AVAILABILITY AND HISTORICAL DEVELOPMENT OF GROUND-WATER RESOURCES OF LONG ISLAND, NEW YORK--AN INTRODUCTION

by Bronius Nemickas, Gail E. Mallard, and Thomas E. Reilly

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CONVERSION FACTORS AND ABBREVIATIONS

For the convenience of readers who may prefer to use metric (International System) units rather than the inch-pound units used in this report, values may be converted by using the following factors:

Multiply inch-pound unit	by	To obtain metric unit
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.59	square kilometer (km^2)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

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 both the United States and Canada, formerly called "sea level datum of 1929."

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ABSTRACT

Ground water is one of Long Island's most valuable natural resources. Without it, the extensive growth of population and industry that have occurred on the island since the 1940's would not have been possible. The present population, with its industry and agriculture, will continue to require a supply of high-quality water in the future. Several past human activities have adversely affected this resource; for example, excessive pumping in some areas has caused saltwater intrusion, plumes of leachate from solid-waste landfills have caused local contamination of the aquifers, cesspool discharges have caused nitrate contamination of ground water, and application of pesticides has caused ground-water contamination in eastern Suffolk County. Some of the problems can be or have been corrected or avoided through proper management. An understanding of the ground-water system is requisite for proper management of the resource. This report describes, for the general public, the water resources of Long Island and methods used to obtain information on the resource. It also presents four historic examples of ground-water contamination to illustrate how management can respond to real or potential threats to this resource through knowledge of the hydraulics and chemistry of the aquifer system.

INTRODUCTION

Long Island (fig. 1) extends from the southeastern part of the mainland of New York State eastward about 120 miles into the Atlantic Ocean and has a total area of about 1,400 mi^2 (square miles). Kings and Queens Counties, which are part of New York City, occupy slightly less than 200 mi^2 of the western part of the island and have a combined population of more than 4.1 million people. Nassau and Suffolk Counties, which form the central and eastern parts of the island, have areas of about 290 and 920 mi^2, respectively, and a combined population of over 2.5 million.

Background

Although the New York City part of Long Island derives most of its water supply from upstate surface-water sources, Nassau and Suffolk Counties derive their entire water supply from wells that tap the underlying ground-water reservoir. Approximately 1,000 public-supply wells supply about 400 Mgal/d (million gallons per day) to the 3.1 million people that use ground water.

The use and development of the ground water and the land uses associated with the island's large population have affected the patterns of ground-water recharge and discharge and thereby altered the quantity of water available. In addition, the land uses have affected the availability and chemical quality of the water.

The ground-water reservoir under Long Island contains large quantities of water of high quality suitable for human consumption and most other uses, but the supply is neither limitless nor invulnerable to the effects of human activities. The principal ground-water problems at present concern water quality, such as contamination from leaky gasoline and oil tanks, leachate from municipal landfills, urban runoff from paved areas into recharge areas, use of lawn chemicals, industrial chemical spills, and saltwater intrusion.

Although the threats to this important sole source of water may seem limitless, knowledge of the hydraulics and chemistry of the system has enabled informed management decisions to be made. Some problems involving saltwater intrusion now appear to be under control, and the sources of some domestic contaminants such as detergents and nitrates have been removed. The supply of potable water beneath Long Island is large, and a well-informed management with a sound understanding of the hydrologic system is the key to optimal use of this renewable resource.

Purpose and Scope

This report explains the scientific aspects of Long Island's ground-water resources, summarizes much of the information obtained during the more than 45 years of the U.S. Geological Survey's study of Long Island's ground-water system, and describes the causes of four selected ground-water-contamination problems and the management responses.

The first two sections introduce the basic principles of ground-water occurrence and describe some techniques used to obtain information on this resource. The third section describes the physical characteristics of the Long Island ground-water system, and the fourth section describes the development of Long Island's ground-water resources since the time of the earliest European settlers. The fifth section presents four historic examples of problems that have developed to illustrate the variety of threats to the island's ground-water resources and how management, through a scientific understanding of the resource, has addressed such problems.

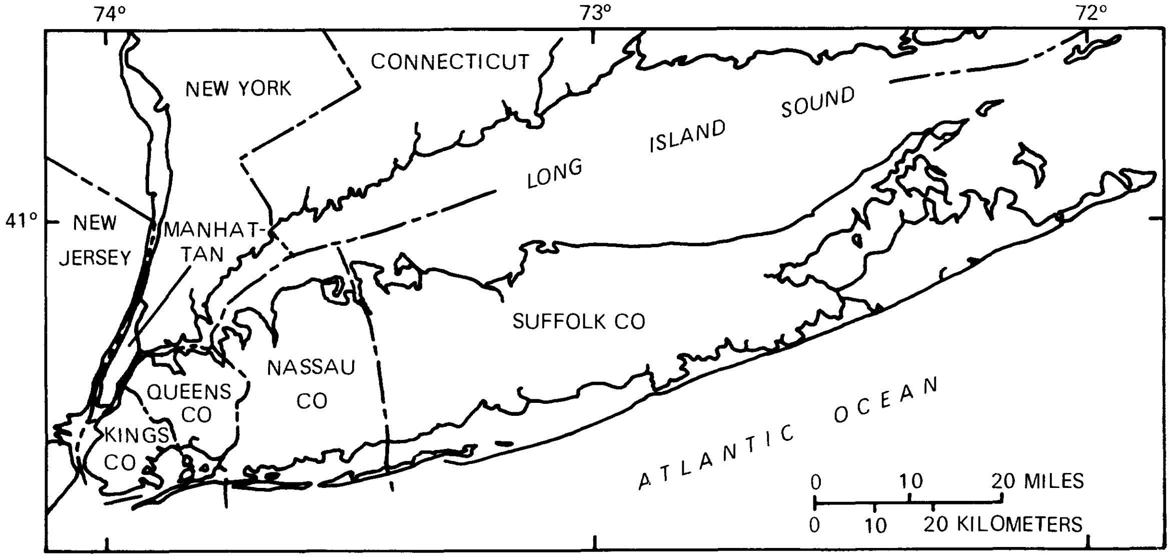


Figure 1.--Location of Long Island, N.Y., and its four counties.

THE HYDROLOGIC SYSTEM

Water is continuously migrating between the atmosphere, the ground, the ocean, and back to the atmosphere within a system known as the hydrologic cycle, depicted in figure 2. Water evaporates from the oceans and land surface, and much of it accumulates into rain clouds, some of which move inland and release water onto the land. Of the water that reaches the land surface, some flows overland to streams, some evaporates, and some infiltrates the soil and percolates to underlying formations, where it eventually moves as ground water to streams or the ocean.

All water originates from and returns to the oceans, but not all of it completes all phases of the hydrologic cycle; some water may take short cuts or be detained in the overall circulation. An example of water that does not complete the full cycle is that which is evaporated from land and is returned as precipitation, only to evaporate again.

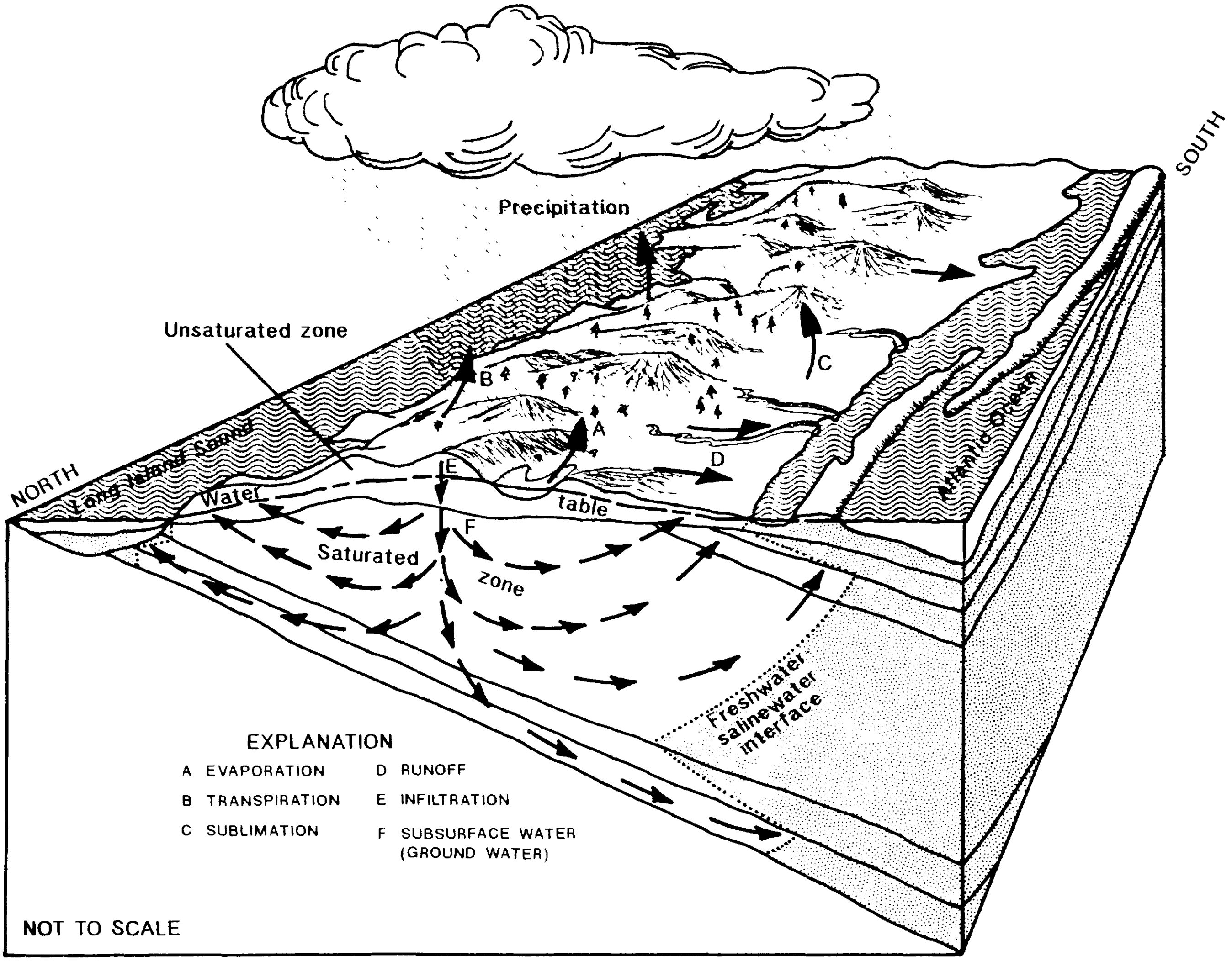


Figure 2.--Major components of the hydrologic cycle. Arrows show direction of water movement.

The phases of the hydrologic cycle are precipitation, evaporation, transpiration, sublimation, runoff, infiltration, and subsurface water (ground water), which are explained in the glossary and illustrated in figure 2. Ground water, the source of water supply for 3.1 million people on Long Island, is described below.

Ground-Water Reservoir

Subsurface water is found in both the unsaturated zone (zone of aeration) and the saturated zone (fig. 2). The quantity of water in the unsaturated zone fluctuates in response to precipitation and evapotranspiration. This water seeps downward to the water table (the top of the saturated deposits) under the influence of gravity but is not recoverable to any extent for water supply above this level.

All material below the water table is saturated with ground water. Geologic units below the water table that transmit water readily to wells are known as aquifers; those that do not transmit water readily to wells are known as confining units. An aquifer that is in direct contact with the atmosphere through open pores in the overlying geologic material is called an unconfined aquifer; an aquifer that is separated from the atmosphere by relatively impermeable geologic material, such as clay, is called a confined aquifer. The Long Island ground-water reservoir contains confined and unconfined aquifers, as described later on.

Ground-Water Quality

Almost all materials on and beneath the land surface are soluble in water to some extent; therefore, all ground water contains dissolved elements and compounds. The chemical nature of these substances and their concentrations determine the quality of the water.

As ground water moves through the aquifer system, its quality may change considerably. The type and degree of change is determined by the flow path of the water and by the type of materials with which it comes into contact. These processes also are discussed further on.

METHODS OF STUDYING THE GROUND-WATER SYSTEM

Understanding a specific ground-water system (such as Long Island) requires knowledge of (1) the physical laws that govern the hydraulic and chemical processes within the ground-water system; and (2) the geologic, hydrologic, and geochemical environments within that system. Applying the physical laws to the available data on the local geology, hydrology, and chemistry yields a general concept of the system's operation.

A review of the basic laws of physics, hydraulics, and chemistry is beyond the scope of this report but is available from many sources. The collection of data needed to describe a ground-water system involves several steps and many considerations, as described in the following sections.

Types of Information Required

The types of information needed to describe the geologic, hydrologic, and geochemical environments of a specific aquifer system include:

(1) The distribution, thickness, and composition of the subsurface deposits to develop a concept of the internal and external dimensions of the groundwater system. The thickness and lithologic characteristics of the geologic materials provide an indication of their water-transmitting and storing properties--that is, how rapidly the materials transmit water and how much water is stored.

(2) The three-dimensional distribution of the mechanical energy of the water in the deposits, in terms of the measured water level, to define the directions of water movement. (In unconfined aquifers, the water table also forms the top boundary of the saturated deposits.)

(3) The type and distribution of chemicals dissolved in the water; and

(4) The transmitting and storing properties of the geologic deposits, to calculate the rate and direction of water movement. These data are needed to predict the response of the aquifer to future stresses such as increased pumping and the direction and extent of contaminant migration.

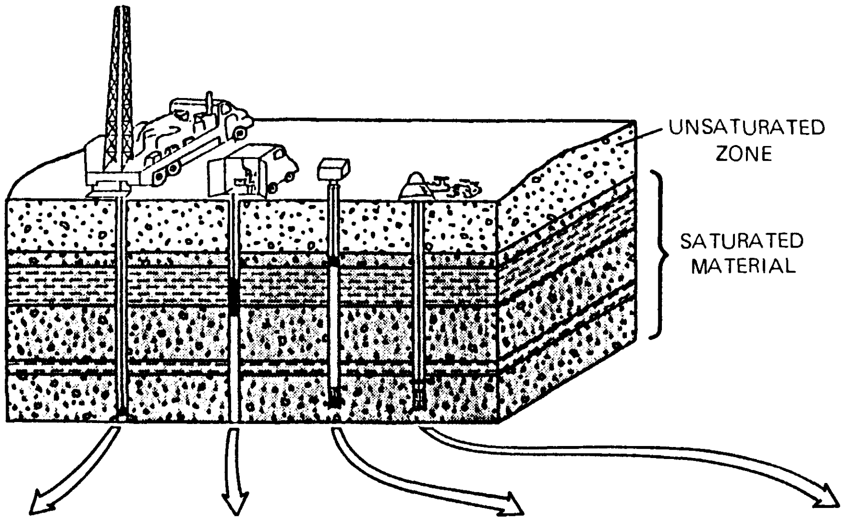
The above categories are not all-inclusive but indicate the type of information required for a hydrologic study. The following sections describe methods of collecting these data. The types of data collected are classified into two groups here for convenience--data collected from the subsurface, and data collected at land surface.

