologic conditions at East Meadow Brook were not affected until the early 1940's because the storm- and sanitary-sewer systems were not extensive (Seaburn, 1969). Even though the East Meadow Brook drainage area had moderate pumpage and storm sewers during 1939-43, this is the earliest period for which extensive hydrologic data were available. These data can be used to approximate predevelopment conditions. The first major effect of urbanization was in 1944, as observed by Seaburn (1969) from a plot of cumulative precipitation and direct runoff for 1937-43. Even though the effects of storm sewers and pumping before 1944 had already begun to affect the hydrologic system, they were relatively small, especially in relation to the changes observed later, after major urbanization.

Streamflow

Streamflow on Long Island is derived from two sources—ground-water seepage (base flow) and direct runoff of stormwater from land surface (especially roads and parking lots) and from nearby wetlands. In this study, a hydrograph-separation technique described by Reynolds (1982) was used to quantify the amount of flow contributed by base flow and direct runoff to allow comparison of their proportions before and after urbanization.

Base flow.—Despite the effects of urbanization, most of Long Island's streams maintain a substantial base-flow component. The percentage of streamflow contributed by ground water to East Meadow Brook each year during 1938-49 is shown in figure 10. The stream's base-flow contribution remained between 85 and 95 percent of total flow through 1949; the lesser values indicate that base flow might have already been affected by the slight lowering of ground-water levels by storm sewers along new roads in the area. A.D. Randall (U.S. Geological Survey, retired, written commun., 1994) notes that some years with an above-average base-flow contribution (1939, 1941, 1943, 1947) had low annual precipitation (fig. 5), and years with a below-average contribution (1942, 1944, 1948, 1949) had above average precipitation. A probable reason is that, in years of high precipitation, more of the precipitation became direct runoff than in years of low precipitation; hence, the percentage of streamflow derived from direct runoff increased, and the percentage derived from base flow decreased. This 85- to 95-percent range also indicates, however, that hydrologic conditions were not yet severely affected, and the stream was still fed mainly by ground water.

Direct runoff.—Under predevelopment conditions, direct runoff, also referred to as storm runoff, was derived from precipitation falling directly on the stream's surface and from overland runoff flowing into the stream channel (about 2 percent of precipitation) (Cohen and others, 1968). Because Long Island's soils and surficial sediments allow rapid infiltration, direct runoff to streams under predevelopment conditions averaged only about 5 percent of total annual streamflow. During 1938-49 (fig. 10), the percentage of East Meadow Brook's streamflow that consisted of direct runoff ranged from 5 to 15 percent; the higher values indicate that storm sewers along main roads had begun to cause a reduction in recharge and, thereby, decreased base flow.

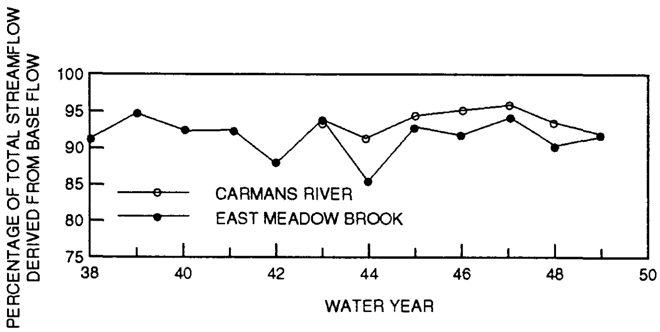


Figure 10. Percentage of streamflow derived from base flow at East Meadow Brook, 1938-49, and Carmans River, 1943-49, Long Island, N.Y. (Locations are shown in fig. 1.)

Water Table

The water-table aquifer provides base flow to Long Island's streams wherever it intersects a streambed, and fluctuations in ground water levels near the stream alter the stream length.

Altitude and fluctuations.—The first water-table map of Long Island was compiled by Veatch and others (1906) for the year 1903; the part that includes the study area is plotted in figure 11. This map is the best available representation of the water table before urban development. The water-table altitudes in the early 1900's were higher, on average, than during the period of urbanization (1944-90). Ground-water levels near the head of East Meadow Brook in 1903 were about 70 ft above sea level, and were about 56 ft and 61 ft above sea level in 1988 and 1990, respectively.

Ground-water levels at three selected wells during 1938-43 are plotted in figure 12. Well N1197 is east of the headwater culverts, just south of the ground-water divide and in the northern part of the area that eventually was established as Sewer District 3 (fig. 2). Well S1812 (fig. 1) is in a part of Suffolk County that was almost completely undeveloped at that time. Well N1615 is near East Meadow Brook, about midway along the stream's length, near the border between Sewer Districts 2 and 3 (fig. 2). The water-table altitude at this well is about midway between that at the regional ground-water divide and that at the south shore. These hydrographs illustrate the normal water-level fluctuations during the period of light urbanization; the difference between maximum and minimum measured levels was about 4 ft at well N1197, 5 ft at well N1615, and 6 ft at well S1812.

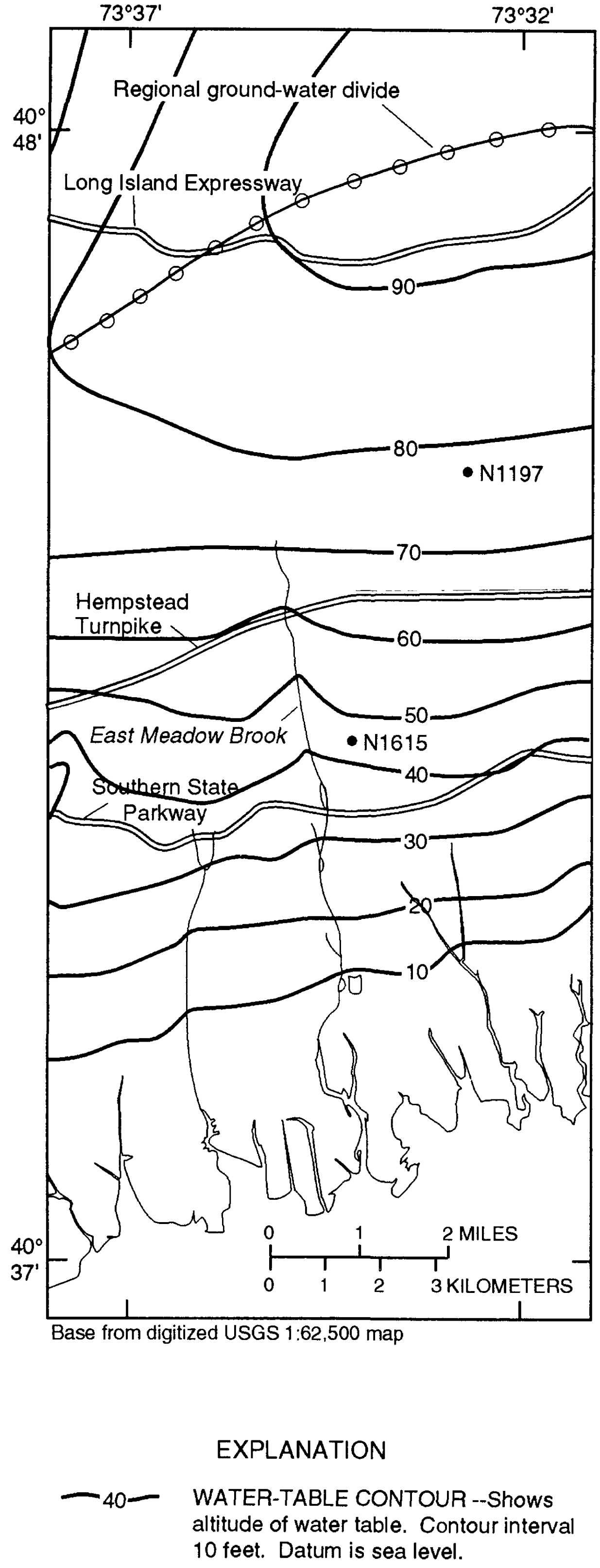


Figure 11. Water-table altitude in study area in 1903, Nassau County, N.Y. (Modified from Veatch and others, 1906, pl. 12.)

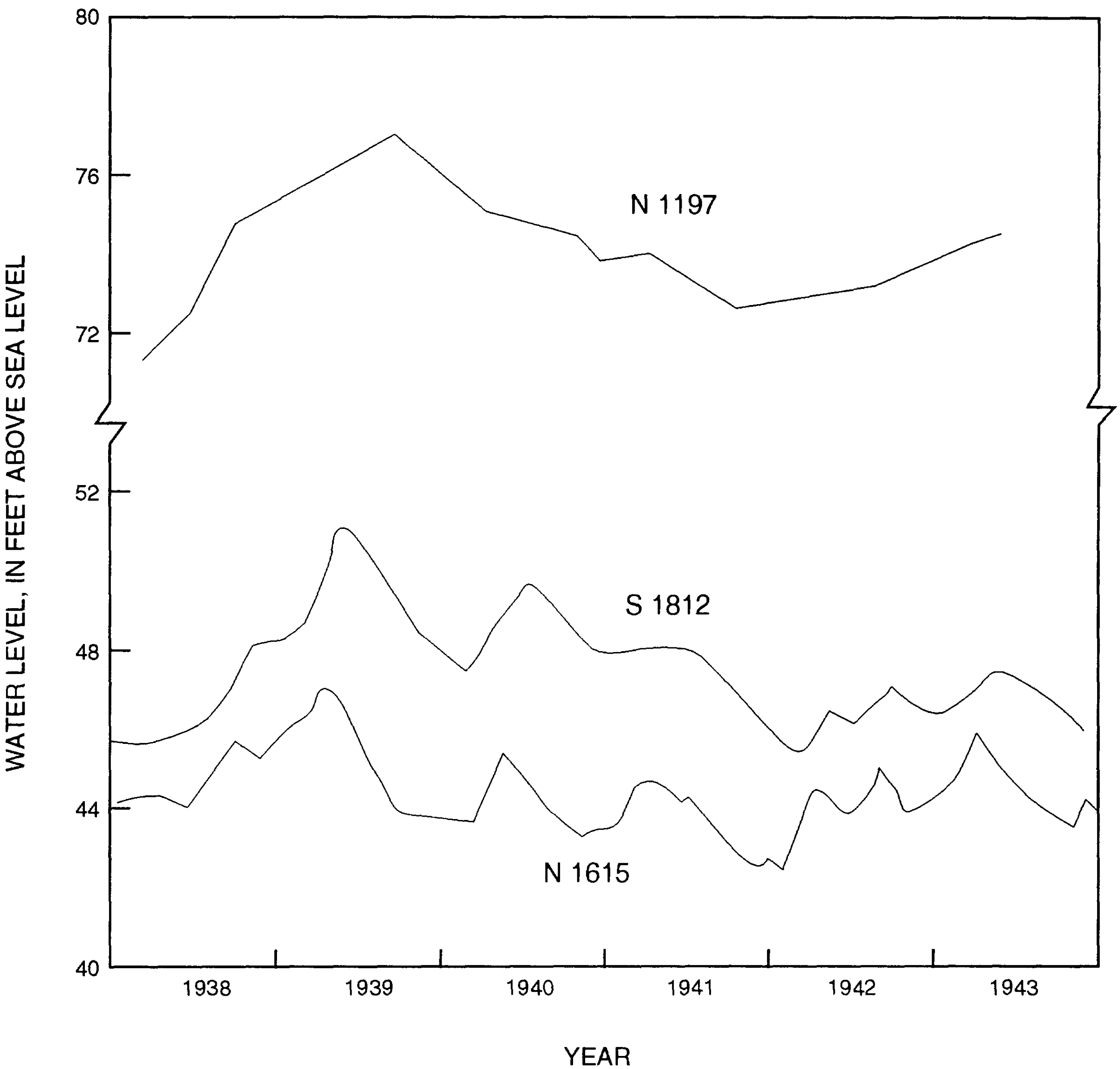


Figure 12. Ground-water levels at three selected wells, Long Island, N.Y., 1938-43. (Locations are shown in fig. 1.)

These ranges were the result of fluctuations in rainfall and seasonal variations in recharge.

Ground-water-contributing area.—The area from which ground water discharges into a stream forms a shallow flow system (fig. 7), generally referred to as a ground-water-contributing area to that stream. The thickness of the shallow flow system and the positions of ground-water divides (especially the upstream boundary of the shallow flow system) are dependent on hydrologic conditions and can shift over time (Prince and others, 1988). The boundaries of a ground-water-contributing area are estimated from water-table maps and the inferred positions of interstream divides, but the thickness of the shallow flow system and the start-of-flow shift constantly with water-table fluctuations. The shallow flow system of East Meadow Brook has been estimated to be 50 to 75 ft thick (Franke and Cohen, 1972).