Data from Subsurface Investigations

Ground-water systems cannot be analyzed by direct visual examination. The most common means of obtaining information on a ground-water system is to drill wells; this provides information on the geologic units, water levels, and the chemistry of the system (fig. 3).

One of the first steps of a ground-water-system analysis is to identify the geologic deposits beneath land surface. The geologist's log of the material encountered during drilling (fig. 3A) generally gives an accurate indication of the type of materials present. Samples of the geologic deposits obtained during drilling can be used for detailed visual examination and laboratory tests. Some of these laboratory tests are sieve analyses, which indicate the grain-size distribution of the materials, and permeability tests, which indicate the ability of the material to transmit water.

A geophysical logger can be used to delineate in detail the changes in materials with depth below land surface by measuring the natural gamma radiation and the electric resistivity of the formation. A geophysical log is obtained by slowly lowering a probe down the well and continuously recording the response to the geologic units at successive depths. A trained geohydrologist can then interpret the measurements and make inferences as to



A. GEOLOGIC DATA FROM DRILLER'S LOG

Depth below land surface (feet)	Description
0-150	Sand, brownish orange to brownish gray, medium to very coarse grained, angular to subangular; gravel, granular to pebble size. Contains quartz and feldspar with some iron staining.
150-210	Clay, dark gray, with gravel, granular, consisting of quartz and feldspar; sand, white, coarse to very fine grained, includes muscovite mica.
210-270	Sand, white-gray, very fine to medium grained. Contains lignite and muscovite mica.
270-280	Clay and sandy clay, gray, coarse grained to silt. Contains grains of lignite and muscovite mica.

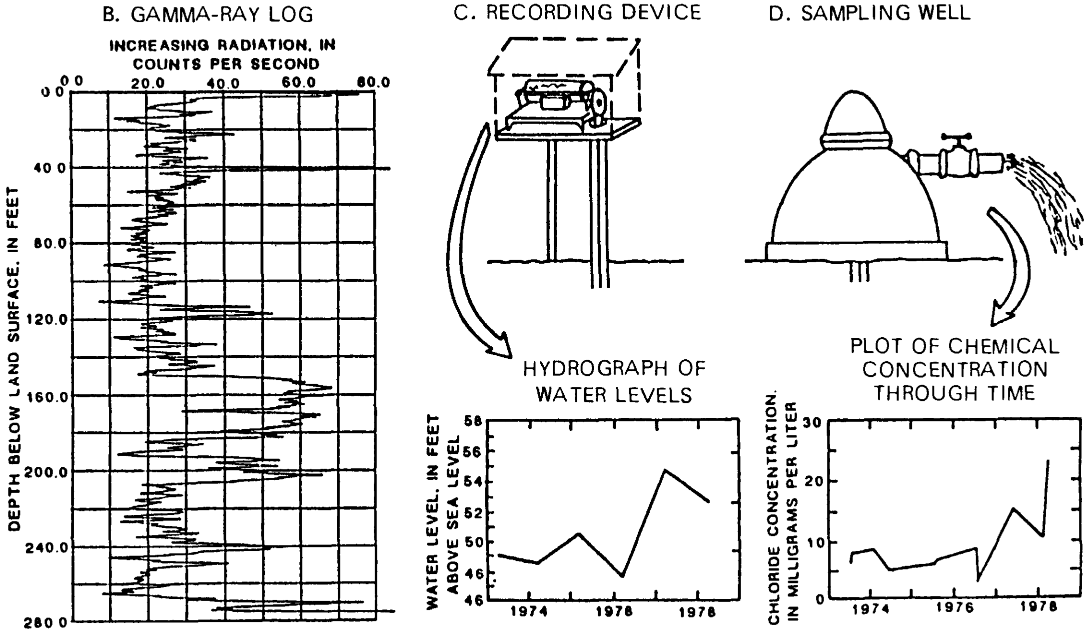


Figure 3.--Types of hydrologic data available from wells: A. Geologic data from driller's log. B. Geologic data from gamma-ray log. C. Water-level data from recording device. D. Chemical data from water samples.

the physical makeup of the formation. For example, the gamma-ray log shown in figure 3B indicates an increase in gamma reflection where the line is deflected to the right; to a geohydrologist, this indicates that clay is present at those depths. These clay layers are corroborated in the geologist's description of sampled material (fig. 3A).

If the hole is drilled to obtain only geologic information, it is later filled and will provide no other information. However, if it was drilled to obtain a water supply or information on the hydraulics and(or) chemistry of the ground-water system, a steel or plastic pipe (called a casing) usually is installed in the hole to prevent it from collapsing, especially if the well is drilled in unconsolidated sediments. A section of the well casing called the well screen has holes or slots to allow water to flow into the well from the formation while preventing large particles from entering. The size of the hole drilled and the type of casing installed depend on the desired use. Most deep public-supply wells have a large diameter (1 to 3 feet), whereas wells installed for water-level observations or sampling commonly have a diameter as small as 2 inches.

The altitude of water in the well (water level) is essential for an accurate description of the ground-water system at that location because the water level reflects the hydraulic pressure in the part of the aquifer that is screened. The water level can be measured manually at selected time intervals or by continuous water-level recorder (fig. 3C) to obtain a graph of the water-level fluctuation through time.

The well also can be pumped to provide water samples (fig. 3D) for analysis by a chemical laboratory to identify the elements and compounds present and determine their concentrations. If the well is sampled on a regular basis, the concentrations can be graphed through time to indicate trends in the chemical quality of the water.

The water-level and chemical data from wells describe conditions of the aquifer at only the screened depth in the aquifer, and the geologic data describe the geologic formation throughout the depth of the well, but these data pertain only to the well's immediate vicinity. Data from this location must then be correlated with data from other wells and then extrapolated to define the entire continuous aquifer system. All measured data have an inherent degree of uncertainty, and the extension of the data from one locality to an entire aquifer system increases the uncertainty. Thus, the greater the amount of subsurface information available, the more certain will be the resulting description of the ground-water system.

Data from Land-Surface Measurements

Data collected at land surface are important in describing the ground-water system, and collection of surface data is usually much easier and more economical than subsurface investigations. The data that are collected at land surface can be placed into two broad classes: (1) factors that are independent of the ground-water system, such as precipitation, and (2) factors that are dependent on the ground-water system, such as ground-water seepage to streams.

Probably the most important natural factor within the first category is precipitation. Rainfall is the initial source of all fresh ground water; thus, an accurate measurement of annual rainfall is needed to quantify the hydrologic system. Small weather stations are used to collect these and other data, such as air temperature and evaporation rates.

Other surface factors that can affect the ground-water system are large streams whose main source of water is distant from the area being studied but provide recharge to the ground-water system through streambed infiltration, and chemical spills at land surface that infiltrate with rainwater into the ground-water system.

A major element in the second category (factors that depend on the ground-water system) is ground-water seepage into lakes and streams. The water-surface altitude in lakes and streams that are in hydraulic connection with the ground-water system is the same as the water level in the aquifer at the edge of the lake or stream. Similarly, the chemical quality of the water leaving the ground-water system as seepage to lakes and streams is an indicator of the quality of water in the aquifer itself.

Data collected from the land surface--water levels and water-quality data--indicate the hydraulic head (water-table altitude), rate and direction of flow, and chemical quality. Accurate measurement of these factors is an integral part in formulating a concept of the system's operation to enable prediction of the effects of future stresses.

Water-Quality Analysis

Water-quality data are obtained from laboratory analyses of water samples. These analyses are rarely comprehensive, however, because any given sample can have hundreds of separate physical, chemical, and biological characteristics. The constituents tested for depend on the purpose of the study and may differ widely from study to study, even among studies conducted in the same general area.

Although no water-quality study can be called "typical," most such studies have two things in common. First, the data are obtained by three general steps, illustrated in figure 4, and second, the data generally are interpreted, in part, through comparison with previous analyses or with State or Federal water-quality standards and analysis of spatial trends. Therefore, individuals working at different times or in different places must use essentially the same procedures so that results can be compared. Each step in the data-collecting process described below has standard methods and procedures that have been adopted by national and international organizations.

To obtain accurate water-quality data, one must begin with suitable water samples; therefore, the first consideration in ground-water sampling is to obtain samples that are representative of the water being studied and to prevent contamination or alteration of samples during collection and storage.

Once a water sample has been collected, its chemical character begins to change almost immediately; a major goal in water-quality studies is to

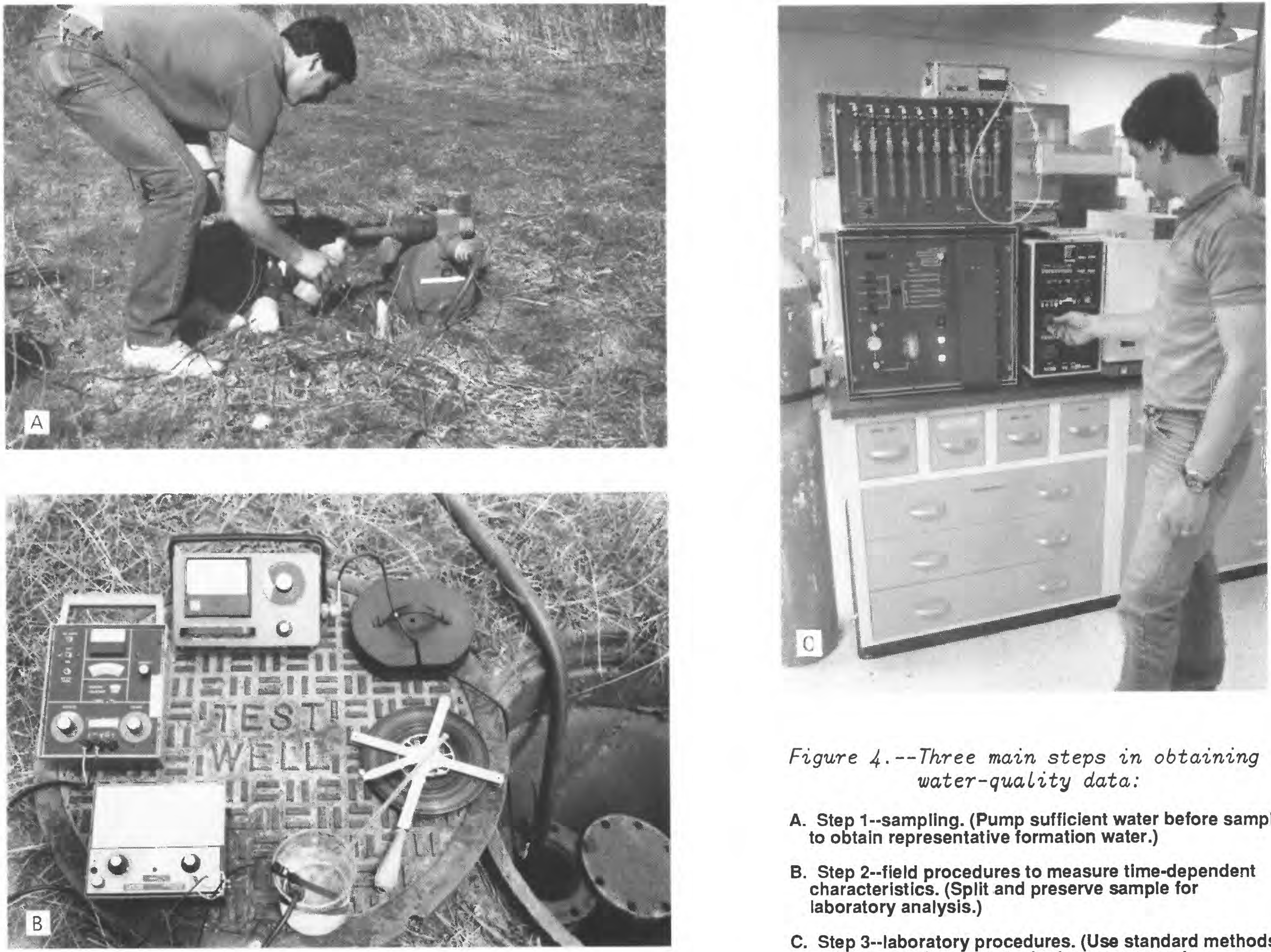


Figure 4.--Three main steps in obtaining water-quality data:

A. Step 1--sampling. (Pump sufficient water before sampling to obtain representative formation water.)

B. Step 2--field procedures to measure time-dependent characteristics. (Split and preserve sample for laboratory analysis.)

C. Step 3--laboratory procedures. (Use standard methods, maintain quality control, obtain accurate and reproducible results.)

minimize the amount of change. Thus, the second step in data collection is to measure, in the field, those characteristics that change most rapidly as soon as possible after the sample is obtained. Among these characteristics are temperature and the concentration of dissolved gases. Because the large majority of water-quality characteristics can be more conveniently and accurately measured in the laboratory, the samples must be preserved in the field to prevent significant changes during transit or storage.

The third step in data collection is performed in the laboratory. Established procedures are used to identify and quantify inorganic and organic chemicals that are dissolved or suspended in the sample. Regardless of the substance being tested for, standard methods are used, and careful attention is paid to quality-control procedures so that the results obtained are both accurate and reproducible.

The final step in the analysis of water quality is interpretation of the results from the laboratory. This step generally includes a comparison of results with those obtained earlier from the same site or with published water-quality values or standards. For example, the chloride concentration in figure 4D indicates that the chloride concentration in 1981 was 60 mg/L (milligrams per liter). Comparison of this value with the New York State drinking-water standard of 250 mg/L (the approximate taste threshold) indicates that the water is acceptable in relation to this particular constituent. Comparison of the chloride concentration of April 12, 1981, with one obtained earlier would indicate an increase or decrease over time.

Plotting the chemical concentrations of a water sample and the changes through time are only part of the process of interpreting water quality; these results must then be related to other hydrologic information to obtain a detailed concept of the system and its dynamics.