The ground-water-contributing area of East Meadow Brook in 1961, as delineated by Franke and Cohen (1972), is shown in figure 13. Subsequent water-table maps (Donaldson and Koszalka, 1983;

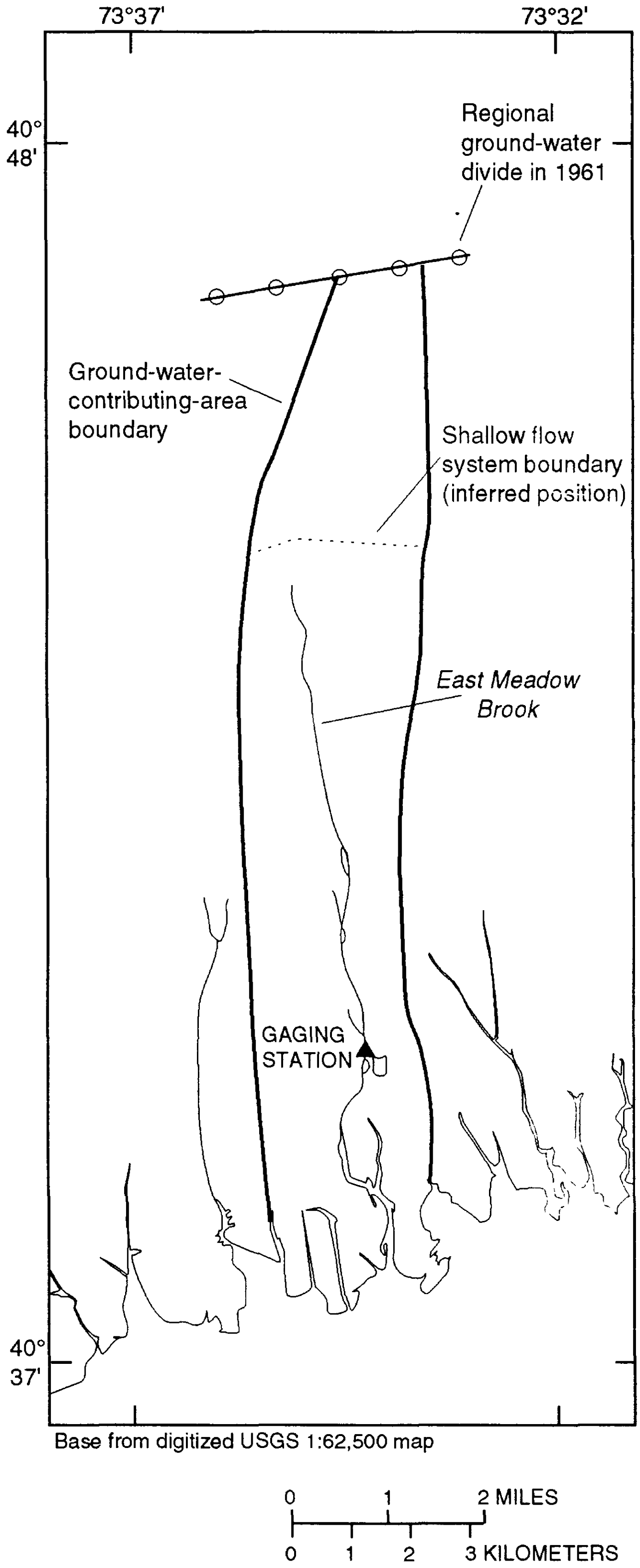


Figure 13. Ground-water-contributing area to East Meadow Brook, Nassau County, N.Y., 1961. (Modified from Franke and Cohen, 1972, fig. 4.)

Doriski, 1987) indicate that the positions of local interstream divides and the ground-water-contributing area have remained fairly stable south of the shallow flow-system's upstream boundary, even though the water-table altitudes have changed. North of that boundary, the local interstream ground-water divides shift significantly in response to water-level changes, but these shifts do not affect the ground-water-contributing area to East Meadow Brook because most of the ground water in this area moves into the regional flow system, rather than into the shallow flow system.

Water Budget (1939-43)

Water budgets provide estimates of flow through the major components of a hydrologic system. The estimates developed in this study provide only an approximation of conditions during the lightly urbanized period because (1) some of the major components cannot be measured directly, and (2) methods for measurement of the other components have limitations. A simplified water budget for the 10-mi^2 study area surrounding East Meadow Brook (fig. 8) is given in figure 14. This area was selected for water-budget analysis because it encompasses the southern part of the topographic drainage area, the storm-sewer network (described in detail further on), and the ground-water-contributing area.

Under lightly urbanized conditions, the main components of the hydrologic system (fig. 14) were precipitation, evapotranspiration, ground-water recharge, direct runoff, ground-water seepage to streams (base flow), surface-water outflow (total streamflow), and subsurface (ground-water) inflow and outflow. Precipitation and streamflow, including base flow and direct runoff, are quantifiable and have been measured in the study area, but evapotranspiration, ground-water recharge, and subsurface inflow and outflow cannot be measured and must be estimated as the difference between measured quantities.

The 1939-43 period represents the first 5 years in which streamflow and precipitation data were collected at East Meadow Brook and vicinity. Seaburn (1969) used cumulative values of precipitation and direct runoff to show that annual direct runoff after 1944 was consistently greater than in 1937-43, and that changes in precipitation were negligible, indicating that the storm-sewer network had begun to affect the hydrologic system.

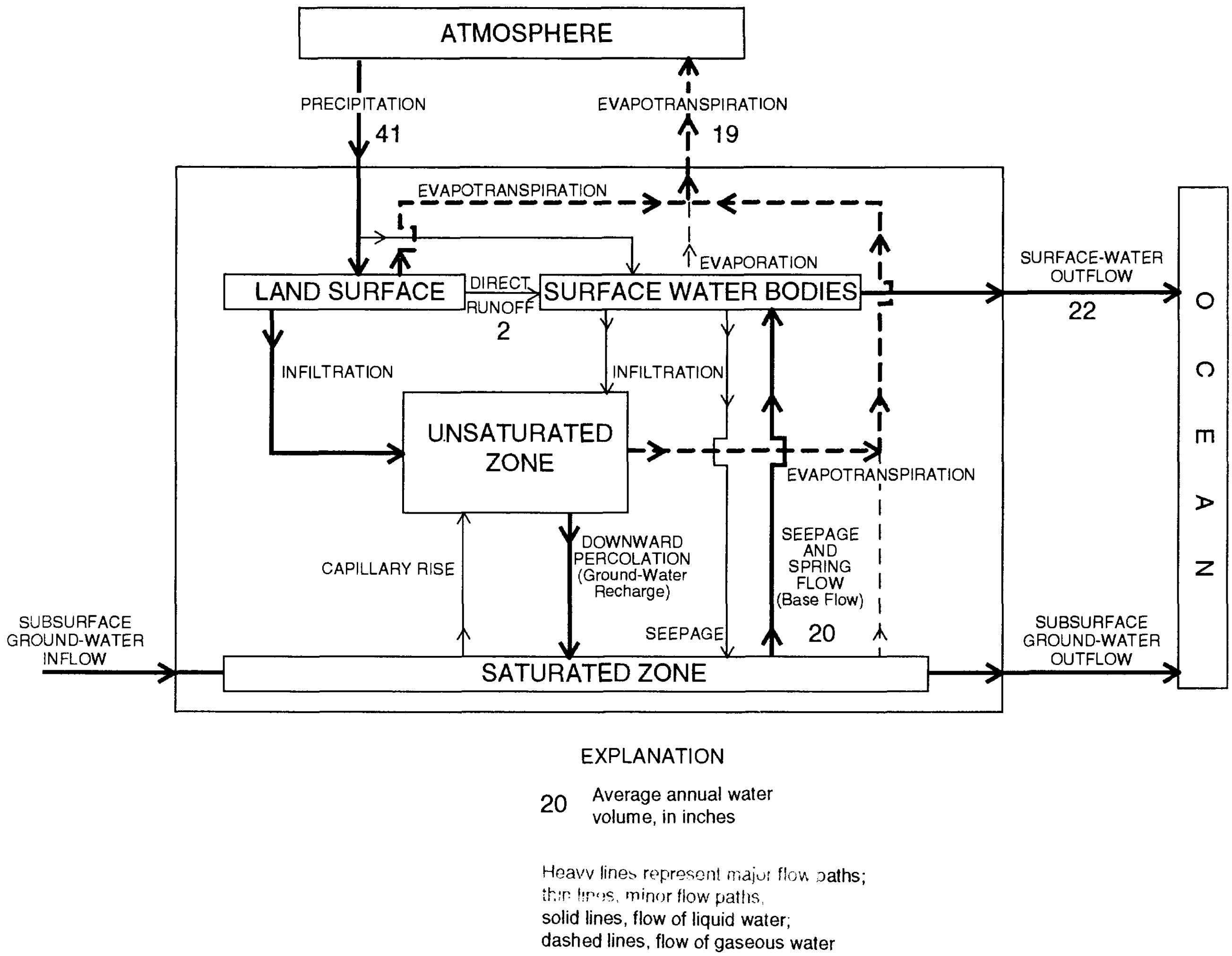


Figure 14. Water budget for the East Meadow Brook area, Nassau County, N.Y., during 5 years (1939-43) of the lightly urbanized period. (Modified from Franke and McClymonds, 1972, fig. 13.)

Average 1939-43 measured values of water-budget components were converted into annual average volumes of water, in inches, and are included in figure 14. Precipitation at the Mineola station (fig. 2) averaged 40.6 in. during 1939-43, about 4 in. below the long-term average of 44.82 in/yr. Annual-mean discharge values for streamflow, base flow, and direct runoff during the period were 16.0 ft^3/s, 14.8 ft^3/s, and 1.2 ft^3/s, respectively. Direct runoff during this period, estimated by hydrograph separation of measured streamflow discharge, accounted for 8 percent of the total streamflow, and base flow accounted for 92 percent.

Evapotranspiration is not easily measured and has been estimated by previous investigators by subtracting known quantities in a water budget and calculating potential evapotranspiration through methods developed by Thornthwaite and Mather (1955, 1957). In this study, the amount of water lost through evapotranspiration and direct runoff during the lightly urbanized period was estimated to average about 50 percent of precipitation (Franke and McClymonds, 1972).

The hydrologic system represented in figure 14 indicates that, in areas of shallow depth to water (near the stream), evapotranspiration causes a loss of water from every part of the system, including the saturated zone. In this budget, average evapotranspiration was calculated as precipitation minus the average surface-water outflow, a difference of 19 in/yr. Adding this value (19 in.) to direct runoff (2 in.) gives a sum of

21 in., similar to the estimate calculated by the method suggested by Franke and McClymonds (1972).

The volume of water that infiltrates through the unsaturated zone into the saturated zone from land surface probably exceeds 20 in. but is not quantified in this budget because some is lost through evapotranspiration in the soil zone and also from the saturated zone, especially where the depth to water is small. Previous investigators have estimated that recharge to the ground-water system averages about 50 percent of precipitation (Franke and McClymonds, 1972).

Neither subsurface inflow to the system, nor outflow from the system, are measurable. An assumption in this analysis of lightly urbanized conditions is that subsurface inflow equals subsurface outflow and that these components, therefore, do not affect the other components of the water budget (Cohen and others, 1968).

Hydrologic Effects of Sewers

Population growth on Long Island during the 20th century has expanded eastward from Kings and Queens Counties through Nassau County and into Suffolk County. At the turn of this century, the population of Nassau County was about 55,000; by 1920 it had more than doubled to 126,000 and, by 1940, had reached 406,000. After World War II, the population again doubled from 673,000 in 1950 to 1,300,000 in 1960. In 1987, almost all of the southern half of Nassau County (fig. 15) had a population density of 5 to 20 persons per acre (U.S. Bureau of the Census, written commun., 1987), which represents medium- to high-density suburban residential communities (Long Island Regional Planning Board, 1982).

Water-management projects have been undertaken on Long Island since the early 1900's in response to the need for the removal of sewage and of storm runoff, which had increased with urbanization. Sewer projects that have affected the East Meadow Brook drainage area are summarized in table 2. Additional information on the development of sewer systems and their hydrologic effects can be found in Reilly and others (1983), Seaburn (1969), Pluhowski and Spinello (1978), Garber and Sulam (1976), and Franke and McClymonds (1972).

Table 2. Water-management projects and events that have affected flow in East Meadow Brook and its drainage area, Nassau County, N.Y.

[mi^2, square miles]

Date	Project or event
1925	Earliest confirmed construction of storm sewers in East Meadow Brook drainage area. Construction could have begun as early as 1905.
1927	First sanitary-sewer system in Nassau County that discharged to tidewater, constructed in the Village of Freeport (4.25 mi^2).
1935	First recharge basins constructed to replenish aquifer system with stormwater from streets.
1950-59	Intensive construction of streets and housing developments in East Meadow Brook drainage area.
1950-60	Population of Nassau County virtually doubles from 673,000 to 1,300,000.
1952-64	Construction of Sewer District 2 in southwestern Nassau County (70 mi^2); sewer hookups completed in 1964.
1969-76	Modest construction of streets and housing developments in East Meadow Brook drainage area.
1974-88	Construction of Sewer District 3 in southeastern Nassau County (105 mi^2); sewer hookups completed in 1988.
1980	Consolidation of Freeport Sewer District with Sewer District 3. Cedar Creek facility began to treat and discharge sewage that was formerly discharged at Freeport facility.

Storm Sewers

One result of urbanization on Long Island has been the conversion of permeable land to impervious surfaces (such as streets, sidewalks, and parking lots) that prevent infiltration of precipitation to the water table (Franke and McClymonds, 1972). Before urbanization, surface runoff to streams was minimal because the soils were permeable and allowed rapid infiltration, but the increase in impermeable-surface area has caused the volume of direct runoff to increase. Runoff from impervious areas flows into the storm-sewer system, which carries it either to nearby streams or to recharge basins.

Diversion to streams.—Diversion to streams has been the most common method of stormwater disposal in the southern part of Nassau County, which includes much of East Meadow Brook's drainage area, because the stream is readily accessible and because the shallow depth to water makes recharge basins impractical

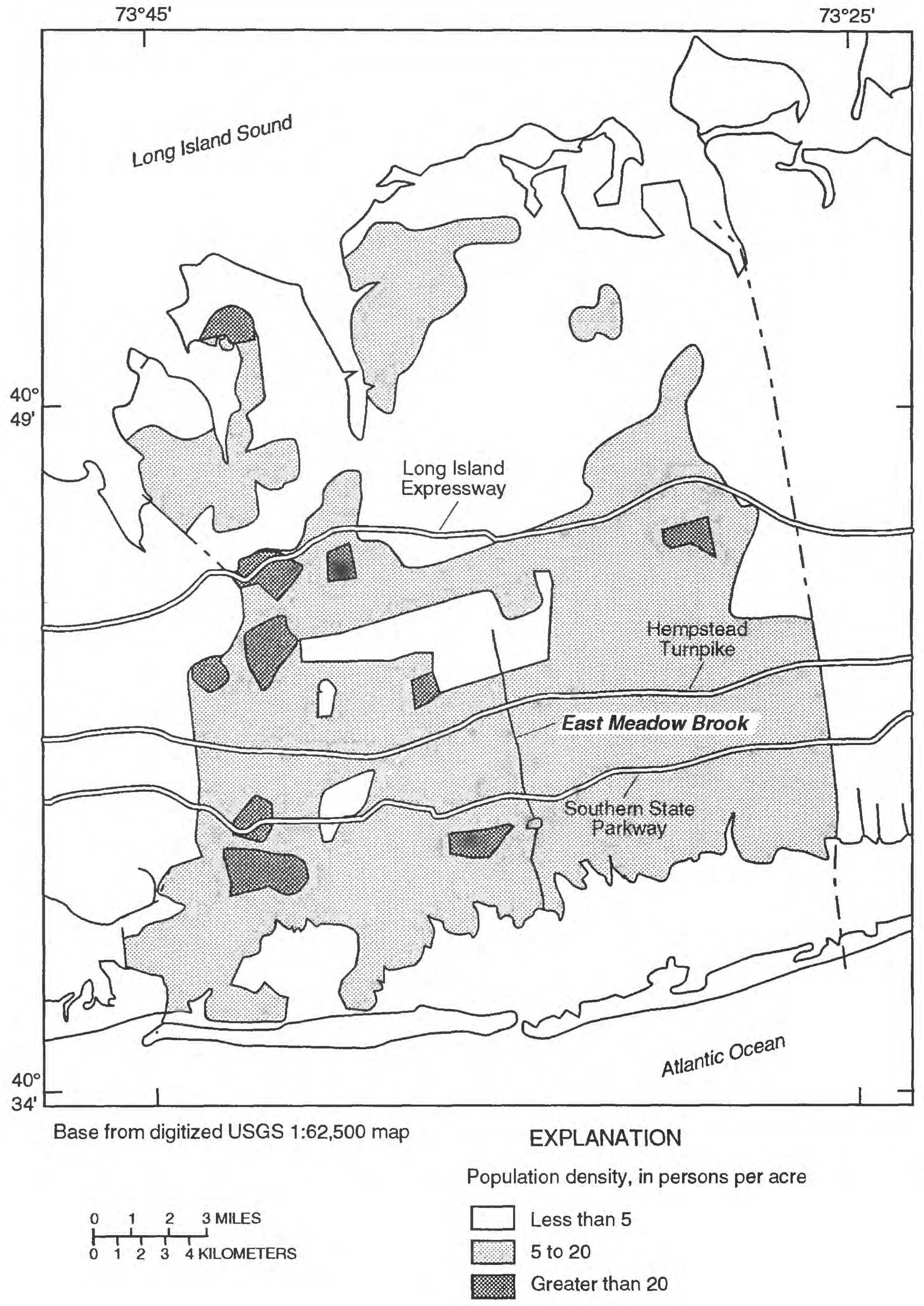


Figure 15. Population density in Nassau County, N.Y., 1985 (Data from U.S. Bureau of the Census, written commun., 1987.)

(Franke and McClymonds, 1972). The yearly construction of roads drained by storm sewers that discharge into East Meadow Brook is summarized in table 3 and plotted in figure 16; boundaries of the storm-sewer network are delineated in figure 17. Most storm-sewer construction, which generally paralleled the construction of housing developments, occurred during 1950-59 and 1969-76. The fivefold increase in the length of roadway in the southern half of East Meadow Brook's drainage area (from 25 mi to 132 mi) during 1940-84 reflects the area's transition from lightly developed to suburban residential.

The main hydrologic consequence of diverting stormwater to streams is that the water flows to bays or the ocean and cannot recharge the ground-water system. Ku and others (1992) estimated that, in areas on Long Island where stormwater is diverted to streams, the rate of ground-water recharge is decreased 10 percent. Franke (1968) attributed a 1- to 2-ft decline in ground-water levels in southwestern Nassau County to the diversion of stormwater to streams. Pluhowski and Spinello (1978) estimated that 25 percent of the base-flow decline observed at East Meadow Brook during 1965-74 was the result of the extensive storm-sewer network, which totaled about 125 mi by 1974. Another effect of stormwater diversion is that peak stream discharges during individual storms became larger and more variable than under predevelopment conditions (Seaburn, 1969).

Diversion to recharge basins.—The second method for disposal of storm runoff from streets is to divert it to recharge basins—shallow, unlined pits, commonly about 10 ft deep and 1.5 acres in area (Ku and Simmons, 1986) that allow surface runoff to infiltrate to the ground-water system and prevent the loss of recharge that would result from diverting the runoff to streams. Recharge basins are a significant source of recharge to the shallow aquifer system in many parts of Nassau and Suffolk Counties; Ku and others (1992) estimated that recharge in areas with recharge basins is about 10 percent greater than in areas without them. This practice also has an economic benefit in that it permits relatively short sewerlines, which are less costly to construct than long trunk sewerlines.

The first recharge basins on Long Island were constructed in 1935, but the practice did not become widespread until after World War II (Seaburn and Aronson, 1974). At present, Nassau County has more than 800 basins (Spinello and Simmons, 1992), and these structures are standard in most housing develop-

Table 3. Length of roads with storm sewers discharging into East Meadow Brook, Nassau County, N.Y., through 1984

[Data from James Ahearn, Nassau County Department of Public Works, written commun., 1991. --, no data available]

Year	Annual length constructed (miles)	Cumulative sum (miles)
pre-1940	--	21.85
1940	3.36	25.21
1941	.40	25.61
1942	.68	26.29
1943	0	26.29
1944	.29	26.58
1945	0	26.58
1946	0	26.58
1947	1.25	27.83
1948	0	27.83
1949	.73	28.56
1950	4.29	32.85
1951	5.18	38.03
1952	6.05	44.08
1953	15.03	59.11
1954	20.56	79.67
1955	9.96	89.63
1956	2.29	91.92
1957	4.91	96.83
1958	1.91	98.74
1959	3.45	102.19
1960	4.76	106.95
1961	.34	107.29
1962	1.87	109.16
1963	.32	109.48
1964	.97	110.45
1965	0	110.45
1966	.85	111.30
1967	.22	111.52
1968	.03	111.55
1969	2.61	114.16
1970	4.58	118.74
1971	1.92	120.66
1972	4.61	125.27
1973	0	125.27
1974	0	125.27
1975	5.86	131.13
1976	1.71	132.84
1977	0	132.84
1978	0	132.84
1979	0	132.84
1980	.05	132.89
1981	0	132.89
1982	0	132.89
1983	0	132.89
1984	.06	132.95

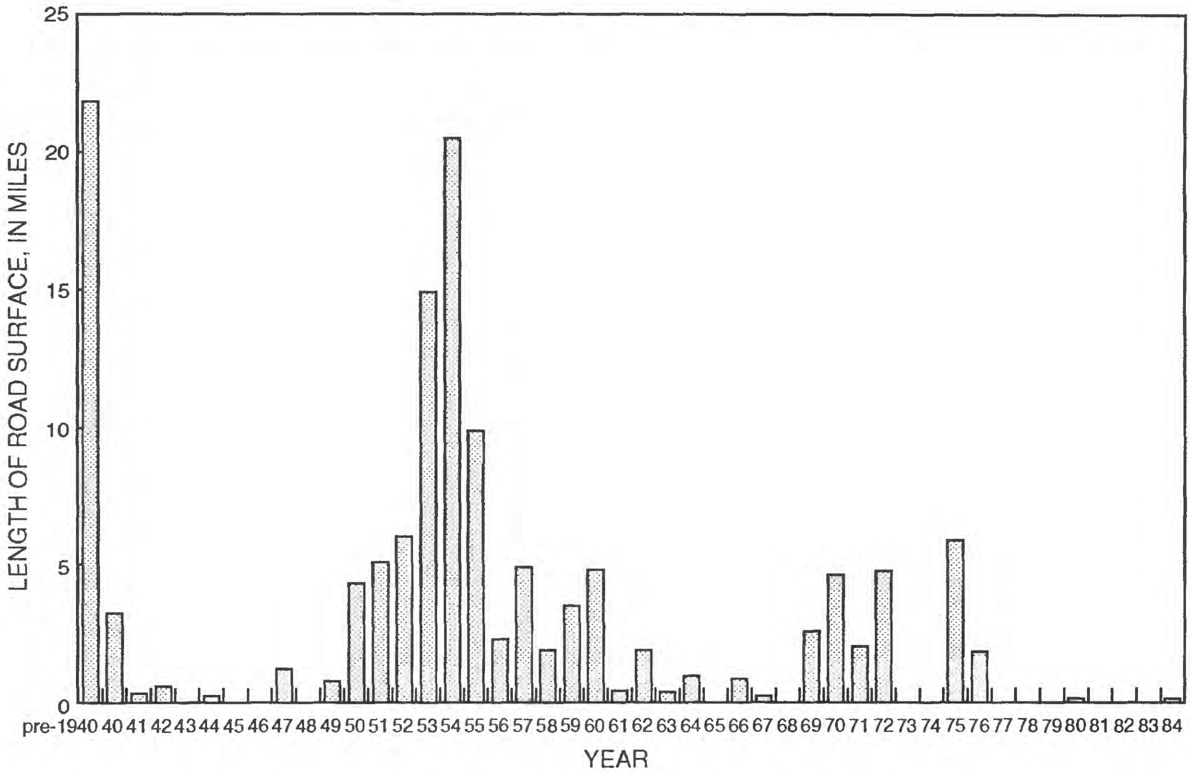


Figure 16. Annual construction of roads with storm sewers that discharge into East Meadow Brook, Nassau County, N.Y., 1940-84.

ments in areas where the depth to water is greater than 20 ft. Locations of recharge basins in Nassau County are shown in figure 18.

The northern half of East Meadow Brook's topographic drainage area, where the depth to water greatly exceeds 20 ft (Franke and McClymonds, 1972), contains many recharge basins. The southernmost part, in contrast, contains only about 20 basins because the shallow depth to water (less than 20 ft) hinders their efficiency; therefore, most storm runoff is diverted directly to the stream, and the effect of these few basins on the local hydrologic system in the water-budget area is probably only minor.

Sanitary Sewers

Individual homes throughout Nassau County during the 1940's had cesspools or septic tanks that returned wastewater to the shallow (upper glacial) aquifer, a major source of supply at the time. This practice returned about 90 percent of public-supply pumpage to the aquifer; the remaining 10 percent was lost through evapotranspiration by activities such as lawn sprinkling (Franke and McClymonds, 1972). The return of wastewater eventually caused water in the shallow aquifer to become impotable in many parts of Nassau and western Suffolk Counties, however; water quality differences between sewered and unsewered areas of Long Island are documented by Ku and Sulam (1979) and Ragone and others (1981). Because cesspools and septic tanks do not operate efficiently where the water table is close to land surface, as in most of the southern half of Nassau County, the Village of Freeport in 1927 constructed the first sanitary-sewer system in Nassau County that discharged to tidewater (Pluhowski and Spinello, 1978).

Extensive urbanization and the attendant increase in water-supply pumpage in Nassau County that accompanied the rapid population growth after World War II created the need for large-scale sewering to protect shallow ground water from further contamination. Construction of Sewer District 2 (70 mi^2) in southwestern Nassau County (fig. 2) resulted in the first discharge of treated effluent from the Bay Park

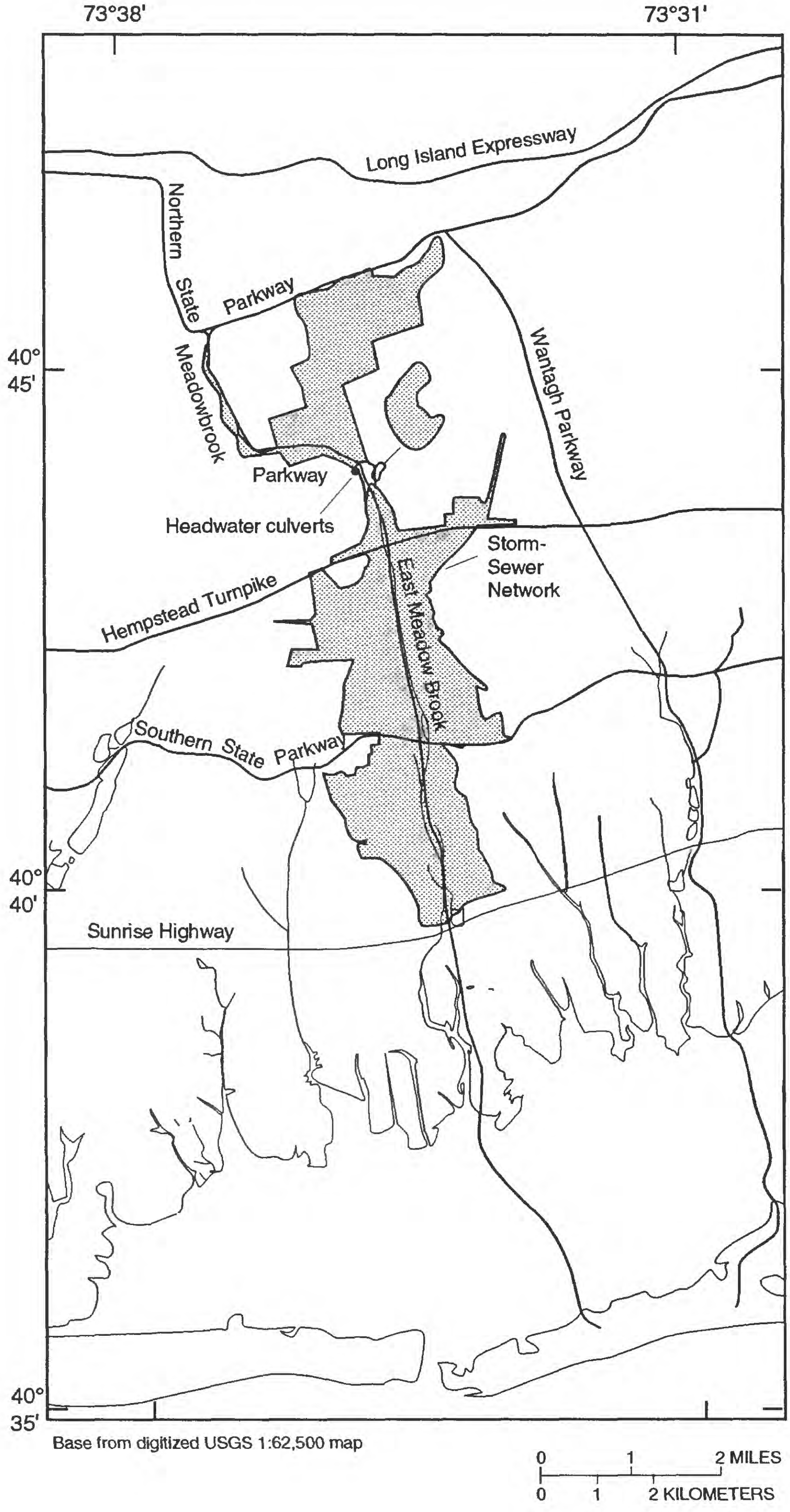


Figure 17. Area served by storm-sewer network of East Meadow Brook, Nassau County, N.Y.