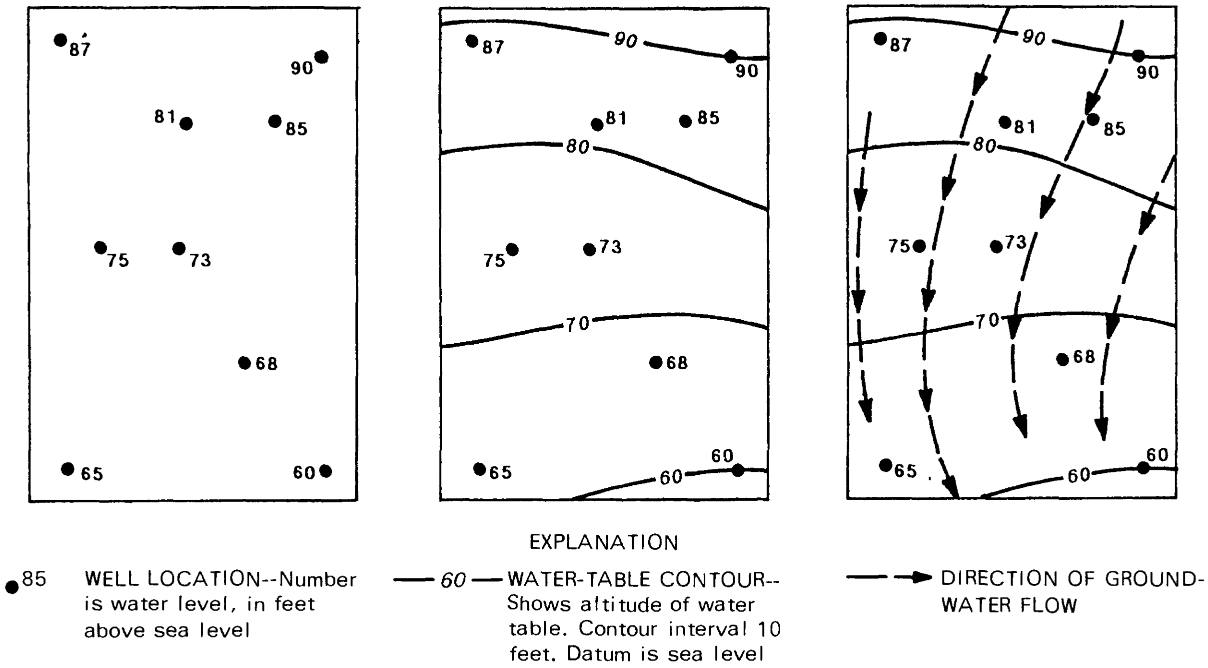
Use of a Monitoring-Well Network for Data Compilation

As stated earlier, the data obtained from a well are representative of the aquifer only in the vicinity of the well bore, screen, and(or) opening. The acquisition of data from the entire aquifer system requires a network of wells in conjunction with the precipitation and other surface data. The data obtained from this network can then be used to describe the aquifer's geologic, hydrologic, and geochemical characteristics both in a horizontal and vertical direction.

Networks of monitoring wells have been installed on Long Island to obtain water levels. The water-level measurements, when plotted on a map (fig. 5A), can be used to contour the water-table altitude (fig. 5B). Ground water moves from high areas to lower areas, roughly perpendicular to water-table contours. Thus, the water-table contours can be used to approximate the paths (flow lines) of the water (fig. 5C). Further interpretation based on hydraulic-conductivity estimates can be used to predict approximate traveltimes for the movement of water through the mapped system. The traveltimes, used in conjunction with data on the distribution of chemical concentrations, may be used to generate hypotheses as to the source and fate of the chemical constitutents moving with the ground water.

Most monitoring networks designed for a specific purpose require wells in addition to those already in the area. Care must be taken in evaluating data from random wells to ensure that no bias is introduced in the data collection. For example, a potential bias can occur in areas where all wells that have had contamination have been abandoned and all remaining active wells indicate acceptable quality, which can lead to inaccurate conclusions.

The purpose of a monitoring network is to identify the geologic conditions and to measure water levels, chemical concentrations, and related characteristics periodically to determine the changes over time. The data obtained from a monitoring network can be used in conjunction with data on the hydraulic boundaries of the hydrologic system to construct contour maps and graphs of these aquifer characteristics. This in turn allows testing of hypotheses through computer simulations to formulate a concept of the dynamics of the aquifer system.



A. Location of monitoring wells

B. Water-table contours

C. Inferred direction of ground-water flow

Figure 5.--Generalized maps showing: Use of water-level data (A) to indicate water-table altitude (B) and inferred direction of ground-water flow (C).

Computer Simulations

Management of ground-water resources is based on legal and political considerations, but the response of the aquifer system to development and stress is independent of legal and political boundaries and is not confined to the vicinity of a specific town or other sociopolitical entity. Thus, effective local management requires information on the occurrence and movement of water throughout the entire system as well as locally.

Many hydraulic characteristics of an aquifer system, such as natural recharge and discharge, are related to one another in a quantifiable way. If these relations can be correctly represented mathematically over a broad area, the future response of ground-water levels throughout the system to a given stress or to various water-management schemes can be estimated. The ability to estimate the aquifer's response to future stresses--for example, increased pumping--is a great help in developing long-term water-management plans.

The physical processes that govern the flow of water and chemicals in a ground-water system operate continuously in space and time and can be defined mathematically. These mathematical expressions, known as mathematical models, are based on the conservation of mass and energy and represent the cause-and-effect relationships within ground-water systems.

A method commonly used to solve these mathematical expressions is computer simulation (modeling), which enables quantitative predictions of the effects of proposed actions on ground-water levels. A simulation of a ground-water system requires that the hydraulic properties throughout the breadth and thickness of the aquifer system be specified accurately. Because these values are only approximately known, and because the roles of some aquifer characteristics are poorly understood, the model predictions are subject to error and can be only as accurate as the data and assumptions used in model construction and operation.

A model is a simplified representation of some aspects of a real system. A computerized ground-water flow model is designed to indicate the patterns of flow within the real ground-water system by solving the mathematical equations that describe the system. A three-dimensional ground-water flow model of the Long Island aquifer system (fig. 6) was developed in the early 1980's and used to predict the effects of sanitary sewers on water levels and streamflow. In this particular model, the ground-water system is represented in three dimensions by a grid of many blocks, each representing a certain area (fig. 6A) and depth interval. Values are assigned to each block to represent the hydraulic properties of that block, and the model is then used to calculate the hydraulic head that would result within each of these blocks when a stress is applied, such as lack of recharge, and then to plot the resulting head distribution as shown in figure 6D, which shows the predicted declines in water levels that would prevail after the installation of sewers. The conceptual process and the products of computer simulation are identical to the process of using water-level measurements to draw water-table contours and inferring flow lines as described in the previous section and illustrated in figure 5. The principal difference is that in delineating water-table contours by hand, actual field values (measured water levels) are used, and the contours between points are inferred by a hydrologist or generated by a computer. The water-table contour represents the ground-water conditions at the actual time of measurement. With computer simulations, many hydrologic variables are considered at once over a large area and represented mathematically. Imagined or proposed changes in one or more variables can then be applied to the model to predict or estimate the response of the system.

Even though quantitative analyses (and computer simulations in particular) provide information on hydraulic relations within the ground-water system and can be used to estimate the system's response to future stresses, they are

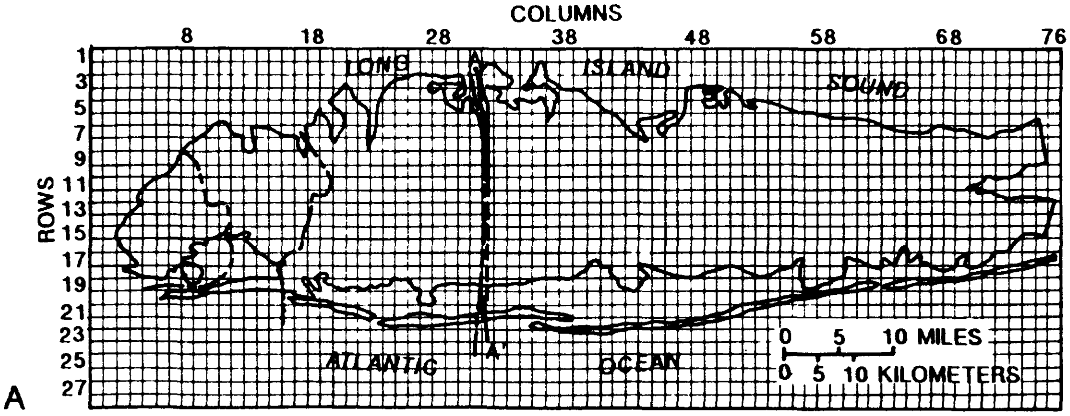


Figure 6A. Horizontal grid of finite-difference ground-water flow model of Long Island. (Modified from Reilly and others, 1983, fig. 12.)

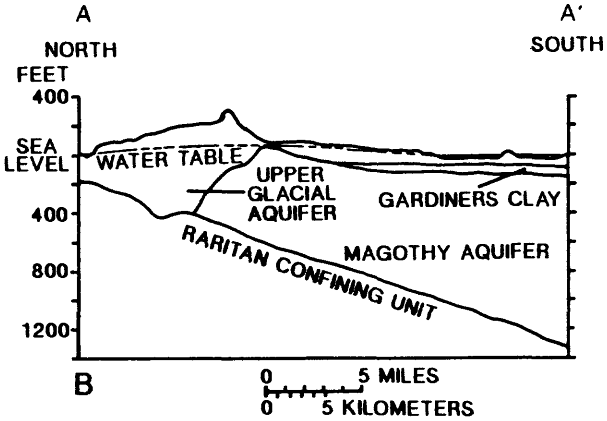


Figure 6B. Generalized hydrogeologic section of Long Island.

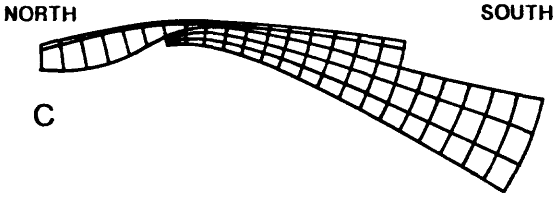


Figure 6C. Typical vertical grid for geologic section in figure 6B.

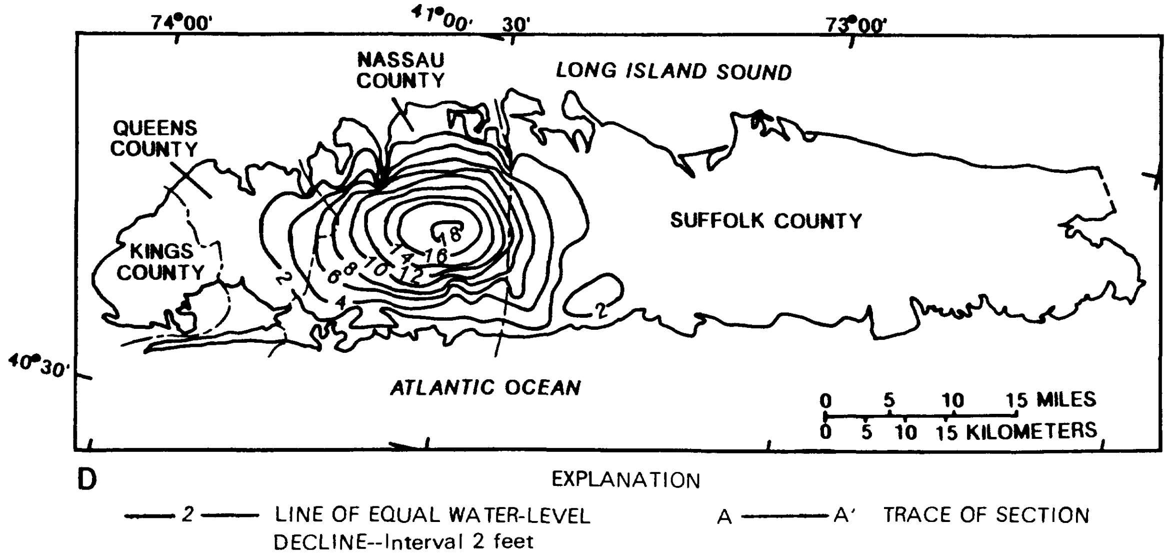


Figure 6D. Example of flow-model output showing predicted decreases in hydraulic head in upper glacial aquifer as a result of sewering. (Modified from Reilly and others, 1983, fig. 11A.)

not a panacea because they are only as reliable as the assumptions and data on which they are based. When developed properly, however, they provide an indication of the system's response to specific stresses, which can then be used by water managers to evaluate the best choices for future development.

LONG ISLAND'S GROUND-WATER SYSTEM

Ground water on Long Island occurs in a wedge-shaped mass of unconsolidated sand, gravel, and clay deposits that dip southward (fig. 7). These unconsolidated deposits can be classified into several hydrogeologic units on the basis of hydraulic properties, composition, and age. The major hydrogeologic units of the ground-water reservoir of Long Island are shown in figure 7.

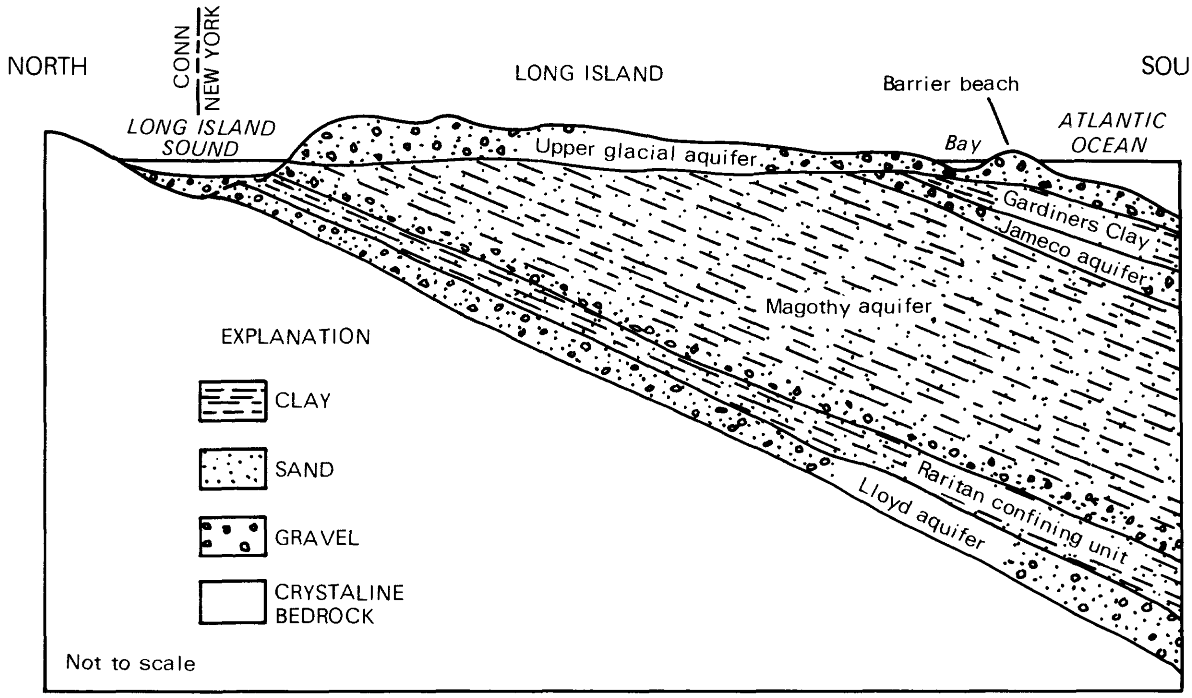


Figure 7.--Generalized hydrogeologic section showing relative position of major aquifers on Long Island. (From McClymonds and Franke, 1972, fig. 3).