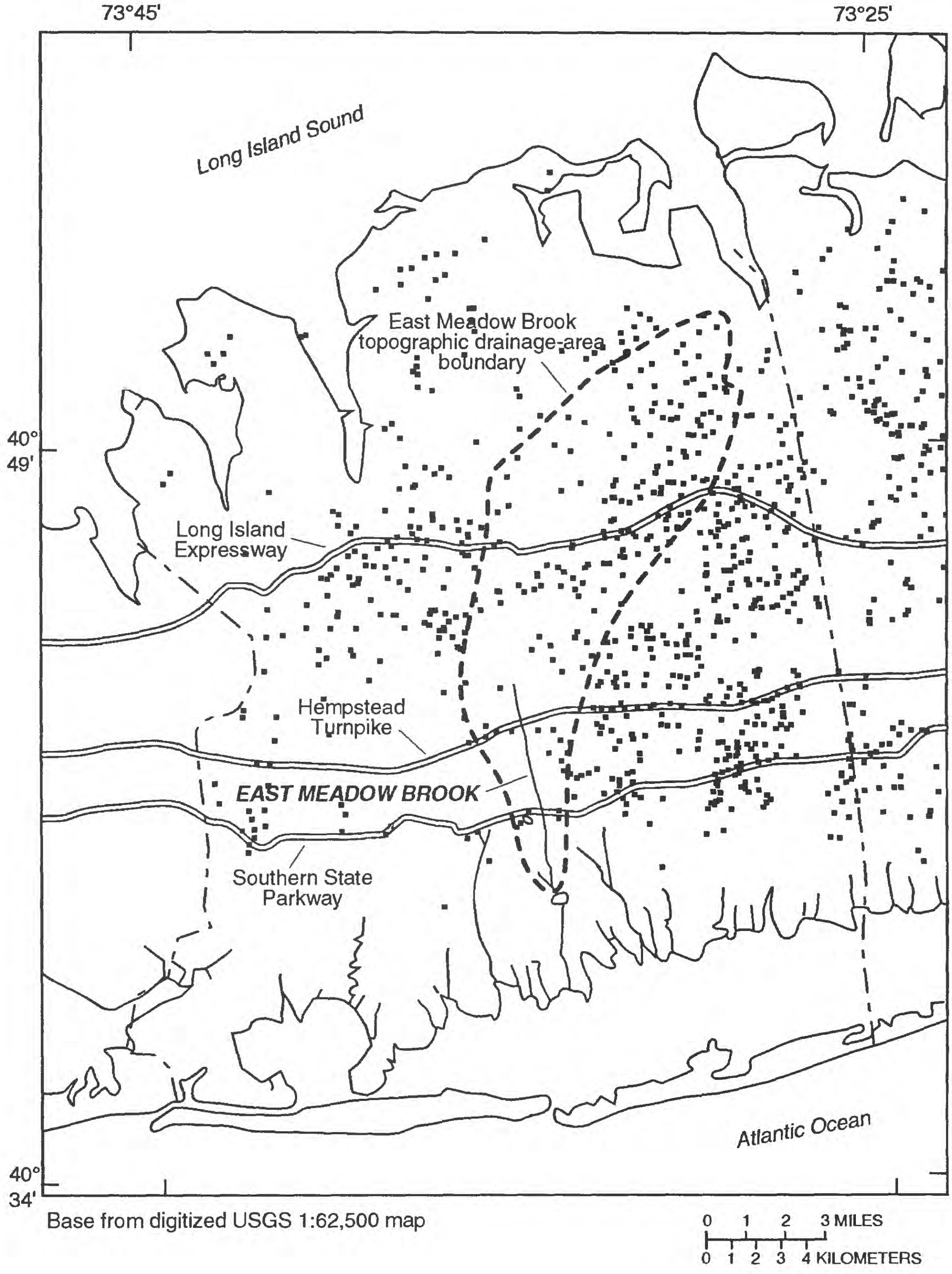


Figure 18. Locations of recharge basins in Nassau County, N.Y.

Sewage Treatment Plant to Hewlett Bay in 1952. Sewer construction in this district was completed in 1964.

Increased eastward development in southeastern Nassau County during the 1960's prompted the construction of Sewer District 3 (105 mi^2). The Cedar Creek Water Pollution Control Facility in Wantagh (fig. 2) released its first discharge to the Atlantic Ocean in 1975, and sewer construction in this district was completed in 1988.

Annual discharges from the two sewage-treatment plants are listed in table 4. The combined discharge of the two plants currently (1985-90) averages about 110 Mgal/d. The removal of this large volume of water from the shallow aquifer system has had major hydrologic consequences, which include a decline of the water table, decreased base flow and total streamflow in several streams, drying up of lakes or lowering of lake-water levels, saltwater intrusion into aquifers near the shores, decreased stream length, and decreased freshwater outflow to the south-shore bays (Franke, 1968; Pluhowski and Spinello, 1978; Garber and Sulam, 1976; Simmons and Reynolds, 1982; Reilly and others, 1983). About 75 percent of the observed decrease in base flow at East Meadow Brook before construction of Sewer District 3 has been attributed to sanitary sewering; the remainder of the decrease was the result of stream-directed storm sewers (Pluhowski and Spinello, 1978). An additional consequence is the possibility of adverse effects on the shellfish population as a result of the decreased outflow of freshwater to the south-shore bays (Reilly and others, 1983).

The boundaries of the East Meadow Brook storm-sewer network, ground-water-contributing area, and the southern part of the topographic drainage area are depicted in figure 19. The southern part of the topographic drainage area generally encompasses the ground-water-contributing area and the storm-sewer network; therefore, this 10-mi^2 area represents a reasonable estimate of the effective drainage area to East Meadow Brook and is used for water-budget analysis in the following section.

Table 4. Annual discharges from Bay Park and Cedar Creek sewage-treatment plants, Nassau County, N.Y., 1952-90

[Data from Spinello and Simmons, 1992 (table 3) and Donald Myott, Nassau County Health Department, written commun., 1992. Values are in million gallons per day. Locations are shown in fig. 2]

Year	Bay Park[1] (Sewer District 2)	Cedar Creek[2] (Sewer District 3)	Year	Bay Park[1] (Sewer District 2)	Cedar Creek[2] (Sewer District 3)
1952	8.8		1972	68.1	
1953	10.5		1973	71.7	
1954	9.9		1974	65.0	
1955	12.1		1975	63.2	9.8
1956	16.3		1976	57.7	12.3
1957	20.9		1977	58.8	15.2
1958	26.1		1978	59.9	19.0
1959	28.0		1979	60.7	19.4
1960	35.8		1980	63.6	29.6
1961	42.4		1981	65.0	29.8
1962	46.5		1982	63.9	34.7
1963	48.4		1983	66.2	40.6
1964	47.7		1984	69.6	43.7
1965	49.9		1985	68.7	45.9
1966	51.6		1986	56.5	48.2
1967	54.0		1987	58.9	50.0
1968	55.9		1988	56.9	51.1
1969	61.3		1989	60.4	56.3
1970	65.0		1990	58.3	56.2
1971	68.6				

[1] Flows before 1986 may be overreported by about 25 percent.
[2] Freeport and Roslyn plants connected in 1980 and 1988, respectively.

Period of Urbanization (1944-90)

As described in previous sections, the increasing urbanization of the East Meadow Brook area from 1944 to 1990 coincided with construction of sanitary and storm sewers, and the resulting declines in ground-water levels (Franke, 1968; Garber and Sulam, 1976) caused a sharp decrease in the base-flow contribution to total streamflow of East Meadow Brook. During the 1970's the USGS used analog and digital models of the ground-water system to predict the long-term hydrologic effects of sanitary sewers in Sewer District 3 and in southwestern Suffolk County (Kimmel and others, 1977; Reilly and Buxton, 1985). The initial conditions used in these models were those of the early 1970's. Results indicated that (1) equilibrium conditions would be reached by 1995, at which time ground-water levels would have declined 16 to 18 ft in the north-central part of Sewer District 3 as a result of sanitary sewers, that (2) water levels at wells N1615

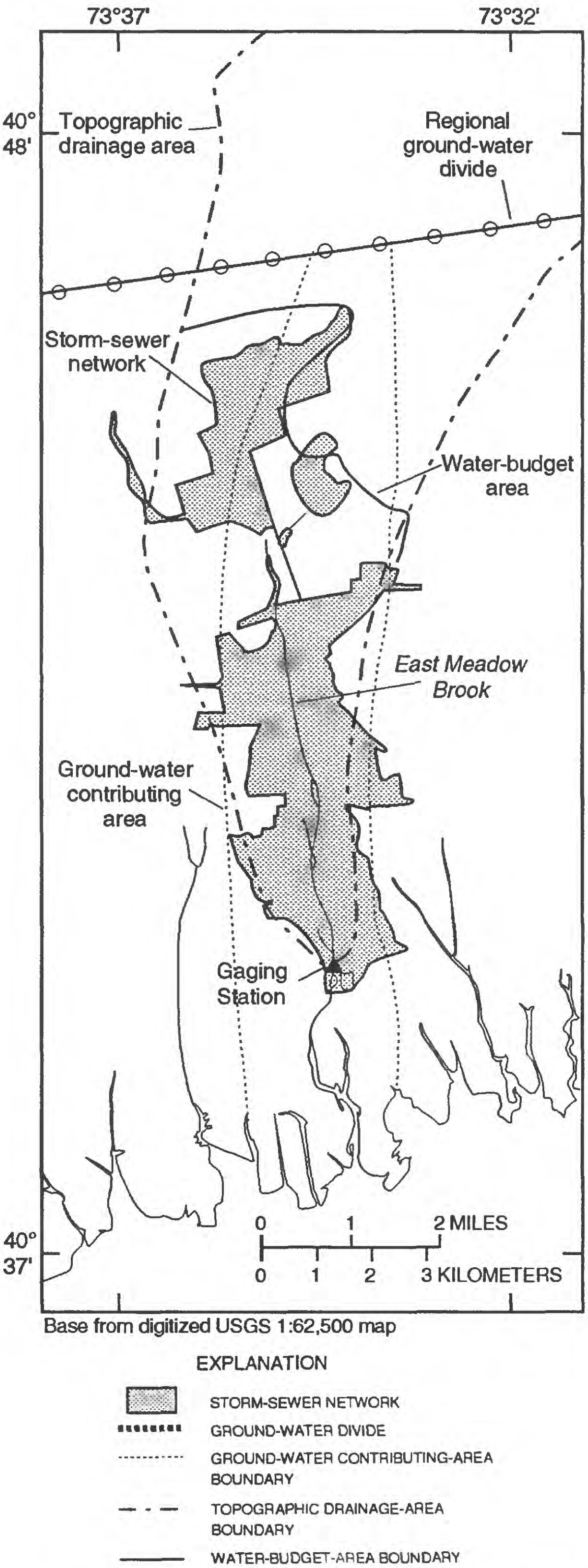


Figure 19. Boundaries of storm-sewer network, ground-water-contributing area, topographic drainage area, and water-budget area of East Meadow Brook, Nassau County, N.Y.

and N1197 (fig. 1) would have declined 6 to 8 ft and 16 to 18 ft, respectively; and that (3) the base flow of East Meadow Brook would have decreased 83 percent, from 8.9 ft^3/s to 1.5 ft^3/s.

Streamflow

The effects of sewers on total annual discharge and on the base-flow and direct-runoff components are illustrated in a bar graph derived from the continuous record of flow from East Meadow Brook at the Freeport gaging station for 1938-90 (fig. 20). The maximum annual discharge was recorded in 1961 and probably resulted from a combination of two factors: (1) above-average rainfall in 1960 and 1961 (52.44 in. and 48.03 in., respectively) that raised ground-water levels and contributed to the second-highest base flow on record, and (2) above-average runoff to the stream from the extensive storm-sewer network. This year of maximum annual streamflow was followed by the 1962-66 drought, which, coupled with the effects of the completion of Sewer District 2, severely decreased streamflow. Total streamflow and base flow reached minimum values in 1966 and, for the first time, the amount of annual streamflow derived from direct runoff exceeded 50 percent. Also, mean daily discharges of less than 1 ft^3/s were recorded on several days during 1965-67 (U.S. Geological Survey, 1966, 1967, 1968).