Depositional History

Long Island is underlain by unconsolidated deposits of clay, silt, sand, and gravel that rest on southward-dipping crystalline bedrock. The geologic units and corresponding hydrogeologic units are summarized in table 1. The deeper (older) unconsolidated units were deposited during the Cretaceous Period (63 to 138 million years ago) and now form, in ascending order, the Raritan Formation, Magothy Formation and Matawan Group, undifferentiated, and Monmouth Group (table 1).

The Tertiary Period (2 to 63 million years ago) throughout Long Island was either a time of nondeposition or of deposition followed by complete erosion, inasmuch as all traces of Tertiary deposits are absent. The Pleistocene Epoch, which followed the Tertiary Period and lasted from 1.8 million years ago to 10 thousand years ago, was a period when much of northern North America, including most of Long Island, was overlain by continental glaciers. Recent studies on Long Island indicate the final Wisconsin glaciation stage to have contained two stades and an interstade--an early and

Table 1.--Major geologic and hydrogeologic units on Long Island, N.Y.

[Modified from Nemickas and Koszalka, 1982, table 3]

System	Series	Geologic unit		Hydrogeologic unit
Quaternary	Holocene	Recent shore, beach, and salt-marsh deposits and artificial fill		Recent deposits
	Pleistocene	Glaciofluvial deposits Moraine and outwash deposits (Ronkonkoma Drift) Montauk Till Member of the Manhasset Formation		Upper glacial aquifer
		Unconformity?		
		Gardiners(?) Clay (Marine clay)		Gardiners(?) Clay
		Unconformity?		
		Jameco Gravel		Jameco aquifer
Cretaceous	Upper Cretaceous	Monmouth Group		Monmouth greensand
		Unconformity?		
		Matawan Group and Magothy formation (undifferentiated)		Magothy aquifer
		Unconformity		
		Raritan Formation	Clay member	Raritan confining unit
			Lloyd Sand Member	Lloyd aquifer
		Unconformity		
Paleozoic and Precambrian		Bedrock		Bedrock

a late stade (glacial advance) separated by an interstade (glacial retreat) during middle Wisconsin glaciation (Sirkin and Mills, 1975; Nieter and others, 1975). The Montauk Till Member of the Manhasset Formation, which consists of moraine and outwash sediments, was deposited on Long Island during the Wisconsin glaciation. A layer of marine clay, the Gardiners Clay (fig. 7), was deposited during the Sangamon interglaciation before Wisconsin glaciation.

As the glaciers retreated northward, meltwater ponded between the ice and the central moraine of Long Island and formed streams that flowed through topographic lows. These streams subsequently eroded the moraine itself and formed north-south-trending channels.

With the final recession of continental glaciers 10 thousand years ago, sea level rose to its present position or higher. As a result of this rise, parts of the glacial deposits were inundated.

Hydrogeologic Units

The hydrogeologic units that lie between bedrock and the water table are saturated and form Long Island's ground-water reservoir. The reservoir ranges in thickness from zero in the northern part of Queens County to more than 2,000 feet in south-central Suffolk County. (See fig. 7.)

The ground-water reservoir consists of three major aquifers that are, from oldest to youngest, the Lloyd aquifer, the Magothy aquifer, and the upper glacial aquifer. (See fig. 7 and table 3, at end of report.) Ground water in the upper glacial aquifer and locally in the Magothy aquifer generally is under water-table conditions; water in the Lloyd and most of the Magothy aquifer is under confined (artesian) conditions.

Major clay beds between the aquifers, as well as thinner clay beds within the aquifers, form confining units. The major confining units in the ground-water reservoir (table 3) are the Raritan confining unit, which underlies the entire island, and the Gardiners Clay, in the southern part of Long Island. The extensiveness, continuity, and low hydraulic conductivity (the ability of a unit to transmit water) of the Raritan clay make it an important component in the flow pattern of the system.

The upper glacial aquifer generally corresponds to the saturated upper part of the highly permeable Pleistocene deposits; in most of Long Island, it is under water-table conditions and is the major source of water supply in Suffolk County.

The upper part of the Magothy aquifer is under water-table conditions where it is in direct contact with the upper glacial aquifer, but, in most areas, it is overlain by units of lower permeability and therefore is confined. It is the major source of water in Nassau County.

The Lloyd aquifer directly underlies the unnamed clay member of the Raritan Formation. Bedrock forms the lower limit of this deep confined aquifer and of the ground-water system. The Lloyd aquifer is the major source of water supply for many south-shore coastal communities. Its use elsewhere is restricted because other freshwater supplies are available.

Movement of Water

Precipitation that infiltrates and percolates to the water table is Long Island's only natural source of freshwater because the ground-water system, as on any island, is bounded on the bottom by relatively impermeable bedrock and on the sides by salty ground water or saline bays and the ocean. The flow path of freshwater from the water table to a point of discharge is three dimensional and is affected by the geometry and hydraulic characteristics of the aquifers, the distribution, geometry, and hydraulic characteristics of the confining units, the rate and location of precipitation and recharge, the proximity and type of discharge points, and the distribution of hydraulic head (water levels) throughout the geohydrologic system.

About half the precipitation that falls enters the ground-water system through infiltration; the rest flows overland to streams or is lost through evapotranspiration. Much of the precipitation that reaches the upper glacial aquifer moves laterally and discharges to streams and surrounding saltwater bodies; the remainder seeps downward to recharge the deeper aquifers. Water enters these deep aquifers very slowly in areas where confining units are present but enters freely in other areas. Water in the deeper aquifers also moves seaward, along upward vertical gradients that cause seepage into overlying aquifers (fig. 8). Some of this water enters the freshwater-bearing parts of the overlying aquifer and thus remains within the system for long periods before discharging to the surrounding salty surface-water bodies, but some enters the nearshore part of the overlying aquifer, in which the water is salty. Thus freshwater is continuously being lost from the system.

Saltwater has a greater density than freshwater, and, when the two fluids are adjacent to each other in the aquifer, they do not readily mix under natural conditions. Rather, a zone of diffusion forms at the interface, through which virtually no flow occurs. A generalized vertical hydrologic section showing the flow patterns in the Long Island aquifer system under natural conditions is given in figure 8.

Under natural conditions on Long Island, the rate of horizontal ground-water flow through the aquifers ranges from a few feet to several hundred feet per year. The rate of vertical flow is much slower--probably 10 to 100 times slower than in the horizontal direction because stratification and clay layers within and between the aquifers impede vertical flow.

Chemical Quality of Water under Predevelopment Conditions

As water moves through the hydrologic cycle, it dissolves some of the substances with which it comes in contact. The kinds of chemicals in the water and their concentrations are therefore determined by the flow path of the water, by the type and solubility of the materials, and by the amount of time that the water is in contact with these materials.

Data on the chemical quality of water at several points in Long Island's hydrologic system before development are presented in table 4 (at end of report); the locations of these points are shown in figure 9. The water at these points is probably unaffected by human activities (although it is affected by precipitation, which carries particulates from the air, some of which are generated by man). Although much of the upper glacial aquifer on Long Island has been affected by human activities, water in the deeper aquifers may be hundreds to thousands of years old and is, therefore, largely protected from surface contamination by the confining units.

A logical point at which to begin any study of water quality on Long Island is the precipitation phase of the hydrologic cycle because it is the only natural source of freshwater. Even before precipitation reaches land surface, it acquires low concentrations of several compounds. (See sample 1 in table 3.) The most probable sources of these chemicals are the salts from sea spray, which are picked up as air moves over the ocean, and particles of dust and gases in the air.

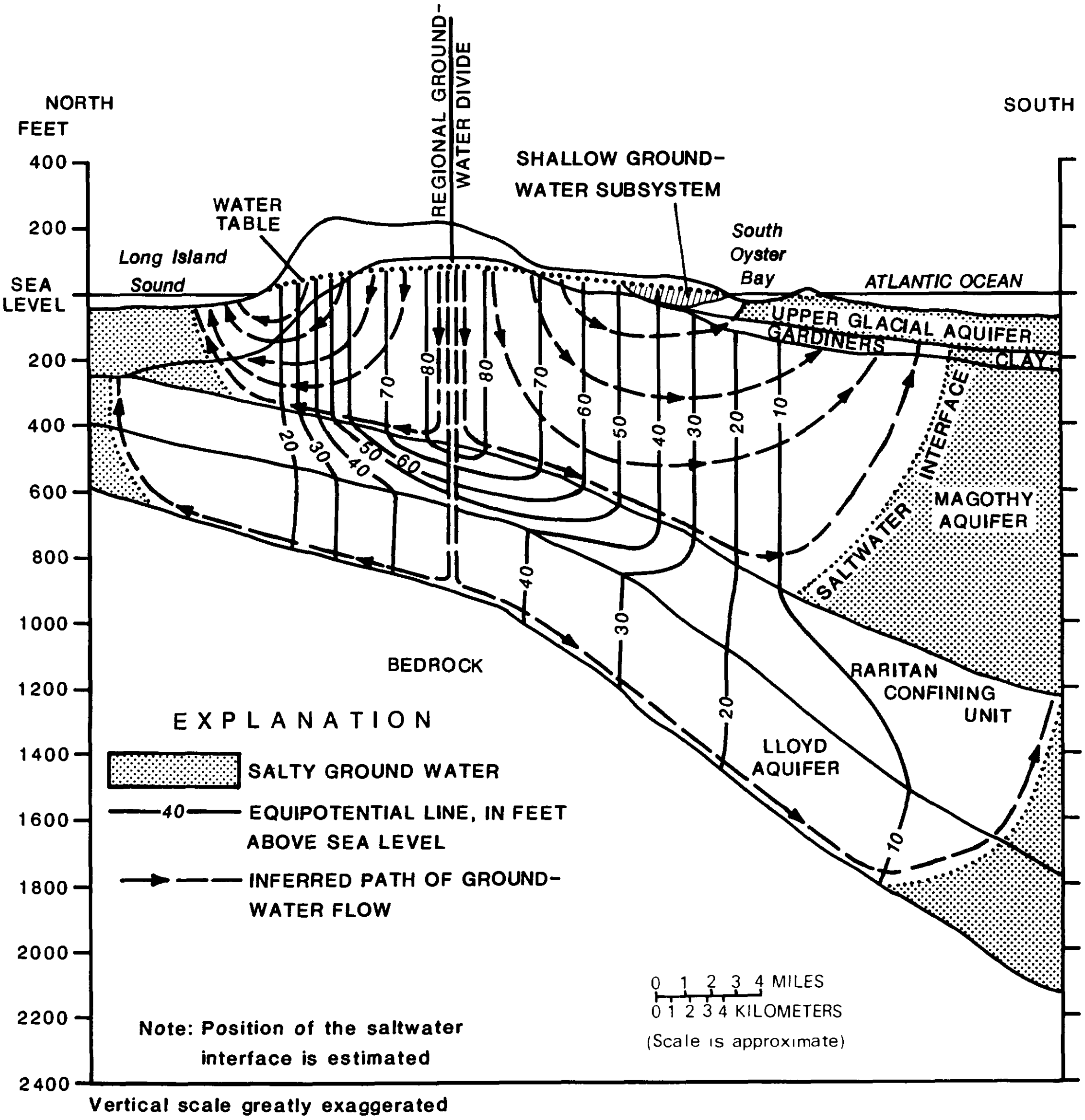


Figure 8.--Generalized flow lines in the ground-water system of Long Island under natural (predevelopment) conditions. (Modified from Reilly, Buxton, Franke, and Wait, 1983, fig. 4.)

After precipitation reaches land surface, it undergoes significant changes. Almost half of the water (but not the dissolved chemicals) returns to the atmosphere through evaporation from land surfaces and from the soil zone through transpiration by plants. As a result, the concentration of most chemicals in recharge water is almost double that of precipitation. As the water percolates through the soil zone, it acquires new chemicals, and this process continues in the lower, less chemically and less biologically active zone of aeration below the soil, although at a slower rate (fig. 2). Comparison of precipitation data with shallow ground-water (upper glacial aquifer) data (table 4) shows an increase in the concentration of almost all constituents as the water moves from land surface to the upper glacial aquifer.

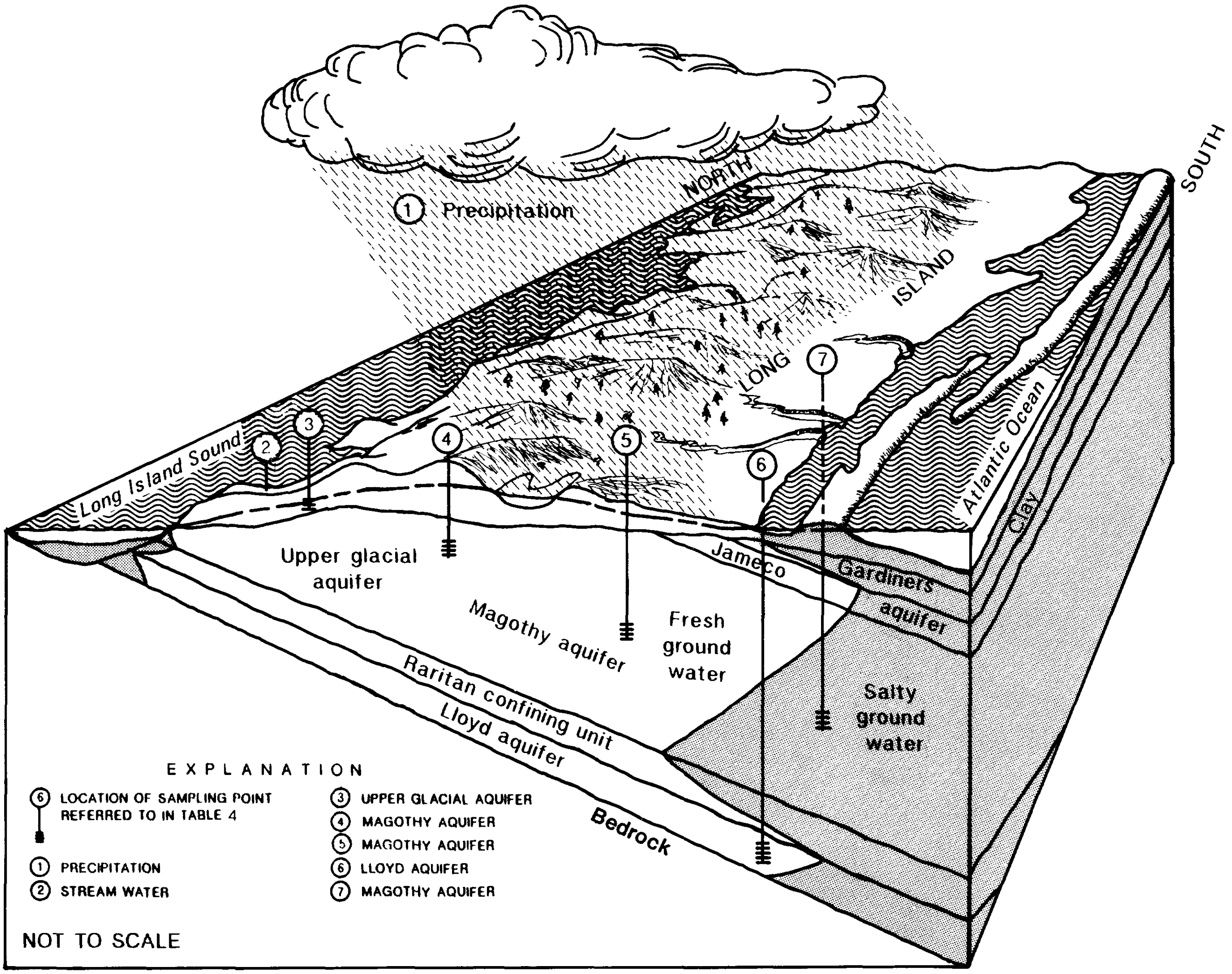


Figure 9.--Types and relative locations of ground-water sampling points.