Base flow and ground-water levels recovered during the next few years but did not return to predevelopment levels, owing to the effects of Sewer District 2 and storm sewering. The contribution of direct runoff to streamflow continued to increase as a result of continued road and storm-sewer construction during 1969-76. The Cedar Creek Treatment Facility in Sewer District 3 began to discharge effluent in 1974, and its discharge increased annually through 1990.

After 1979, the decreasing trend in total streamflow and base flow continued as discharge from Sewer District 3 continued to increase. Although a few years of especially high precipitation briefly interrupted this decline, the second-lowest annual streamflow and base flow were recorded in 1988.

Streamflow conditions during the first two periods analyzed (1939-49 and 1950-64) differ markedly from those during the last two periods (1965-73 and 1974-90), as indicated by box plots (fig. 21A). The median and range of stream discharges for 1939-49 are fairly similar to those for 1950-64, but during the next period (1965-73), median annual-mean streamflow declined to 7.5 ft^3/s, less than half the amount recorded in either of the first two periods, even though the median precipitation during 1965-73 (43.13 in/yr, fig. 5), was similar to that of the previous period (1950-64) and about 2 in. below the median for 1939-49 (45.51 in/yr). The most recent period (1974-90) shows the widest range in discharge and a much lower median discharge than the first two periods, despite higher precipitation (figs. 4B and 5). Some of the increased range of the box plot can be attributed to the increased variability in precipitation during this period (figs. 4C and 5).

In summary, box-plot analysis of streamflow statistically supports the trends indicated in figure 20. Streamflow remained fairly steady from the 1940's through the 1950's but plummeted during 1965-73 as a result of the combined effects of the 1962-66 drought and the completion of Sewer District 2. Some recovery occurred after the drought, but the effect of Sewer District 3 has kept streamflow well below predevelopment levels.

Base flow.—The bar graph in figure 20 indicates that, during 1939-49, base flow was a much larger component of total streamflow than direct runoff was. The highest recorded annual precipitation during 1939-90 (69.64 in.) was in 1984, which followed a year during which above-average precipitation (50.43 in.) was recorded. Even though the high rainfall in 1984 produced the largest amount of direct runoff on record, total streamflow in that year was less than in several years during 1939-64. Therefore, even the record high rainfall was insufficient to compensate for the loss of base flow during this time.

The second lowest total streamflow and base-flow discharges were recorded in 1988, when precipitation was 40.08 in., only 4.7 in. below average; in the previous year it had been 50.33 in., 5.3 in. above average. These observations indicate that, since the completion of Sewer District 3, even a moderate decrease

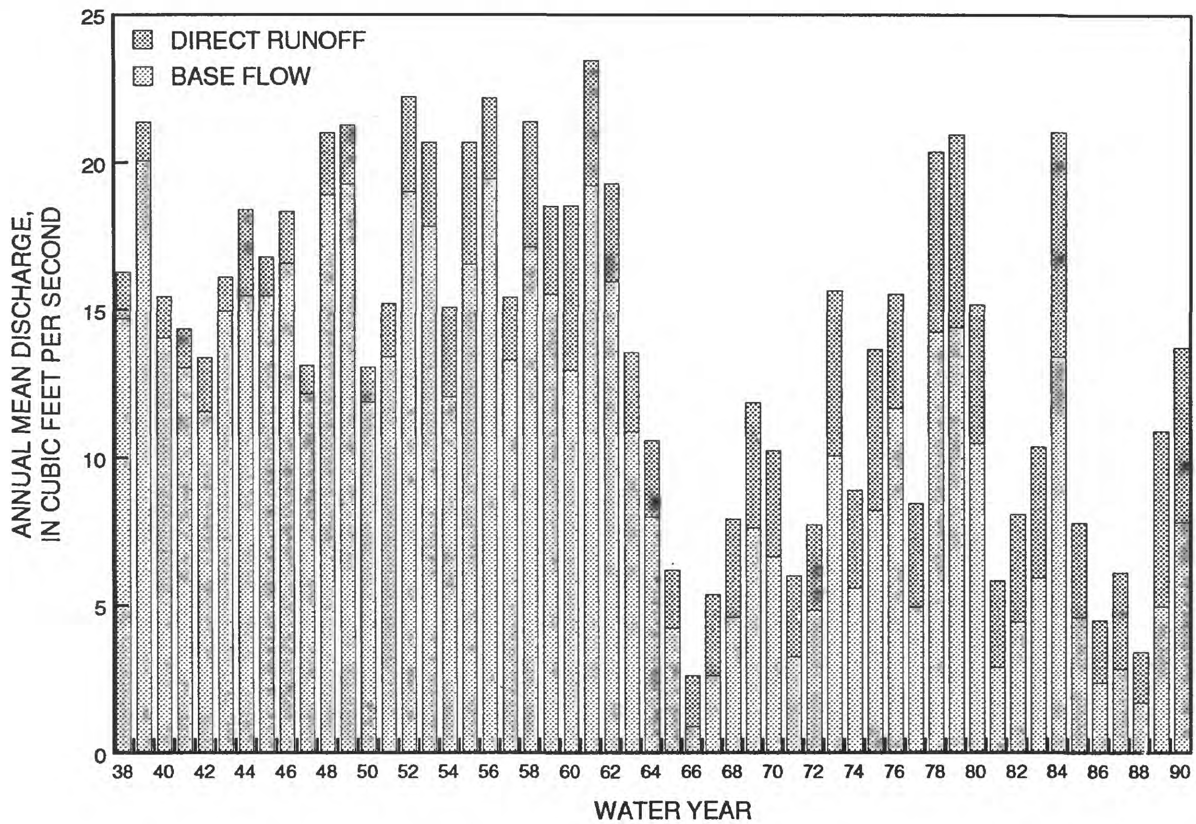


Figure 20. Direct-runoff and base-flow components of total annual discharge, East Meadow Brook at Freeport, N.Y. (station01310500), 1938-90.

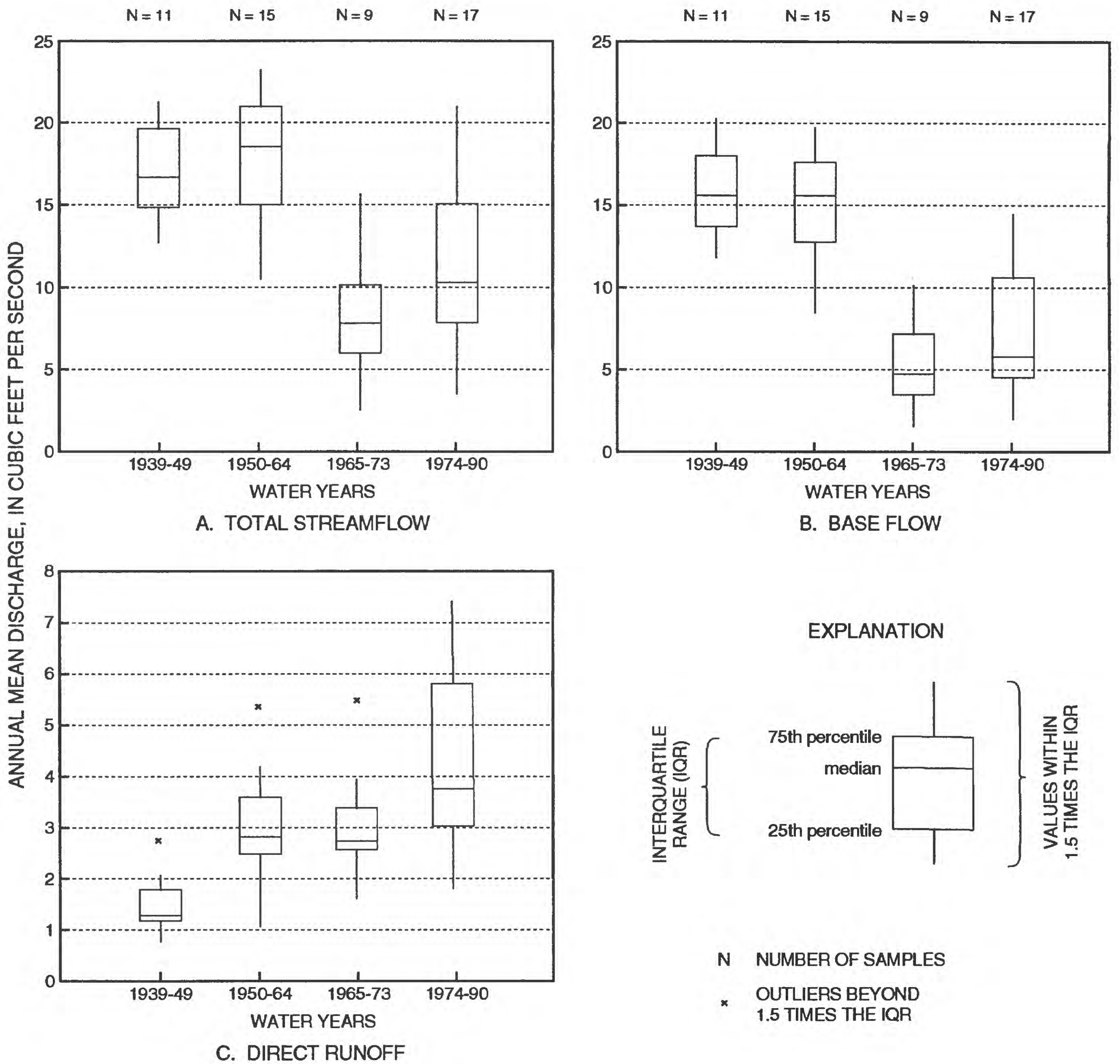


Figure 21. Discharge of streamflow components at East Meadow Brook, Nassau County, N.Y., during four selected periods: A. Total streamflow. B. Base flow. C. Direct runoff.

in annual precipitation immediately causes a substantial decrease in base flow. Box plots of base flow (fig. 21B) indicate distributions similar to those for streamflow during all four time periods.

Direct runoff.—The volume of direct runoff is determined by (1) the amount of precipitation, (2) the area of paved surfaces (reflected by sewered-road length) that drain into the stream, and (3) the intensity and other characteristics of individual storms. The construction of roads with storm sewers (table 3) has produced large changes in the volume of direct runoff routed to East Meadow Brook. For example, although average streamflow and precipitation during 1952-59 were 20 and 15 percent higher, respectively, than during 1939-43, the average discharge of direct runoff during 1952-59 was 136 percent higher. The percentage of total streamflow derived from direct runoff also increased through this period (fig. 20).

The contribution of direct runoff to streamflow during each of the four time periods analyzed is depicted in box plots in figure 21C. The median direct runoff more than doubled from the first period (1939-49) to the second period (1950-64). The distribution of direct runoff during the third period (1965-73) is similar to that of the second period (1950-64), but the median of the fourth period (1974-90), is the highest of all, and the range is also the widest as a result of the wide variability in annual precipitation. The skewed distribution of direct runoff in the fourth period, with some values far above the median, is attributed to the increase in road-surface area and storm-sewer construction during 1969-76.

The relations between direct runoff and (1) sewered-road length, and (2) precipitation, are illustrated in figure 22. The relation of direct runoff to road length (fig. 22A) is plotted for two selected ranges of annual precipitation—42 to 44 in. (close to average) and 36 to 38 in. (well below average). The wide scatter about the regression lines is the reason for the low r^2 values and is probably due to variability of intensity and other characteristics of individual storms. Both groups of data reflect the trend of increasing direct runoff to East Meadow Brook with increasing amount of road surface.

The relation between direct runoff and annual precipitation during two periods of stable road length (fig. 22B) illustrates that the greater degree of urbanization in the later period significantly increased the direct runoff to the stream within the storm-sewer network. The first period (1940-49) represented only slight urbanization (25 to 28 mi of road) and indicated a reasonably close linear relation ($r^2 = 0.716$) between precipitation and direct runoff. The second period (1977-90), with about five times the road length (132 mi), represented heavily suburban conditions and shows a new relation between direct runoff and precipitation that produced more direct runoff for a given precipitation amount than in 1940. (The last available value of road length added per year is for 1984, but because few roads were constructed after 1976 (fig. 16) and no major construction has occurred in the area since then, 132 mi is probably a reliable estimate of road length for 1985-90.)

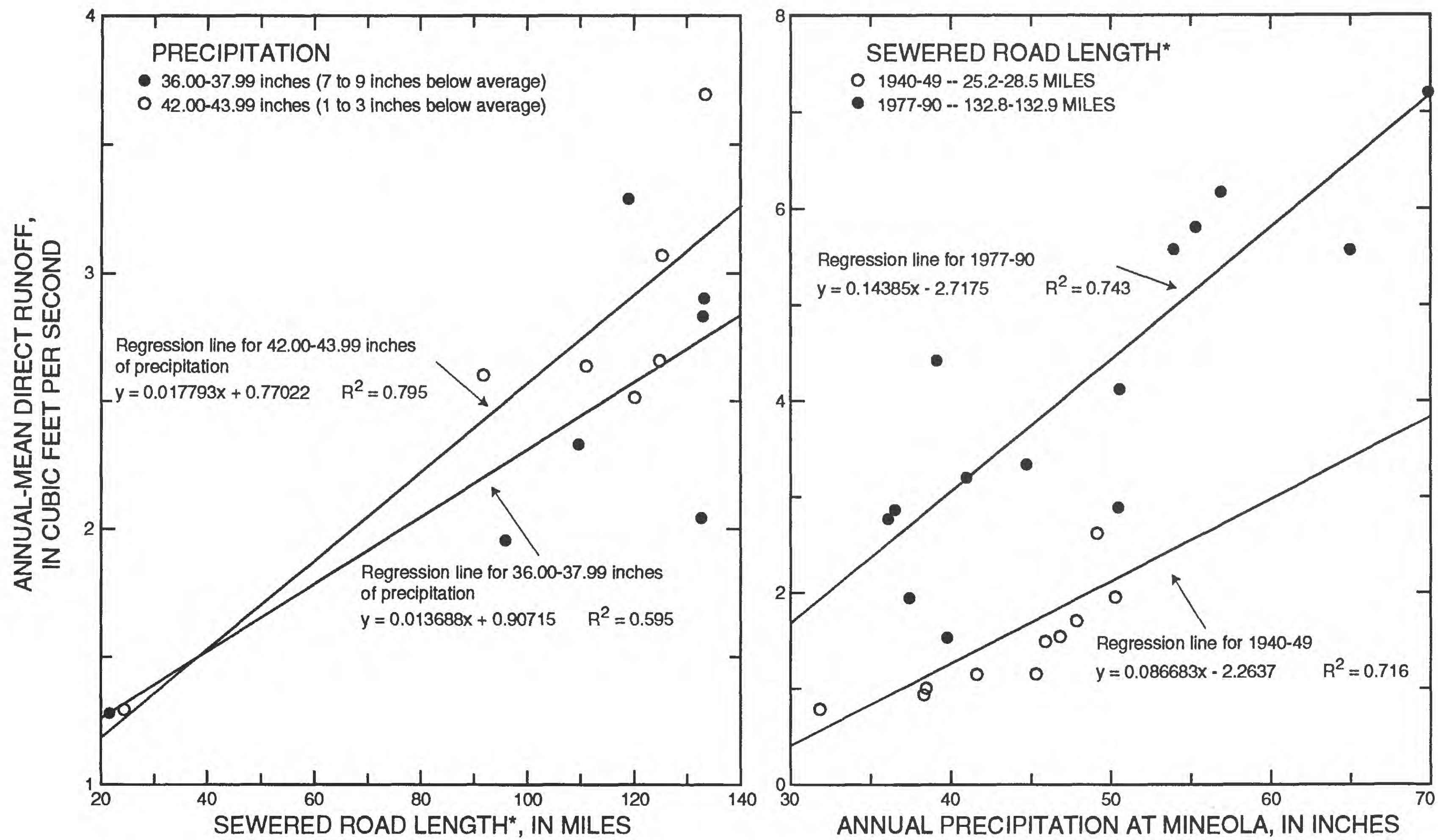
Base-flow contribution to East Meadow Brook and Carmans River—a comparison.—As previously noted, Carmans River is representative of predevelopment hydrologic conditions in that its drainage area is relatively undeveloped, has no sanitary sewers, and uses recharge basins rather than storm sewers as the primary method of stormwater disposal. A comparison of base-flow and direct-runoff contributions to Carmans River with those for East Meadow Brook illustrate the effect of urbanization of East Meadow Brook.

A bar graph of total streamflow at the Carmans River gaging station during 1943-90 (fig. 23) indicates the base-flow and direct-runoff components. Carmans River is one of the largest streams on Long Island and has an annual-mean streamflow of 24.2 ft^3/s for its period of record. Like other Long Island streams under predevelopment conditions, about 95 percent of the flow of Carmans River is derived from base flow, and about 5 percent is contributed by direct runoff. Unlike East Meadow Brook (fig. 20), Carmans River does not show any clear trend of declining total flow or base flow after 1966, although a trend of increased variability of discharge is apparent since 1977. This trend is attributed to the previously noted variability in precipitation as recorded at the Mineola and Setauket gages.

The percentage of total annual streamflow contributed by base flow to East Meadow Brook and to Carmans River during their periods of record is plotted in figure 24. As previously noted, the base-flow contribution to Carmans River has remained greater than 90 percent during the entire period of record, whereas the base-flow contribution to East Meadow Brook declined to about 50 percent during the late 1980's while the contribution of direct runoff increased proportionately.

Double-mass curves can be used to evaluate the effect of a given factor or event at a given site through comparison with data from a site (or group of sites) not affected by that factor or event. This procedure minimizes the effect of factors that affect both sites and emphasizes the effect of factors that produce differences between the two sites (Searcy and Hardison, 1960).

A double-mass-curve analysis was performed on the percentage of streamflow derived from base flow at East Meadow Brook and Carmans River for the period of concurrent record (1943-90). This method was explained by Franke (1968) and was used by Simmons and Reynolds (1982) and Spinello and Simmons (1992) to analyze base flow in streams



*Length of roads with storm sewers directed to East Meadow Brook

Figure 22. Annual direct runoff at East Meadow Brook, Nassau County, N.Y., in relation to sewered road length (left), and precipitation (right).

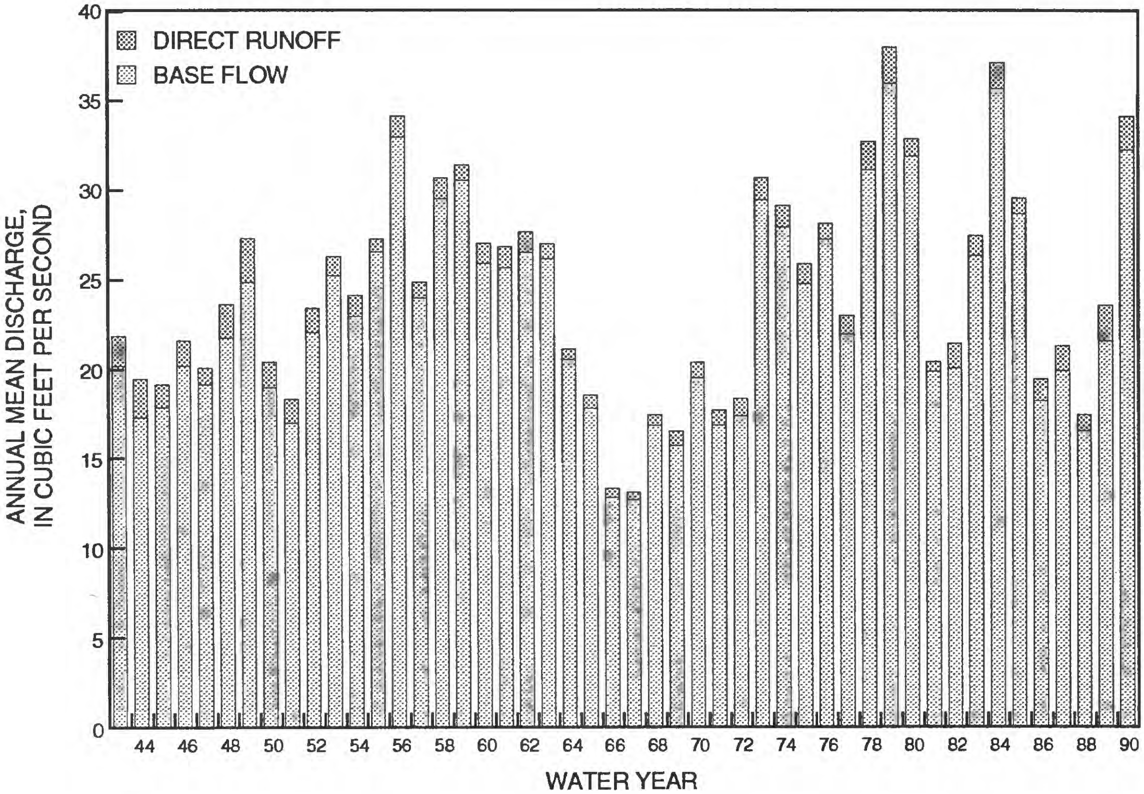


Figure 23. Direct-runoff and base-flow components of total annual discharge, Carmans River at Yaphank, N.Y. (station 01305000), 1943-90. (Locations are shown in fig. 1.)

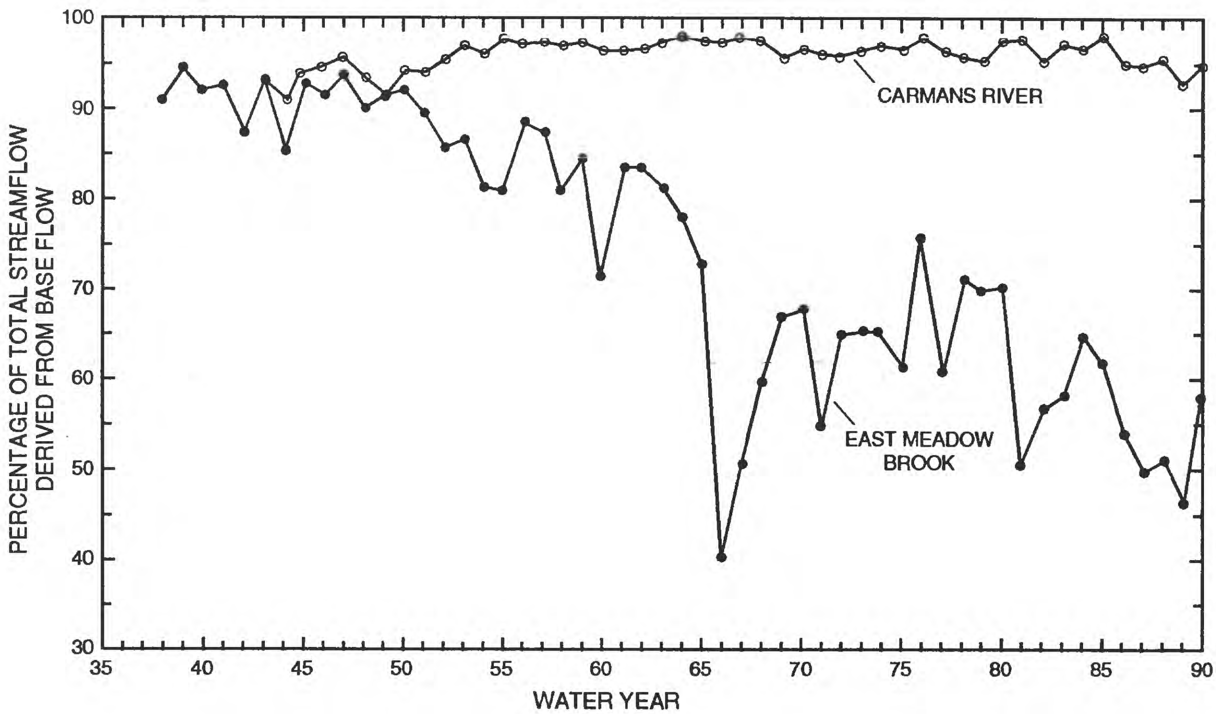


Figure 24. Percentage of streamflow derived from base flow at East Meadow Brook at Freeport, N.Y. (station 01310500), 1938-90, and Carmans River at Yaphank, N.Y. (station 01305000), 1943-90. (Locations are shown in fig. 1.)

affected by sewering. For each stream, the percentage of total streamflow contributed by base flow each year was calculated; the cumulative percentages for each stream (plotted in fig. 25) were proportional to each other during 1943-52, as indicated by the linearity of the initial part of the curve, and reflect the similarity of hydrologic conditions at the two sites. The departure from this proportionality began in 1953 and formed a new line of proportionality that continued until 1965. Pluhowski and Spinello (1978) attribute most of the departure through 1958 to the effects of storm sewers rather than to that of sanitary sewers.

A significant departure from linearity during 1965-67 is attributed to the 1962-66 drought and indicates that the drought did not affect the two areas to the same degree. A new line of proportionality for 1968-80 reflects the continued effects of Sewer District 2, additional road construction, and, perhaps, the effects of early operation of Sewer District 3. Neither the early hydrologic effects of the operation of Sewer District 2 (1953-58) (Pluhowski and Spinello, 1978); nor of Sewer District 3 (1974-80) are clearly discernible.

New departures from the previous proportionality line developed during 1981-90 as a result of the completion of sewer lines in Sewer District 3. The export of water from the system as outflow from the Cedar Creek Treatment Facility increased sharply through the 1980's. Full operation of both sewage-treatment facilities has resulted in an average loss of water of about 110 Mgal/d from the aquifer system.

Annual departures of base flow in East Meadow Brook, as demonstrated by the double-mass-curve analysis, are presented in table 5. The departures represent the difference from the expected value of base-flow contribution to East Meadow Brook for each year, calculated as the percentage of streamflow derived from base flow in Carmans River, for that year, multiplied by the slope of the initial (1943-53) line of proportionality in figure 25, minus the observed base-flow contribution to East Meadow Brook in that year.

The storm sewers and sanitary sewers together reduced the base-flow contribution to streamflow from 95 percent of total streamflow during the predevelopment period to about 55 percent during the late 1980's. A proportional breakdown of this 40-percent decrease indicates that 7.5 percent resulted from storm sewering, 22.5 percent from Sewer District 2 (Pluhowski and Spinello, 1978), and 10 percent from the 1988 completion of Sewer District 3..

Table 5. Departures of percent base flow[1] from expected values[2] for East Meadow Brook, Nassau County, N.Y.

Year	Departure	Year	Departure
1943	3	1967	-45
1944	- 4	1968	-36
1945	1	1969	-26
1946	- 1	1970	-27
1947	0	1971	-39
1948	- 1	1972	-29
1949	2	1973	-29
1950	0	1974	-30
1951	- 2	1975	-33
1952	- 8	1976	-20
1953	-12	1977	-34
1954	-15	1978	-23
1955	-7	1979	-23
1956	-7	1980	-25
1957	-14	1981	-45
1958	-11	1982	-37
1959	-23	1983	-37
1960	-10	1984	-30
1961	-11	1985	-34
1962	-14	1986	-39
1963	-18	1987	-43
1964	-22	1988	-43
1965	-55	1989	-44
1966	-45	1990	-35

[1] Defined as base-flow component of total annual streamflow, in percent.
[2] Based on unurbanized conditions exhibited by Carmans River.