Unlike the soil zone, geologic materials that form the upper glacial, Magothy, and Lloyd aquifers are only slightly soluble; thus, the chemical quality of water changes relatively little within the ground-water system (compare samples 3, 4, 5, 6 in table 4) until it flows into and mixes with the salty ground water near the margins of the island. Sample 7 in table 4 indicates the sudden increase in total dissolved-solids concentration (from tens to thousands of milligrams per liter) at the freshwater-saltwater interface.

Some of Long Island's ground water discharges to streams and ponds; about 95 percent of the streamflow on Long Island is derived from ground water near land surface; thus, the chemical quality of Long Island's surface water is similar to that of the near-surface ground water. (Compare the values for samples 2 and 3, stream water and ground water, in table 4.)

The analyses presented in table 4 illustrate the chemical changes that occur in water as it moves through Long Island's hydrologic system. These are consistent with analyses of many other samples collected at various points on the island and indicate the following conclusions about the quality of Long Island's water in undisturbed areas:

(1) Freshwater in undisturbed parts of Long Island has a low total dissolved-solids concentration--less than 50 mg/L;

(2) The dissolved-solids concentration changes little as the water moves through the ground-water reservoir because the geologic materials beneath Long Island are relatively nonreactive;

(3) Most of Long Island's ground water is slightly acidic (pH is 4.5 to 6.1, table 4), which makes it mildly corrosive to metals, and ground water in some areas contains iron in concentrations that exceed the recommended limit of 0.3 mg/L. The elevated iron concentrations probably are caused by the dissolution of pyrite (iron sulfide) nodules that occur in some parts of the Magothy and Lloyd aquifers. Only minor treatment is necessary to correct these problems, however. Otherwise the water in undisturbed areas is within U.S. Environmental Protection Agency primary drinking-water standards for all constituents.

HISTORICAL DEVELOPMENT OF LONG ISLAND'S GROUND-WATER RESOURCES

Pumping and Wastewater Disposal

Over the last three centuries, the island's ground-water use has developed through three distinct phases. In the first, which began with the arrival of European settlers in the mid-17th century, virtually every house had its own shallow well that tapped the uppermost unconsolidated geologic deposits, and also had its own cesspool that returned wastewater to these same deposits. Because population was sparse, this recycling process had little effect on quantity and quality of shallow ground water. During the next two centuries, the population increased steadily, and, by the end of the 19th century, the individual wells in some areas had been abandoned in favor of shallow public-supply wells.

The second phase began with the rapid population growth and urbanization that occurred during the first half of the 20th century. The high permeability of Long Island's deposits encouraged the widespread use of domestic wastewater-disposal systems, and the contamination resulting from increased wastewater discharge led to the eventual abandonment of many domestic wells and shallow public-supply wells for deeper, high-capacity wells. In general, pumping these deep wells had only a small effect on the shallow ground water and related surface-water systems because most of the water was returned to the ground-water reservoir through domestic wastewater-disposal systems. Contamination of shallow ground water from the surface waste-disposal systems continued, however.

The third and present phase began in the early 1950's with the introduction of large-scale sewer systems in the more heavily populated areas. The purpose of the sewers was to prevent domestic waste-water from entering the aquifer system because contaminants were being detected in deep public-supply wells. Even though the sewers protect the aquifers from further contamination, they also prevent the replenishment that the wastewater had provided to the ground-water reservoir through wastewater-disposal systems. The wastewater is now diverted to sewage-treatment plants and from there to the bays and oceans. As a result, the water table in sewered areas has been substantially lowered, the base flow of streams in turn has been reduced or eliminated, and the length of perennial streams has decreased.

Water-Quality Deterioration

The quality of ground water on Long Island is related to the pumping patterns as well as to changing patterns of land use that reflect the eastward population growth since the mid-19th century. The quality of almost all of Long Island's fresh ground water was excellent before development. Today, the ground-water reservoir still contains a vast amount of potable water, but the quality has changed considerably in some areas that are affected by human activities. Except where saltwater intrusion has occurred, ground-water quality improves with depth because most human-induced contaminants enter the ground water at or near land surface, and the water moves so slowly that it can take thousands of years to move through the deep aquifer system. Because man has been influencing the system only within the last century or so and has had a major effect only within the last few decades, most of the serious contamination remains near the top of the saturated deposits. As a result, the upper glacial aquifer (fig. 7), the uppermost of the three major aquifers, has been most seriously contaminated from surface sources. The Lloyd aquifer, in contrast, is the least contaminated because it is not only the deepest aquifer but is overlain by a confining clay (Raritan clay), which protects it from surface contamination. Saltwater encroachment is a serious threat to water quality in the Lloyd aquifer, however, especially under the barrier islands along the south shore (fig. 1), where the aquifer not only has an offshore saltwater front but is potentially subject to slow infiltration of saltwater from the overlying Magothy aquifer.

The severity of ground-water contamination on Long Island reflects the eastward population growth that has taken place since the mid-19th century. At present, ground-water development and the associated water-quality problems are greatest in the western part of Long Island and diminish eastward.

Western Long Island

Population growth in western Long Island (Kings and western Queens Counties, fig. 1) in the late 19th and early 20th century generated rapid ground-water development. The continued increase in pumping of ground water for industry and public supply, in addition to several other effects of urbanization, resulted in severe water-level declines and saltwater intrusion. As a result, pumping for public supply in Kings County was stopped in 1947. Pumping in parts of Queens County for public supply has continued, but the trend has been to abandon wells that show evidence of contamination and to install new ones farther eastward, farther from the shores, and near the center of the island, where water levels are higher.

Eastern Queens and western Nassau Counties became highly urbanized during mid-1940's and 1950's. The upper glacial aquifer in this area has been extensively contaminated from sources at or near land surface, such as cesspools and industrial waste-disposal sites; therefore, most of the water supply in this area is derived from deep wells that tap the Magothy aquifer, Jameco aquifer, and the Lloyd aquifer (fig. 7). Most of this area is sewered, which has caused a general decline of ground-water levels and an increased potential for local saltwater intrusion into the aquifers.

Eastern Long Island

Eastern Nassau and western Suffolk Counties experienced rapid population growth from the 1950's into the 1970's, and large areas in both counties have been sewered. Saltwater encroachment has not yet been reported, but the increased pumping stress and sewers are causing an imbalance in the ground-water system.

Eastern Suffolk County, including the north and south forks (fig. 1), is undergoing rapid population growth, which has resulted in higher ground-water demands in a delicately balanced freshwater/saltwater system. The increasing water demand has caused local upward saltwater intrusion in the Montauk area, and, on the north fork, some ground water has been contaminated by pesticides used in agriculture, as explained in the case studies farther on.

A summary of the major sources of ground-water contamination on Long Island is given in table 2. The number or quantity of the various sources of contamination given in table 2 are from the Long Island Regional Planning Board (1978); thus, the numbers may now (1988) be somewhat different. Yet, this extensive list clearly indicates many potential threats to the ground-water system of Long Island.

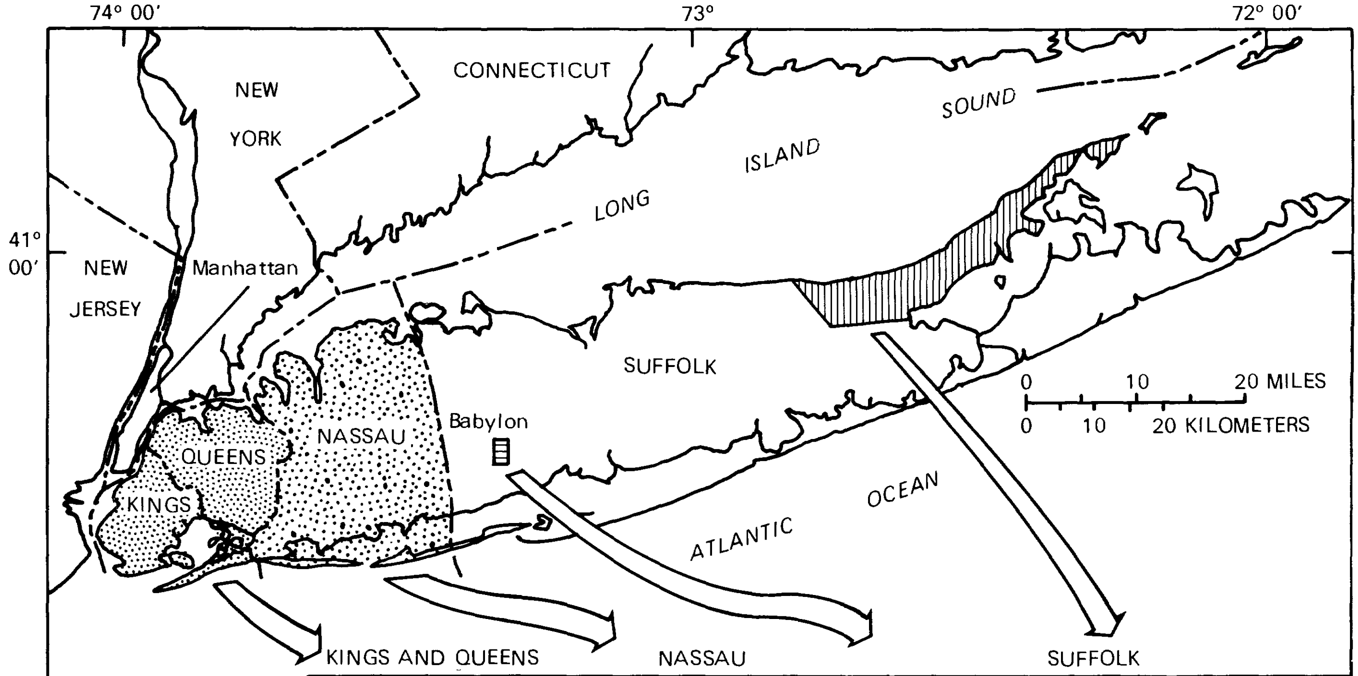
Table 2.--Major sources of ground-water contamination on Long Island.

[Mgal/d, million gallons per day.]

Source	Mechanism and quantity	Contaminants
Domestic disposal systems	1.7 million people discharging 120 Mgal/d of sewage through cesspools and septic tanks	Nitrate, detergents, metals, microorganisms, halogenated hydrocarbons and other organic chemicals
Sewage-treatment-plant effluent	8.59 Mgal/d discharged to land surface in Nassau and Suffolk Counties	Same contaminants as domestic waste plus industrial waste but with some treatment to lower concentrations
Sanitary sewer exfiltration	Unknown amount of leakage from sewers above the water table	Same contaminants as domestic waste plus some industrial waste
Industrial-waste discharge: (1) metal processing; (2) photo processing; (3) commercial laundries; (4) food industry; (5) bottling industry	Reported discharge of 2.1 Mgal/d in Nassau and Suffolk Counties plus unknown quantity of accidental or illegal discharges	Heavy metals, detergents, dyes, halogenated hydrocarbons and other organic chemicals, petroleum, and lubricating fluids
Landfills	40 active and abandoned sites in Nassau and Suffolk Counties; 40 Mgal/yr of leachate per 100 acres of landfill	Heavy metals, chloride, ammonia, iron, organic chemicals
Product-storage tanks and pipelines	Potential for leakage from 3,000 sites storing gasoline and diesel fuel; 640,000 homes and unknown number of industries using heating oil; 141 oil-storage depots; unknown number of other storage facilities for industrial chemicals	Petroleum products such as gasoline, diesel fuel, and heating oil, which are complex mixtures of hydrocarbons, chlorinated hydrocarbons, and other industrial chemicals
Fertilizers and pesticides	Thousands of pounds of fertilizer applied to turf grass and cropland; 420,000 gallons of pesticide per year used in Nassau and Suffolk Counties	Nitrogen, various pesticides
Animal waste	258,000 cats; 425,000 dogs; 30,000 horses; 121,000 chickens; 1,000 cattle; 750,000 ducks	Nitrogen, microorganisms
Highway-deicing salts	95,000 tons of road salt applied in Nassau and Suffolk yearly	Chloride
Stormwater basins	2,000 basins on Long Island receiving runoff from highways, lawns, etc.	Nitrogen, chloride, heavy metals, hydrocarbons, microorganisms

HISTORIC EXAMPLES OF CONTAMINATION

This section examines four cases of past ground-water contamination on Long Island and management's responses. These examples cover a variety of problems: saltwater intrusion in Kings and Queens County, elevated nitrate concentrations in Nassau County, leachate from landfills in western Suffolk County, and the presence of an organic pesticide in eastern Suffolk County (fig. 10).



DESCRIPTION	Saltwater intrusion ▨	Elevated nitrate concentrations ▨	▤ Landfill leachate	Pesticide ▥
When discovered	1930's	1960's	Late 1960's	1970's
Chemical of concern and drinking-water standard	Chloride (250 mg/L)	Nitrate (as N) (10 mg/L)	Dissolved solids (500 mg/L)	Aldicarb (0.01 mg/L)
Sources and degree of toxicity	Occurs naturally in seawater. Relatively nontoxic, taste threshold at 200 to 300 mg/L	Biological transformation of organic nitrogen in human and animal waste and chemical production for fertilizer. Toxic to infants when consumed in large amounts	Inorganic chemicals, disposal of municipal refuse. Toxic when consumed in large amounts	Synthethic organic chemical; used as insecticide and nematodocide. Highly toxic even at low concentrations.
Cause	Localized hydrologic imbalances due to over-pumping of ground water	Fertilizer application to lawns and crops and disposal of domestic waste to cesspools	Disposal of municipal refuse	Application of pesticide to potato crop
Response	Seek alternative water supply; import water from mainland; abandon ground water as supply	Build sewers to eliminate further contamination, drill deeper wells and install new wells for public supply	Cover landfill to prevent entry of water, monitor movement of plume	Treatment at well head; drill new wells for public water supply

Figure 10.--Location and description of the four case studies of ground-water contamination on Long Island.

Because Long Island's ground-water resource is extensive, proper management can, and is, protecting the resource. The following case studies illustrate how each problem may call for a different solution. In these examples, the solutions include the importing of water, improvement in the design of treatment facilities, wellhead treatment, monitoring of water quality, or simply waiting.

Saltwater Encroachment into Kings and Queens Counties

The ground-water supply in Kings and Queens Counties was developed in the 19th century with the rapid population growth of Kings County (Brooklyn) and western Queens County. Water was obtained from shallow wells and also from streams. Most of the water from these sources was returned to the aquifer through underground waste-disposal systems. This caused only minor changes in the water-table configuration, but, as the demand for public and industrial water supply grew, the number of wells and the quantity of water pumped increased, and local declines in the water table became more pronounced. From 1903 to 1943, the ground-water reservoir in Kings and Queens Counties supplied an average of more than 120 Mgal/d for industrial and public supply.

As Kings and Queens Counties became increasingly urbanized, storm sewers and sanitary sewers were installed to divert wastewater to the sea that previously would have recharged the ground-water system. At the same time, paving and construction increased the amount of impervious land surface, which reduced the area available for infiltration of precipitation; this, in turn, decreased recharge further. These changes, along with the continuous increase in industrial and water-supply pumpage, caused severe declines in the water table and potentiometric-head loss in the deeper aquifers through the 1930's and 1940's (Buxton and others, 1981). Figures 11A and 11B show the water-table configuration in 1906 and in 1945. Water-table declines caused many lakes and streams to disappear and severely decreased flow in the remaining streams. At the same time, drawdown near the shores induced the movement of saltwater into the aquifers, which caused the chloride concentrations in ground water to increase. The deterioration of water quality soon required the cessation of ground-water pumping and the development of an alternative source of water supply. Ground water was abandoned as a source of water supply in Kings County in 1947 and in much of Queens County in 1974 (Buxton and others, 1981). Today, the entire population of Kings County and most of Queens County is supplied with water from upstate reservoirs.

Since the cessation of pumping, the ground-water system of western Long Island is recovering, and water levels in parts of Kings County are approaching levels of 1906 (Buxton and others, 1981). Figures 12A and 12B show the water-table configuration in 1974 and in 1981. The latter approaches the 1906 level. One consequence of this is that deep basements and subway tunnels built during the period of low water levels are now being flooded, and continuous dewatering is now required in some areas.

Although chloride concentrations seem to be decreasing in some parts of Kings and Queens Counties, they still exceed predevelopment levels. In addition, some ground water has been contaminated from sources at or near land surface, such as fertilizers, underground sewage-disposal systems, landfills, large cemeteries, road salt, leaking sewers, and spills of toxic chemicals.

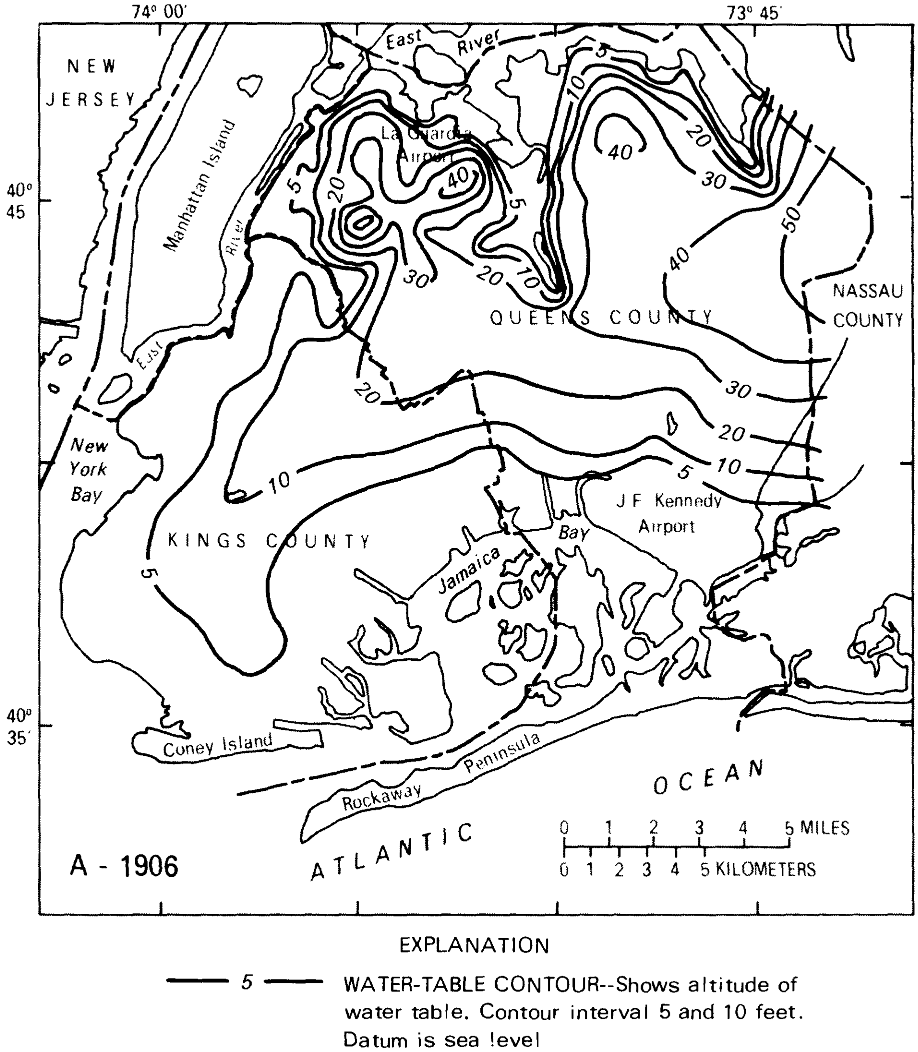


Figure 11A.--Water-table configuration in Kings and Queens Counties in 1906. (Modified from Veatch and others, 1906, plate 12.)

In summary, the problems in Kings and Queens Counties were (1) saltwater encroachment near the shores in response to the severe declines in ground-water levels that resulted from overpumping of the ground-water system, and the loss of recharge through extensive paving and through implementation of storm and sanitary sewers; and (2) a general deterioration of the quality of ground water as a result of urbanization. In response to these problems, water was imported from upstate reservoirs to provide a dependable and high-quality water supply. An adverse side effect was the flooding of deep basements and subway tunnels as the ground-water levels recovered.

Leachate from Onsite Waste-Disposal Systems in Nassau County

Because Long Island has permeable, sandy soil, suburban houses in Nassau and Suffolk Counties were designed to dispose of their wastewater through

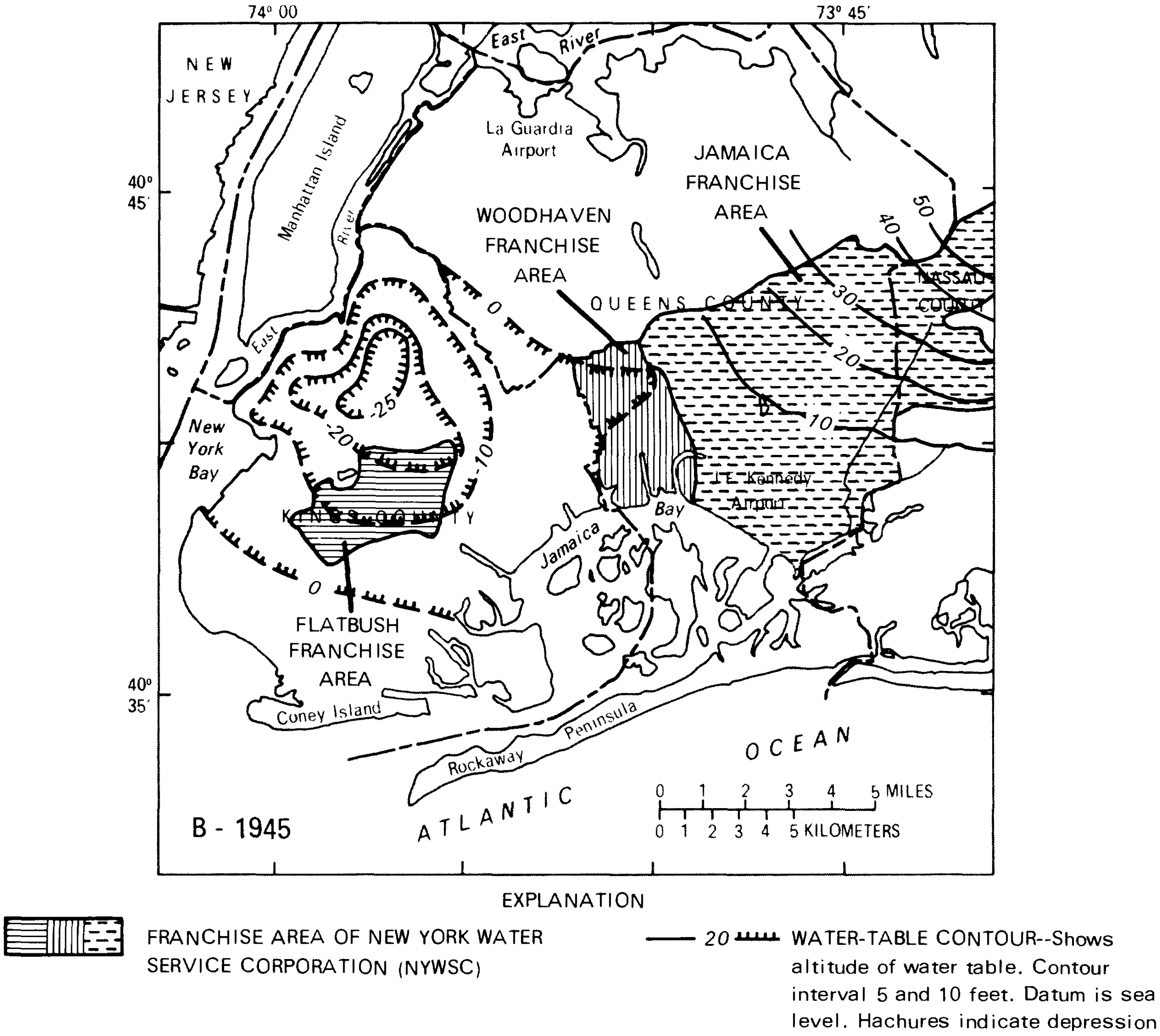


Figure 11B.--Water-table configuration in Kings and Queens Counties in 1945. (Modified from Jacob, 1945, plate 1.)

septic tanks and cesspools. This practice recirculates the water pumped for domestic use back into the ground-water system. Contaminants from these onsite waste-disposal systems move into the ground-water system along with the wastewater. Of these contaminants, nitrate is the most readily observable.

Nitrate also can come from sources other than wastewater-disposal systems. Before 1950, when agriculture was one of the principal industries in Nassau County, much of the land was under cultivation, as documented by Bond (1947) in records of 1875-1945 agricultural practices. Recent isotope data suggest that the use of fertilizers for lawns as well as for agriculture also contributed nitrate to ground water (Kreitler and others, 1978).

By 1962, water in the upper glacial aquifer in parts of Nassau County contained nitrate levels above the State's health standards. In the center of the island, where vertical flow recharges the deeper aquifer systems, nitrate

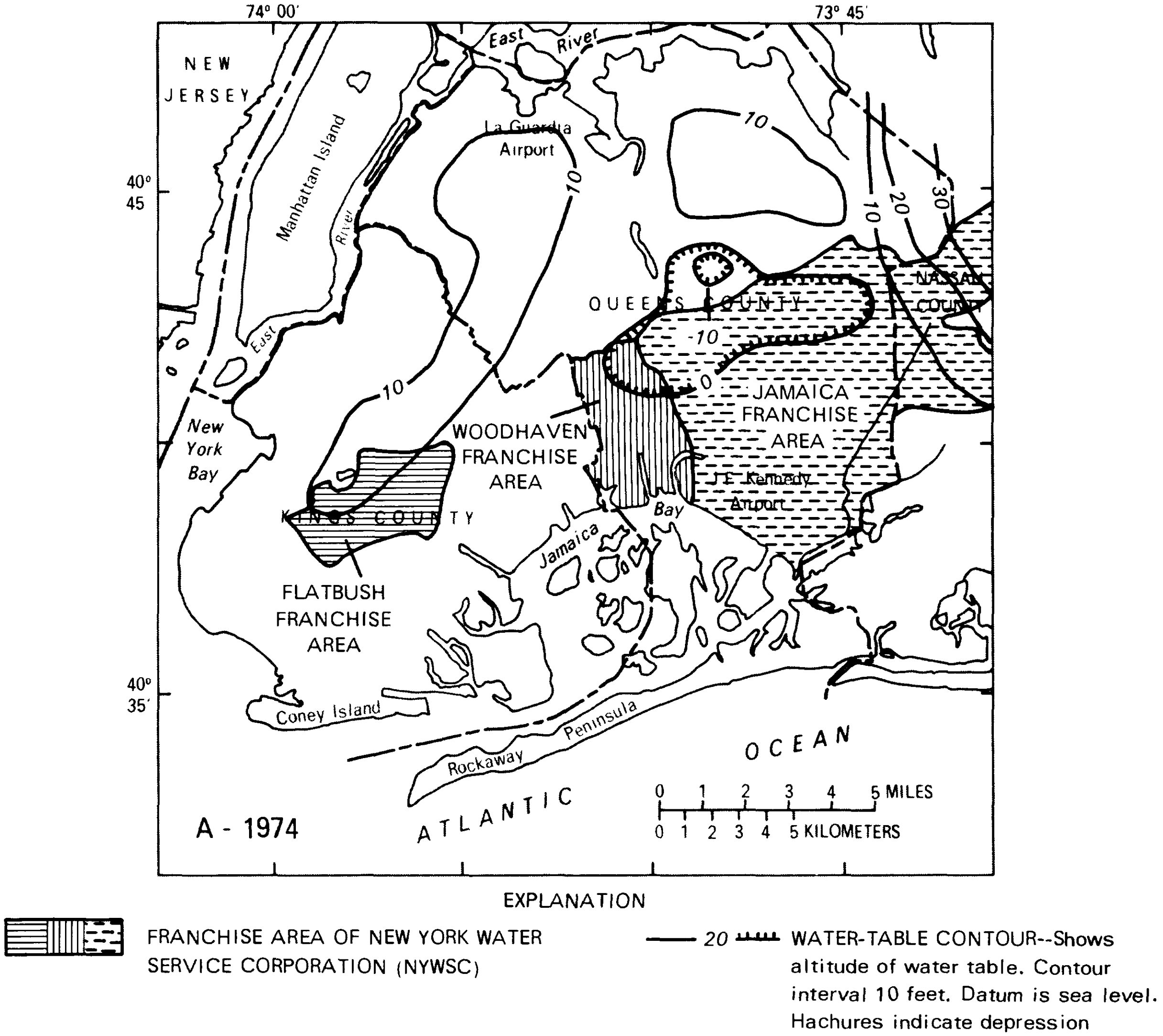


Figure 12A.--Water-table configuration in Kings and Queens Counties in 1974. (Modified from Koszalka, 1975, plate 1.)

concentration increased significantly in the Magothy aquifer (Ragone and others, 1981). Most pumping in the suburban areas is by public-supply wells that tap the Magothy aquifer; this pumping increases the hydraulic gradient toward the well or well field and alters the ground-water flowlines in the aquifer for long distances. This increase in gradient may cause water with elevated nitrate concentration to flow downward from the upper glacial aquifer into the Magothy aquifer near the well and speed the degradation of water quality in the Magothy aquifer.