Water Table

The decline in ground-water levels since the construction of Sewer District 2 has been documented by Franke (1968), Garber and Sulam (1976), and Sulam (1979). In the present study, hydrographs and double-mass curves of water levels for four wells were examined and analyzed to determine whether shallow ground-water levels in Nassau County had declined further since the construction of Sewer District 3. Two of these wells (S3513 and S3521) are in the unsewered area of Suffolk County and represent predevelopment conditions. These wells were selected because they have long-term continuous records and because the hydrologic conditions they represent are similar to those of the two Nassau County wells. Wells S3521 and N1615 have about the same water levels; wells N1197 and S3513, being closer to the regional ground-

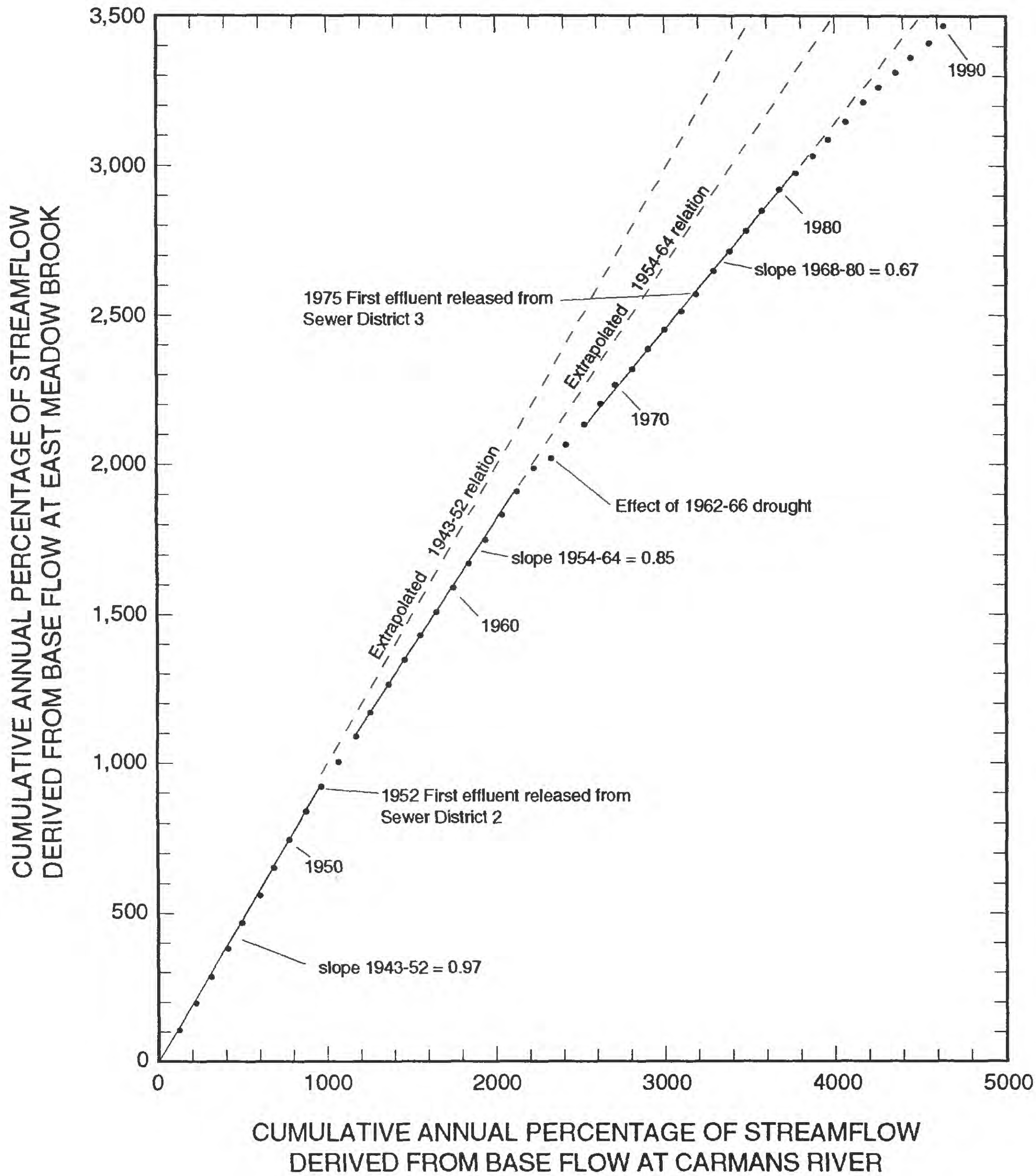


Figure 25. Double-mass curve of percentages of streamflow derived from base flow at East Meadow Brook and Carmans River, Long Island, N.Y.

water divide, show greater water-level fluctuations than S3521 and N1615. Hydrographs of water levels for the four selected wells are presented in figure 26.

Altitude and Fluctuations.—The 1962-66 drought caused water-level declines at all four wells; the largest declines were at N1197 and S3513. Water levels at all wells recovered after the drought, and those in N1197, S3513, and S3521 reached their maximum levels in 1979; those in N1615, which recorded its maximum in 1939, never returned to predrought levels because storm sewers and the operation of Sewer District 2 had altered the ground-water regime. The increased range in precipitation during 1980-90 resulted in increased water-level fluctuations at all four wells.

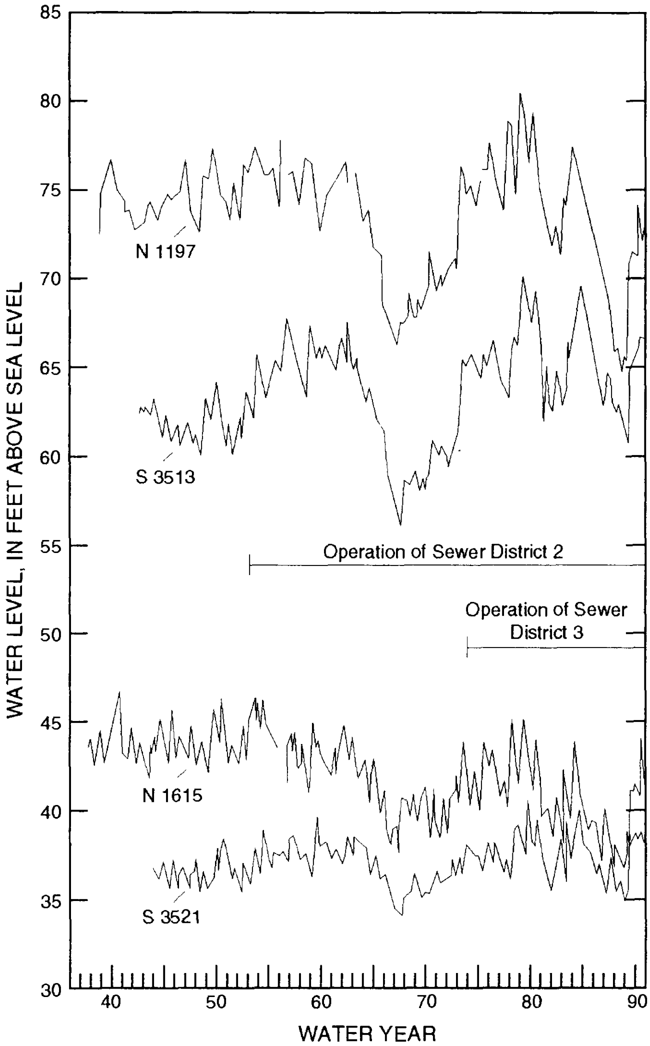


Figure 26. Water levels in four selected wells on Long Island, N.Y., 1936-90. (Locations are shown in fig. 1.)

Record-low water levels at N1197 and N1615 in late 1988 were about 1.5 ft lower than previous record lows set in 1966 during the drought. Water levels also declined at the two Suffolk County wells during 1988 but did not surpass the previous lows—water levels at S3521 remained 0.54 ft above the minimum level recorded during the drought. Similarly, the water level at S3513 in early 1983, although the lowest since 1972, was 4.23 ft above the record-low level of 56.06 ft in 1967, and in 1989 it was similar to levels measured during moderately dry periods during the 1940's and 1950's.

Water levels at wells N1615 and N1197 generally have declined since the late 1970's, except during 2 years of extremely high precipitation (1984 and 1989). This downward trend is exemplified by (1) the new record lows set in 1988, a period of only moderately low precipitation, (2) severely lowered water levels in periods of average precipitation, and (3) only moderate increases in water levels during periods of high precipitation, especially at N1615. This trend supports the conclusion indicated by the base-flow analysis that ground-water levels and, therefore, base flow, in the East Meadow Brook drainage area are continuing to decline.

Double-mass-curve analysis of ground-water levels.—Water levels at the two selected Nassau County wells for the period of concurrent record (1942-90) were compared with water levels at the two wells in unsewered areas of Suffolk County by means of double-mass-curve analysis. The annual average water levels at each of the two Suffolk County wells were averaged, cumulated, and plotted against the cumulative annual average water levels at each of the two Nassau County wells (fig. 27). The resulting departures from expected water levels are given in table 6.

At well N1615, the westernmost of the selected wells, the first deviation from linear proportionality with background water levels occurred in 1954 and was attributed by Franke (1968) to the effects of Sewer District 2 and storm sewers (fig. 27A). By the mid-1970's, water levels at this well were at least 3 ft below the level expected if the 1942-53 proportionality had been maintained (table 6). A deviation from the second line of proportionality, which developed after 1974, reflects an additional 3-ft decline that is attributed mainly to the discharge of treated wastewater from Sewer District 3, although additional road construction could have contributed also.

The calculated departures indicate that water levels at N1615 generally had declined to about 6 ft below those at 1939-43 by the late 1980's. This observed decline is slightly lower than predictions by analog and digital models (Kimmel and others, 1977; Reilly and Buxton, 1985) that water levels would be 6 to 8 ft below early 1970's levels when equilibrium conditions were achieved after 1995.

At well N1197, near the ground-water divide, the proportionality of the water levels with those of the two background (Suffolk County) wells remained constant until 1954 (fig. 27B). Unlike the double-mass curves for base flow (fig. 25) and well N1615

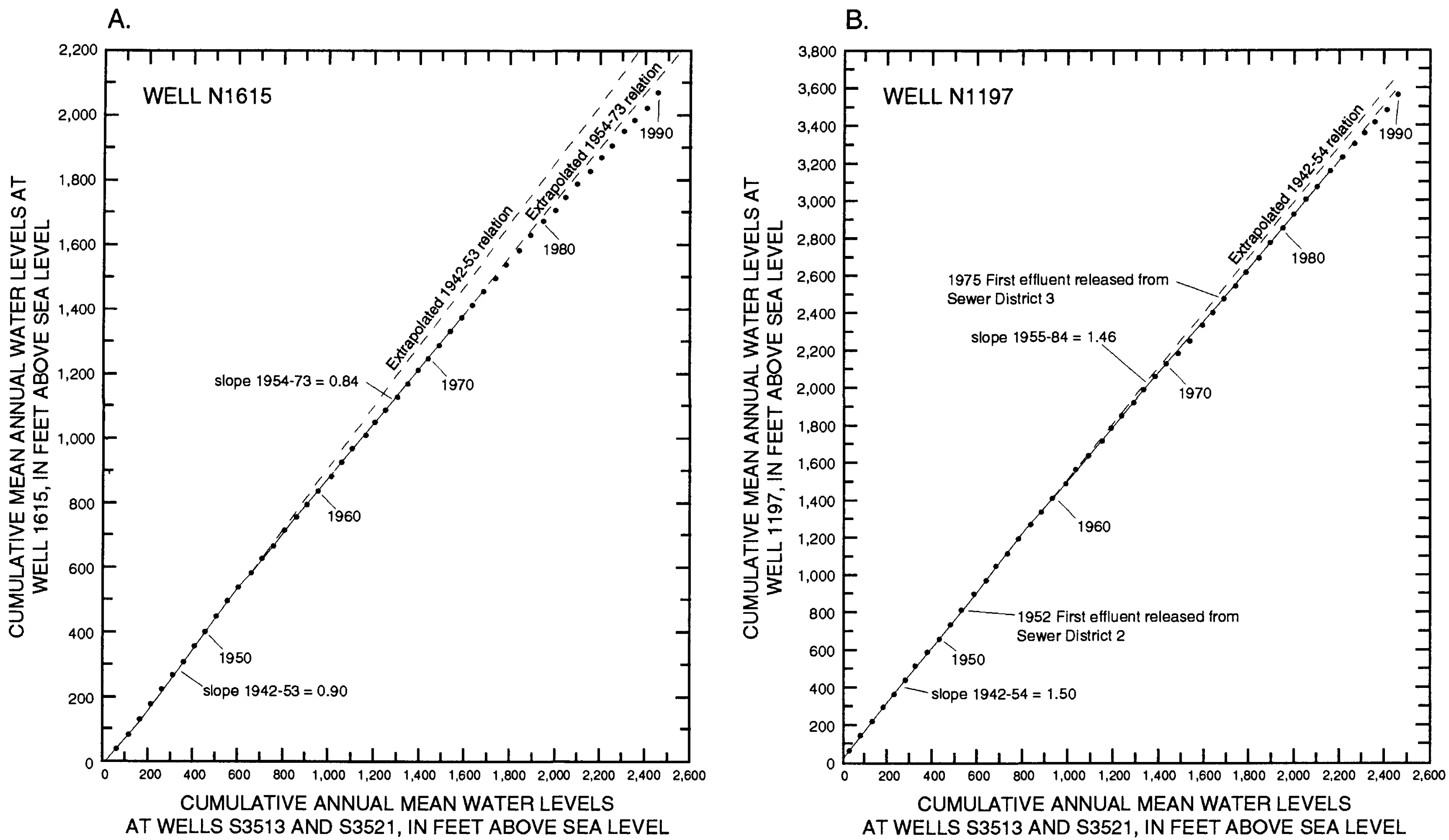


Figure 27. Double-mass curves of annual mean water levels in Nassau County, N.Y., wells N1615 and N1197 in relation to those in Suffolk County, N.Y., wells S3513 and S3521, 1942-90. (Locations are shown in fig. 1.)