Because the onsite disposal systems were the source of much of the nitrate and many other contaminants, parts of northern Nassau County were sewered before the 1950's. The southwestern part was sewered in the early 1950's, and the southeastern part of Nassau County was sewered in the late 1970's and early 1980's. Sanitary sewers collect the domestic wastewater and route it to treatment plants, where it is discharged to tidewater.

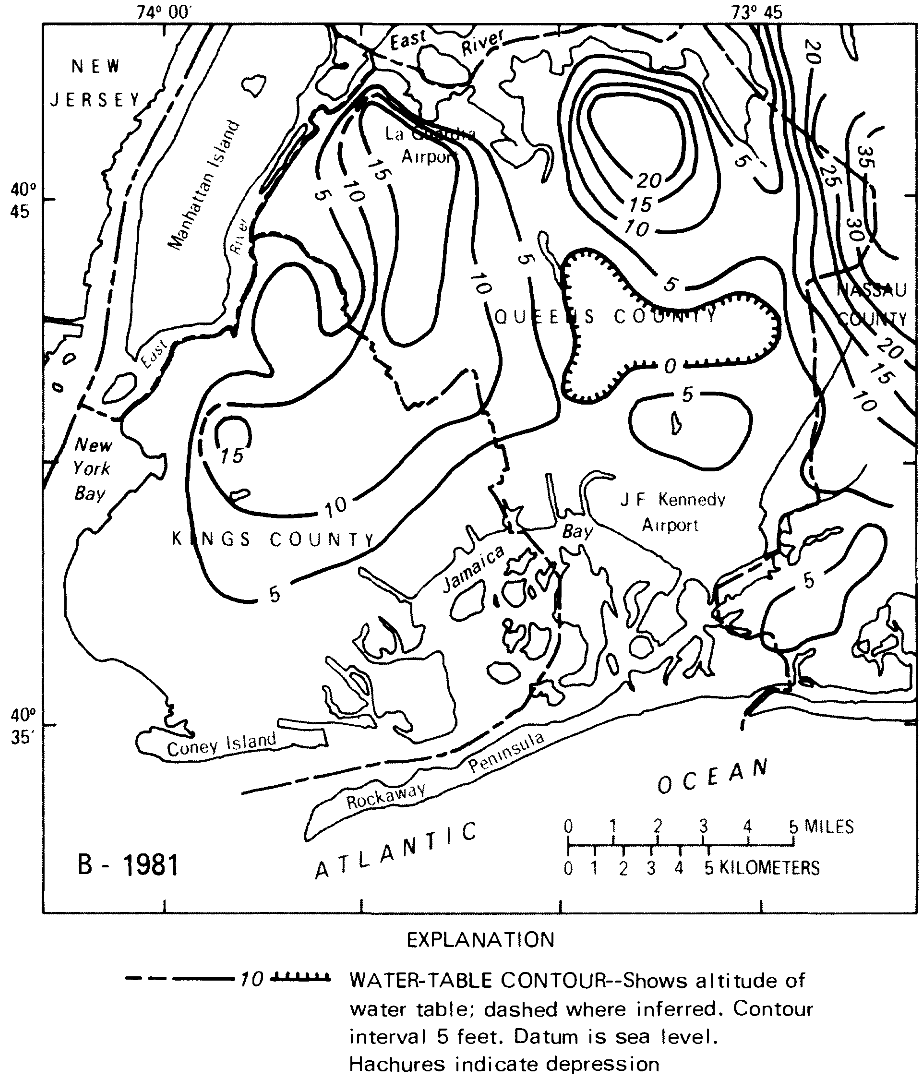


Figure 12B.--Water-table configuration in Kings and Queens Counties in 1981. (Modified from Buxton and others, 1981, fig. 21.)

The introduction of municipal sewers has helped to arrest the contamination of the upper glacial aquifer from sewage (Ragone and others, 1980) but, in so doing, has deprived the ground-water reservoir of a significant volume of water that, in previous years, was returned through wastewater-disposal systems. This loss of water to surrounding tidewater has had marked effects on the hydrologic system (Reilly and others, 1983, p. 35), in particular, a decline in the water table and in the potentiometric head in the Magothy and Lloyd aquifers and a corresponding reduction in streamflow, stream length, lake levels, and freshwater outflow to the bays and ocean. These declines also have created a tendency for saltwater intrusion into the aquifers near the shores. These changes may have adverse aesthetic, ecologic, and economic effects. For example, the lakes and streams are important for wildlife and recreation, and the steady discharge of fresh streamflow and ground water to Great South Bay maintains a specific reduced level of salinity that is essential to the survival of the island's shellfish industry.

In summary, the contamination of ground water was caused largely by nitrates and other chemicals that discharged to the upper glacial aquifer from domestic wastewater-disposal systems. Sewers and sewage-treatment plants were constructed to reduce the number of domestic disposal systems. Benefits were a reliable, sanitary means to dispose of domestic wastewater and prevent it from contaminating the ground water; adverse effects were a lowering of ground-water levels, reduction in base flow to streams, and a decrease in the amount of freshwater flowing to wetlands and bays.

Leachate from Landfills in Suffolk County

Contamination of ground water by leachate from solid-waste landfills has become a problem of general concern on Long Island. Water from precipitation enters and seeps through the landfills, where it dissolves a variety of constituents to form leachate, as illustrated in figure 13. The leachate then migrates to the water table, where it may contaminate the local water-supply wells. The Town of Babylon in southwestern Suffolk County (fig. 10) operates a landfill that contains municipal refuse, incinerated garbage, cesspool waste, and some industrial refuse. The Babylon landfill, started in 1947, is excavated in the upper glacial aquifer and discharges leachate that percolates to the ground water. The upper glacial aquifer is 74 feet thick at the site,

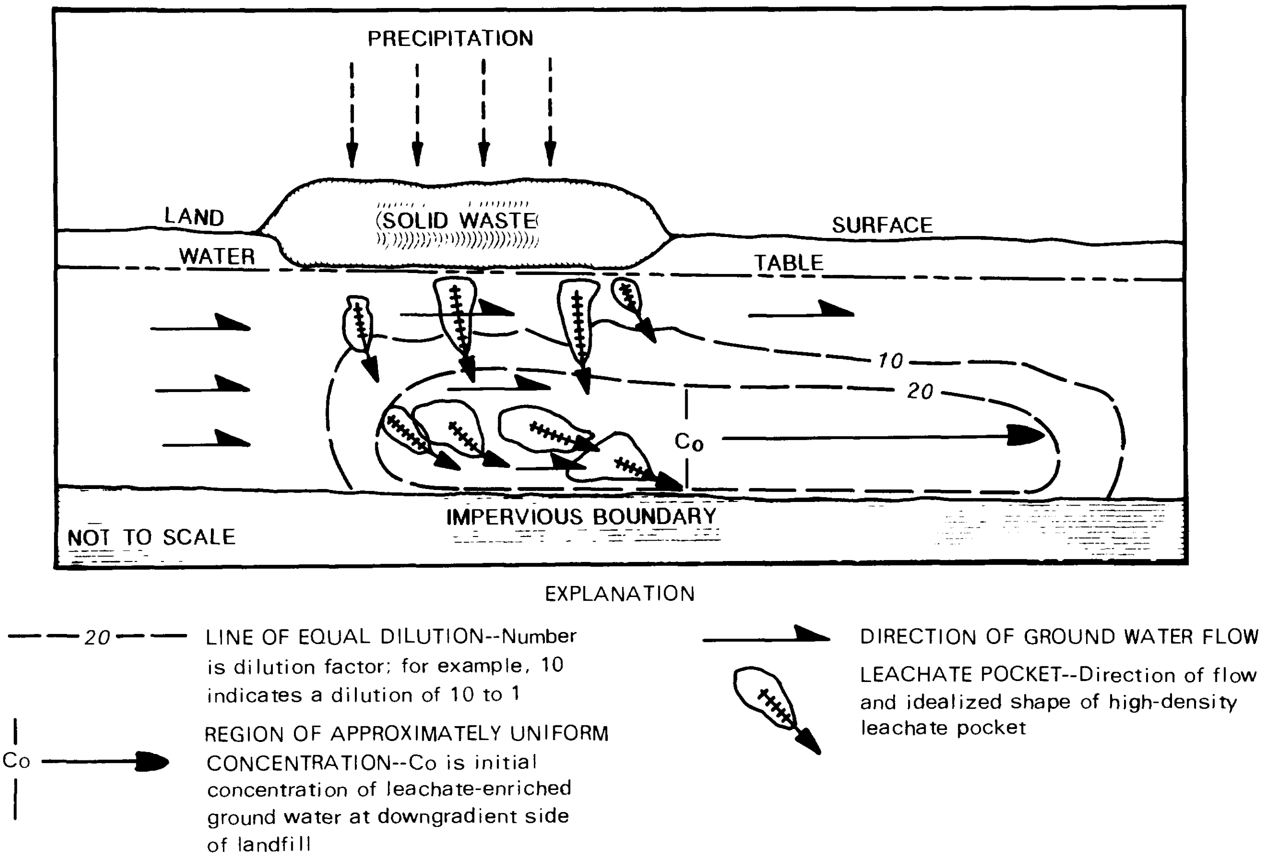


Figure 13.--Leachate movement and dispersion in ground water beneath a landfill. (Modified from Kimmel and Braids, 1980, fig. 19.)

and the leachate has degraded water in the entire thickness of the aquifer beneath and downgradient from the landfill in a plume that is 1,900 feet wide at the landfill and narrows to about 700 feet near its terminus 10,000 feet from the landfill (Kimmel and Braids, 1980). The most highly contaminated ground water contained 860 mg/L sodium, 100 mg/L potassium, 565 mg/L calcium, 100 mg/L magnesium, 2,700 mg/L bicarbonate, and 1,300 mg/L chloride (Kimmel and Braids, 1980).

The movement of the landfill plume is determined by the flow pattern of ground water, which, in central Long Island, is predominantly horizontal and southward. The plume is confined to the upper glacial aquifer by the Gardiners Clay, which restricts downward flow (see fig. 7). As the front of the plume moves, the landfill leachate can degrade the quality of ground water over a wide area. As contaminated ground water moves downgradient from the landfill, dilution and sorption reduce the chemical concentrations, but the size of the leachate-enriched region is expected to increase for many years after the accumulation of refuse ceases.

In summary, the problem in this area was contamination of ground water by landfill leachate. The cause of the problem was leakage of chemicals and the percolation of precipitation through refuse to form leachate that then entered the ground-water system. The response for this particular landfill, where the problem has prevailed for 30 to 40 years, was to cover the landfill with impervious materials and monitor the plume as it moves with the ground water and becomes diluted. The monitoring is done to ensure that no drinking-water supplies become contaminated. The clay below the upper glacial aquifer is preventing the leachate-rich water from entering the lower (Magothy) aquifer, the major source of water for public supply. Capping the landfill with impervious material has reduced the generation of new leachate from infiltration of precipitation, but the size of the leachate plume and area of ground-water contamination will increase for many years.

The policy of prevention and waiting, with monitoring, is appropriate because a large volume of ground water was contaminated at the site, and removal and treatment of this amount of water would be impractical. Dilution and natural chemical reactions will help reduce concentrations of contaminants over time, and, because no public-water supplies are threatened, waiting is feasible.

The general response of water managers to the problem of landfill leachate on Long Island has been to require that landfills be designed to prevent leachate from entering the ground-water system and to allow landfill construction only in areas where leakage due to failures in the design would have a minimal effect on public water supplies.

Pesticides in Suffolk County

Potato growing is one of the major industries in eastern Suffolk County. Aldicarb, a highly toxic pesticide that was widely used in that area during 1975-79 to control the Colorado potato beetle and golden nematode, caused widespread contamination in the upper glacial aquifer on the eastern end of Long Island (Soren and Stelz, 1984). The upper glacial aquifer is the only fresh ground-water supply for parts of eastern Suffolk County. The contamination of ground water by aldicarb led the U.S. Environmental Protection Agency to ban the use of aldicarb on Long Island in February 1980 (Soren and Stelz, U.S. Geological Survey, written commun., 1983). The New York State Department of Health set an interim maximum of 7 ppb (parts per billion) for aldicarb in drinking water.

Ground-water testing in eastern Suffolk County in 1979-80 showed widespread contamination exceeding the 7-ppb limit, and, as a result, the product's manufacturer installed activated charcoal filters on drinking-water wells that exceeded this limit. By 1982, aldicarb had reached to a depth of about 40 feet below the water table on the North Fork of eastern Suffolk County (Soren and Stelz, 1984, p. 1). Pumping by large-capacity wells (such as for public supply and irrigation), which can cause large water-table drawdowns, has increased the depth of aldicarb movement into the aquifer locally (Soren and Stelz, 1984). The extent and depth of contamination are shown in figures 14A and 14B, respectively. Analysis of water samples indicates that aldicarb in eastern Long Island may decline to below 7 ppb some time between 1990 and 2030 (Soren and Stelz, 1984). Monitoring of aldicarb levels in the upper glacial aquifer is continuing.

In summary, ground water in parts of Suffolk County was contaminated by a pesticide. The cause was overuse of the pesticide in a sandy environment underlain by the sole source of drinking-water supply. In response to this pesticide contamination, use of the pesticide was banned and the water was treated before use to reduce the levels to State health standards. Estimates of aldicarb's rate of degradation on Long Island range from half lives of 2 to 10 years, which would indicate its presence in the aquifer until between 1990 and 2030 (Soren and Stelz, 1984, p. 28). Ground-water monitoring will be continued to document the recovery process.