Table 6. Departures of average ground-water levels from expected values[1] for wells N1197 and N1615, Nassau County, N.Y.

[Locations are shown in fig. 1. Departures are in feet]

Year	Water-level departure N1197	Water-level departure N1615	Year	Water-level departure N1197	Water-level departure N1615
1942	-2.23	-1.87	1967	-2.19	-1.50
1943	-9.25	-7.76	1968	-3.30	-2.18
1944	-5.60	-3.22	1969	-1.92	-1.73
1945	7.60	-2.49	1970	-1.35	-3.51
1946	2.04	5.00	1971	-2.87	-3.68
1947	-2.34	-7.47	1972	-2.63	-3.03
1948	2.93	2.38	1973	-1.30	-2.94
1949	1.50	-7.32	1974	-2.63	-4.99
1950	4.70	-1.17	1975	-1.93	-3.78
1951	8.41	5.77	1976	-1.08	-3.94
1952	-2.29	2.86	1977	-1.86	-4.62
1953	-6.10	-6.51	1978	-6.94	-3.59
1954	-2.90	-1.55	1979	-3.63	-5.55
1955	-2.31	-3.48	1980	-2.75	-5.86
1956	-2.64	-3.86	1981	-1.46	-5.61
1957	-2.73	-3.92	1982	-3.00	-5.10
1958	-6.93	-3.00	1983	-3.57	-5.64
1959	-2.53	-3.81	1984	-2.17	-5.45
1960	-4.22	-3.98	1985	-4.70	-7.41
1961	-2.10	-2.64	1986	-6.06	-6.67
1962	-2.41	-3.95	1987	-7.09	-6.24
1963	-2.38	-4.01	1988	-7.96	-6.86
1964	-2.26	-3.92	1989	-7.41	-6.53
1965	-3.16	-4.04	1990	-6.65	-5.40
1966	-3.31	-3.49			

[1] Based on unurbanized conditions exhibited at wells S3513 and S3521.

(fig. 27A), the curve for well N1197 shows a second period of consistently proportional water levels (equilibrium conditions) that lasted about 30 years (1955-84). Water levels during this period were about 2.5 ft below predevelopment levels (table 6); this decline is attributed primarily to storm-sewer construction because well N1197 is too far from Sewer District 2 to be significantly affected by it. The most recent departure from linearity began during the mid-1980's as a result of the completion of Sewer District 3, which has caused an additional 5-ft water-level decline.

By 1990, water levels at N1197 had declined about 7.5 ft from 1939-43 levels. The analog and digital models of Kimmel and others (1977) and Reilly and Buxton (1985) predicted that equilibrium conditions would be reached in 1995 and that water levels in the area around N1197 would be 16 to 18 ft below those measured during 1968-75. This disparity could be partly explained by recharge patterns; Ku and others (1992) suggested that the recharge basins in Nassau County could provide larger amounts of annual recharge than the values used in the models. The model of Ku and others (1992) indicates that, by 1995, the water levels at well N1615 would be from 5.5 to 7.5 ft below early 1970's water levels, and those at well N1197 would be 12 to 14 ft below those of the early 1970's. The observed water-level declines of 1990 that can be attributed to effects of Sewer District 3 were only 3 ft below early 1970's levels at N1615 and 5 ft below 1970's levels at N1197—less extreme than predicted for 1995. Reasons could be that: (1) equilibrium conditions had not yet been reached in 1990, (2) rainfall and recharge increased in the 1980's (see earlier discussion of precipitation), or (3) a combination of these or other factors. Further investigation of these factors was beyond the scope of the study.

Water Budget (1981-90)

A generalized water budget for the East Meadow Brook area under urbanized (1981-90) conditions is presented in figure 28. Most urban development within the water-budget area had been completed by 1990; few new roads were built after 1976 (table 3), and hookups to Sewer District 3 had been largely completed by 1985 (table 4). The effect of recharge basins was not quantified in this budget because the few basins in the water-budget area probably have only a minor effect. Water-supply pumpage also is not quantified in this budget because consumptive use (from activities such as lawn sprinkling) is probably accounted for in the calculated estimate of evapotranspiration (Franke and McClymonds, 1972).

Precipitation at Mineola during 1981-90 averaged 48.45 in/yr. Annual-mean streamflow, base flow, and direct runoff discharges were 9.0 ft^3/s, 5.1 ft^3/s, and 3.9 ft^3/s, respectively. Ground-water inflow and ground-water outflow cannot be measured directly and are difficult to evaluate; they are assumed to be equal, however, and therefore are not quantified in this budget.

Ku and others (1992) estimated that areas served by sewers that route stormwater to streams receive about 10 percent less recharge than areas without storm sewers. Although no direct measurements are available, recharge to the saturated zone in this budget

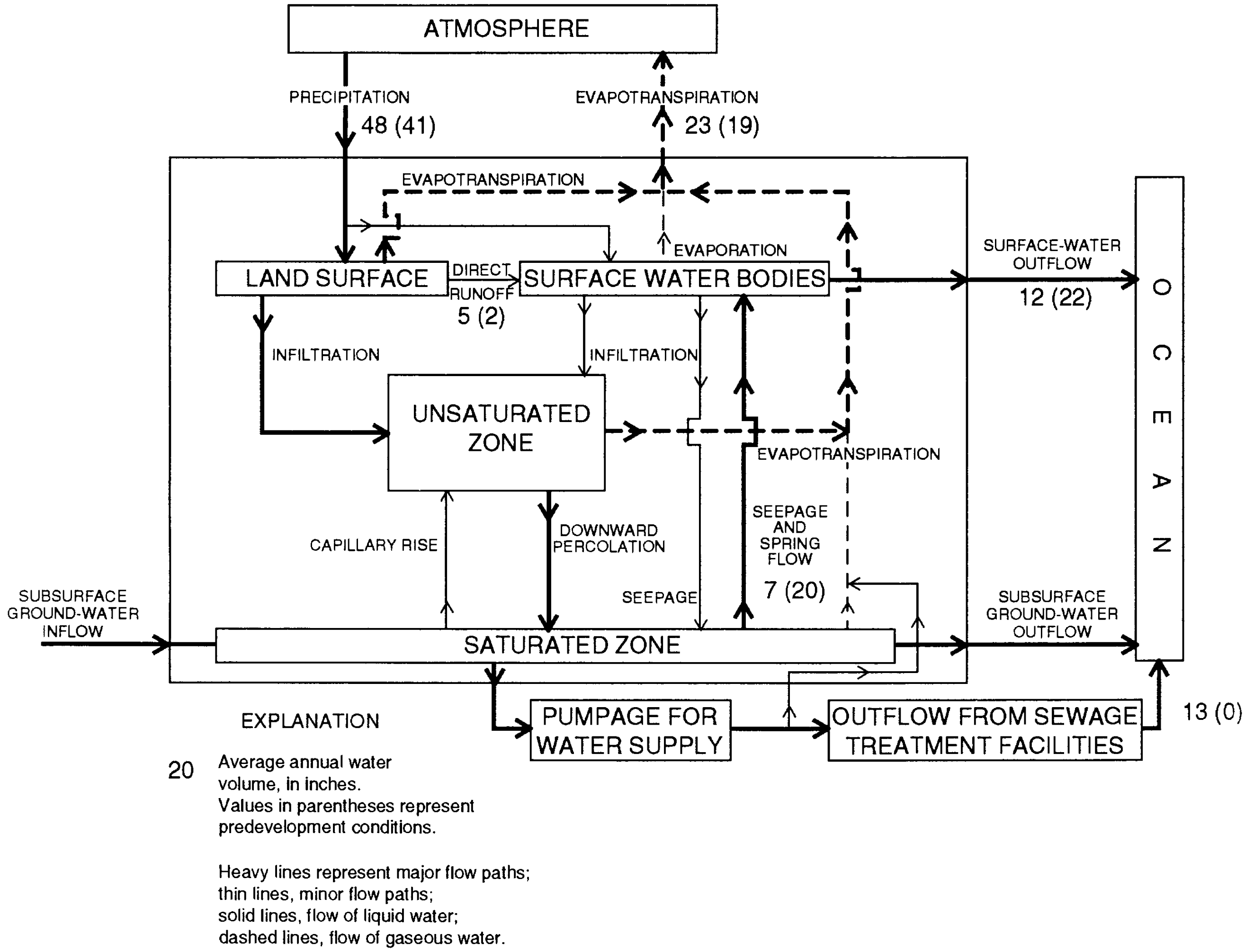


Figure 28. Water budget for the East Meadow Brook area, Nassau County, N.Y., during 10 years (1981-90) of the period of urbanization. (Modified from Franke and McClymonds, 1972, fig. 13.)

is estimated to be about 20 in. rather than the 23 to 24 in. that would be expected under predevelopment conditions with an annual precipitation of 48 in. The 3- to 4-in difference between these volumes represents water that is exported from the system as direct runoff to the stream.

Direct runoff to streams for 48 in. of precipitation under predevelopment conditions is estimated to be about 2 in. Use of the hydrograph-separation method for 1981-90 data indicated 5 in. of direct runoff, which is consistent with the sum of the expected amount (2 in.) and the estimated amount of recharge lost through storm sewers (3 in.). The percentage of streamflow contributed by direct runoff increased from about 5 percent during the predevelopment period to an average of 43 percent during this latter period.

Sewage-treatment plants remove pumped ground water from the aquifer system by discharging it to tidewater rather than returning it to aquifers. The loss incurred by operation of the Bay Park and Cedar Creek sewage-treatment plants was estimated as the combined average outflow of the two plants (about 110 Mgal/d) divided by the total sewered area (175 mi^2) to give the average discharge per square mile. The annual loss from the 10-mi^2 water-budget area was estimated to be 13 in.

As in the 1939-43 water budget, evapotranspiration cannot be measured directly and is calculated as the remainder after subtraction of known quantities. Average annual evapotranspiration in the water-budget area was estimated as total precipitation (48 in.) minus streamflow (12 in.) and sewage outflow (13 in.) and resulted in a total of 23 in.

The lowering of ground-water levels through (1) decreased recharge as a result of storm sewers, and (2) the export of ground water from the aquifer system by sewage-treatment facilities, has decreased the base-flow discharge to the stream (7 in. as estimated by the hydrograph-separation method) by 65 to 70 percent since the 1939-43 period and caused a decrease in total streamflow despite the increase in direct runoff. The digital model of Reilly and Buxton (1985) predicted that base flow would decrease by 83 percent by 1995, when equilibrium conditions were expected to have been reached.

In this budget, the volumes of water leaving the ground-water system (7 in. as base flow and 13 in. as sewage outflow) are about equal to the estimated amount of recharge to the saturated zone (20 in.), and no excess ground water is available to recharge the regional aquifer system within the water-budget area. Whatever small amount of water that could enter the shallow system from the regional system probably is lost through pumping, as sewage outflow and base flow, or through evapotranspiration. Therefore, unlike the period of light urbanization (1939-43), subsurface outflow from the study area during the urban period is probably somewhat less than the subsurface inflow.

SUMMARY AND CONCLUSIONS

Increasing urban development in Nassau County during the last 50 years has altered the natural hydrologic system. This report examines the effects of urbanization on the flow of East Meadow Brook and ground-water levels in the vicinity, with emphasis on the hydrologic effects of the recent completion of Sewer District 3, which had not been previously evaluated.

Urban development in Nassau County increased sharply after World War II; during 1950-60 the population doubled from 673,000 to 1,300,000, and much of Nassau County evolved into suburban residential communities. The attendant increase in amount of road surface drained by storm sewers increased the amount of direct runoff to streams and recharge basins. Most of the storm runoff in the East Meadow Brook area is routed to the stream; recharge basins in the area are few and, thus, have little effect on ground-water levels.

Ground-water contamination resulting from the disposal of sewage through cesspools and septic tanks prompted the construction of Sewer District 2 in southwestern Nassau County during 1952-64 and Sewer District 3 in southeastern Nassau County during 1974-88. The removal of large quantities of water from the aquifer system through sanitary sewers and storm sewers has lowered ground-water levels and decreased streamflow; record low ground-water levels (lower than during the 1962-66 drought) were recorded at two long-term monitoring wells in Sewer District 3 in 1988. Water levels at these wells were compared with those at two wells in similar settings without sewers in Suffolk County. Well N1615, within East Meadow Brook's drainage area, showed an overall ground-water decline of 6 ft since 1939-43, of which about 3 ft can be attributed to the effect of Sewer District 3. Well N1197, in the central part of Sewer District 3 and near the ground-water divide, showed little response to the completion of Sewer District 2; water levels here have declined 7.5 ft as a result of storm sewers and the completion of Sewer District 3.

The lowering of ground-water levels has shortened the continuous-flow reach of East Meadow Brook and decreased its base flow and, thus, its total flow. The start-of-flow was farther south in February 1992 than it was during the 1962-66 drought.

Water-budget analysis indicates that base flow has declined 65 to 70 percent from its estimated predevelopment volume; the percentage of streamflow contributed by base flow also has declined. Base-flow contribution began to decrease in 1953 and, by the 1970's, had declined from its predevelopment level of 95 percent to about 65 percent. An additional 10-percent decline to about 55 percent of total streamflow in 1990 is attributed to the effect of Sewer District 3.

A water-budget analysis indicates that direct runoff volume has increased by 250 percent since predevelopment time as a result of storm sewers that divert runoff to East Meadow Brook. The contribution of direct runoff to total streamflow has increased from its predevelopment level of 5 percent to about 45 percent.

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