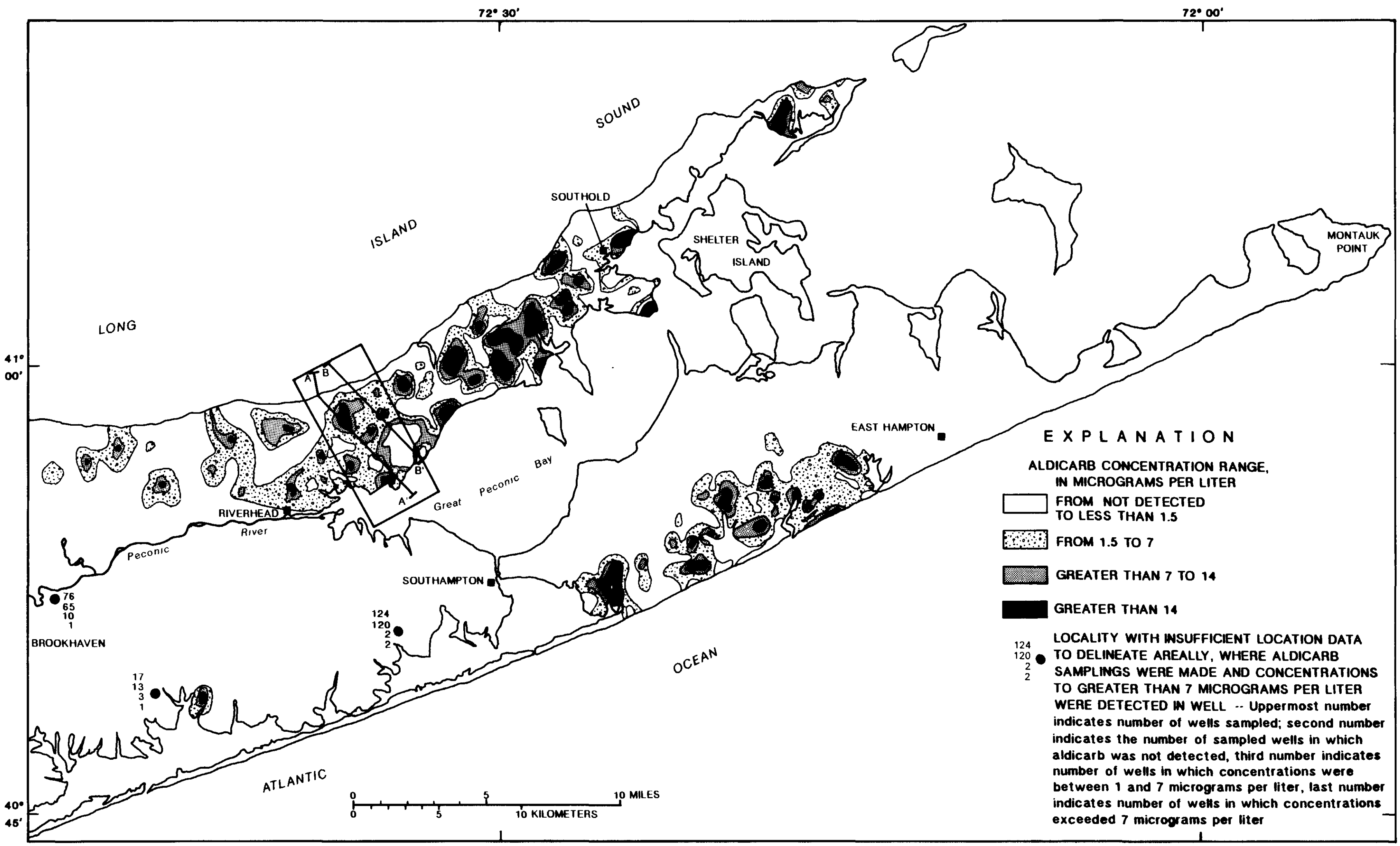


Figure 14A.--Distribution of aldicarb in eastern Suffolk County ground water in 1982. (Aldicarb data from Baier and Robbins, 1982a, 1982b. Map from Soren and Stelz, 1984, pl. 1.)

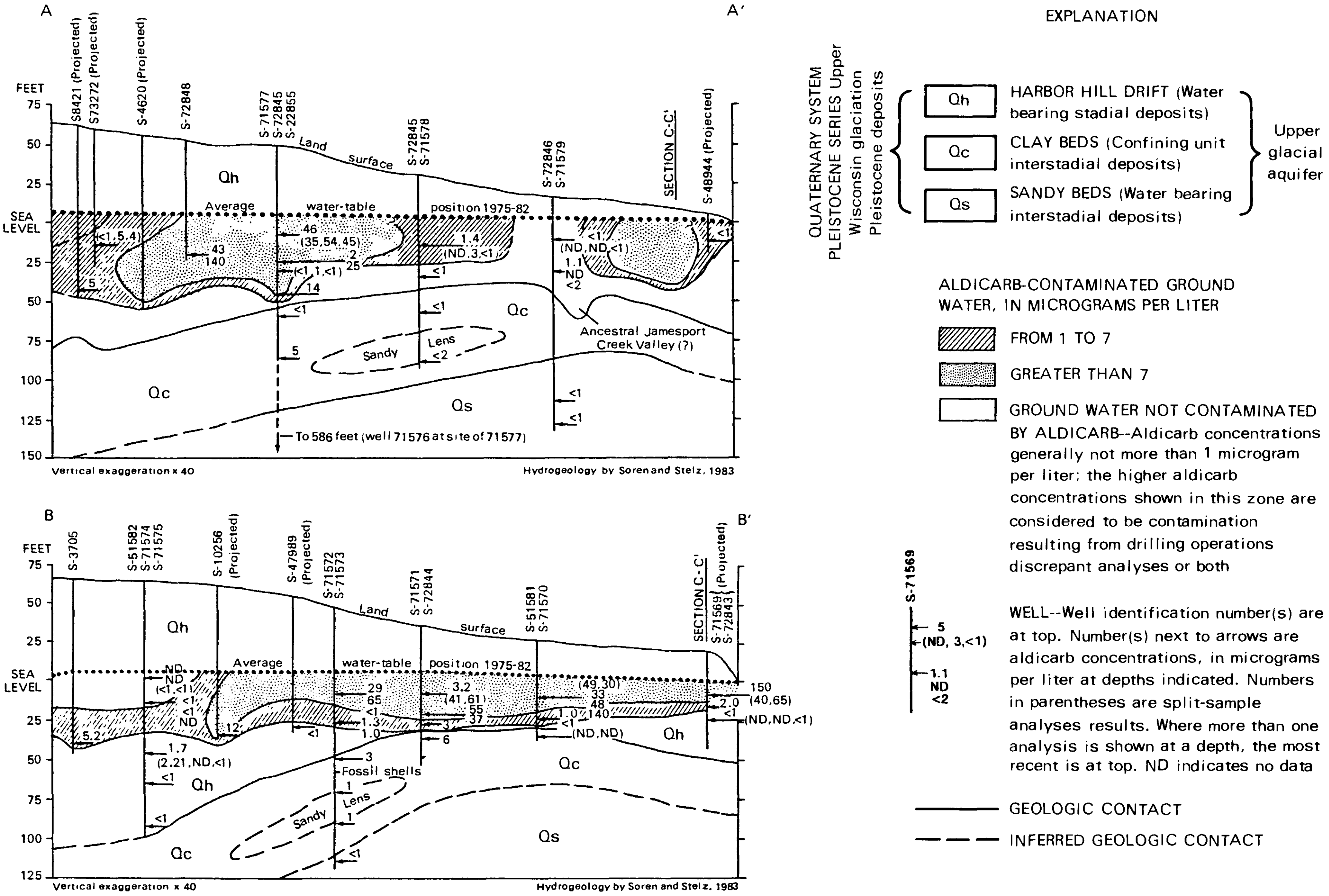


Figure 14B.--Vertical distribution of aldicarb along sections A-AK and B-BK in 1982. (From Soren and Stelz, 1983, figs. 5A and 5B. Locations of sections are shown in fig. 14A.)

SUMMARY

Long Island's ground-water resources are currently the sole source of water supply for 3.1 million people. The ground-water reservoir is extensive and contains an immense quantity of potable water, but the water quality in some areas has been considerably changed by human activities. Ground water moves slowly and can take thousands of years to circulate through the deeper parts of the aquifer system. Human activities have been severely affecting the system for the last 50 years, and some of the resulting changes have the potential for causing long-term damage to the resource without proper State and local management.

Proper management requires an understanding of the basic laws of physics and chemistry that govern the occurrence and movement of ground water and associated chemical constituents; it also requires information on the geometry, hydraulics, and natural chemical quality of the Long Island system. Techniques for studying this hidden resource include collection of ground-water samples and water-level data at wells to define the hydraulics and chemistry of the system, and then interpretation and refinement of this information through techniques such as computer simulation.

The four case studies of human-induced contamination of the ground-water system show how knowledge of the problem and of the hydrologic system can lead to appropriate responses. For the cases discussed, the appropriate responses were: (1) importation of water to reduce or stop saltwater intrusion in Kings and Queens Counties); (2) installation of sanitary sewers to avoid ground-water contamination by domestic waste-disposal systems); (3) improved design, management, and operation of landfills to prevent the formation and entry of leachate into the underlying ground water, and (4) bans on the use of a certain pesticide and temporary treatment of the pumped water until pesticide concentrations are lowered through dilution (flushing) and degradation. All four responses were different, yet appropriate.

Knowledge and understanding are the key to proper management of the island's ground-water resource. Human activities can adversely affect this resource if their effects on the ground-water reservoir are not understood.

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Table 9.--Characteristics of the major hydrogeologic units on Long Island, N.Y.

[Modified from McClymonds and Franke, 1972, table 2]

Hydro-geologic unit	Maximum thickness (feet)	Depth from land surface to top (feet)	Character of deposits	Water-bearing properties
Recent deposits	50	0	Sand, gravel, clay, silt, organic mud, peat, loam, and shells. Colors are gray, brown, green, black, and yellow. Recent artificial-fill deposits of gravel, sand, clay, and rubbish.	Permeable sandy beds beneath barrier beaches yield freshwater at shallow depths, brackish to salty water at greater depth. Clay and silt beneath bays retard saltwater 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 the underlying upper glacial aquifer.
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 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 the "20-foot clay" in southern Nassau and Queens Counties. 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.	Till is poorly permeable; impedes downward percolation of water to underlying beds. Outwash deposits are moderately to highly permeable; good to excellent infiltration characteristics. Glaciolacustrine and marine clay deposits are mostly poorly permeable and generally retard downward percolation of ground water. Contains fresh water except near shores. Till and marine deposits locally retard saltwater encroachment.
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 locally contains glauconite. Occurs in Kings, Queens, and southern Nassau and Suffolk Counties; 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.
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. Occurs in Kings, Queens, and southern Nassau Counties; 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 occurs locally in southeastern Nassau and southern Queens Counties.

Table 3.--Characteristics of the major hydrogeologic units on Long Island, N.Y.--continued

Hydro-geologic unit	Maximum thickness (ft)	Depth from land surface to top (ft)	Character of deposits	Water-bearing properties
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.
Magothy aquifer	1,100	0 - 600	Sand, fine to medium, clayey in part; interbedded with lenses and layers of coarse sand and solid clay. Gravel is common in basal 50-200 feet. Colors are gray, white, red, brown, and yellow.	Most layers are poorly to moderately permeable, some are highly permeable locally. 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 and southern Queens Counties and in small areas along north shore.
Raritan confining unit	300	70 - 1,500	Clay, solid and silty, few lenses and layers of sand; little gravel. 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 aquifer	500	200 - 1,800	Sand, fine to coarse, and gravel, commonly with clayey matrix; locally contains thin lignite layers. Locally has gradational contact with overlying Raritan clay. Colors are yellow, gray, and white, clay is red locally.	Poorly to moderately permeable. Water is confined under artesian pressure by overlying Raritan clay; generally of excellent quality but locally has high iron content. Has been invaded by salty ground water locally in necks near north shore, where aquifer is mostly shallow and overlying clay is discontinuous. Called "deep confined aquifer" in some earlier reports.
Bedrock		0 - 2,700	Crystalline metamorphic and igneous rocks; a soft, clayey zone of weathered bedrock locally is more than 100 feet 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 impractical to develop at most places; however, a few wells near the western edges of Queens and Kings Counties obtain water from the bedrock.

Table 4.--Selected chemical analysis of natural water on Long Island.

[Analyses made by U.S. Geological Survey; reported in milligrams per liter. Locations are shown in fig. 9. Data from McClymonds and Franke, 1972; a dash indicates no data available]

Sample source and number	Approximate age (years)	Total dissolved solids (residue on evaporation at 180°C)	pH	Temperature (°C)	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Remarks
Precipitation: (1)	--	10	4.5	--	--	--	0.5	0.3	1.6	0.1	--	3.8	2.7	0.8	Average of six composite monthly samples collected from rain gage at Brookhaven National Laboratory, October 1965 through March 1966.
Stream water: (2)	--	37	6.8	14	--	1.8	3.3	1.3	4.9	0.5	14	3.2	7.2	0.8	Sample collected at Cold Spring Brook gaging sta tion; May 1966; stream discharge 0.40 ft^3/s.
Upper glacial aquifer (3)	0-100	35	6.1	14	5.4	3.3	4.0	1.0	3.0	1.2	11	6.9	3.9	1.9	Depth 16 ft; depth to water 6 ft; sample collected December 1960.
Magothy aquifer (4)	50	25	6.1	11	7.5	0.01	1.3	0.1	2.7	0.7	5	1.0	4.3	1.4	Depth 255 ft; sample collected March 1957.
Magothy aquifer (5)	300-400	15	5.8	13	6.5	0.61	0.5	0.1	2.4	0.3	3	1.6	2.5	0.1	Depth 500 ft; sample collected September 1953.
Lloyd aquifer (6)	3,000	36	5.3	--	--	1.5	0.9	0.5	6.2	0.5	4	14	2.0	0.1	Depth 1,250 ft; sample collected November 1961.
Magothy aquifer (7)	600	2,180	4.4	16	9.3	39	82	76	520	8.0	--	76	1,150	0.4	Depth 506 ft; sample collected July 1960.

GLOSSARY

(Modified from U.S. Geological Survey, National Water Summary 1984)

Aquifer.--A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs. *See also* Confined aquifer and Unconfined aquifer.

Aquifer system.--A body of intercalated materials that acts as a water-yielding, hydraulic unit.

Artesian aquifer.--*See* Confined aquifer.

Atmospheric pressure.--The pressure exerted by the atmosphere on any surface beneath or within it; equal to 14.7 pounds per square inch.

Base flow.--Sustained low flow of a stream. In most places, base flow is ground-water inflow to the stream channel.

Bedrock.--A general term for consolidated (solid) rock that underlies soils or other unconsolidated material.

Brackish water.--Water that contains from 1,000 to 10,000 milligrams per liter of dissolved solids. *See also* Salt water.

Confined aquifer.--An aquifer in which ground water is under pressure that is significantly greater than atmospheric pressure. Synonym: Artesian aquifer. *See also* Aquifer and Unconfined aquifer.

Confining unit.--A layer or mass of rock having very low hydraulic conductivity that hampers the movement of water into and out of an adjoining aquifer.

Dissolved solids.--Minerals and organic matter dissolved in water.

Drawdown.--The difference between the water level in a well before pumping and the water level in the well during pumping.

Evapotranspiration.--A collective term that includes water discharged to the atmosphere as a result of evaporation from the soil and surface-water bodies and by plant transpiration.

Flow.--As used in this report, movement of water.

Freshwater.--Water that contains less than 1,000 mg/L (milligrams per liter) of dissolved solids; generally more than 500 mg/L is undesirable for drinking and many industrial uses.

Ground water.--In the broadest sense, all subsurface water, as distinct from surface water; as more commonly used, that part of the subsurface water in the saturated zone.

Ground-water reservoir.--Permeable rocks in the zone of saturation. *See* aquifer.

Ground-water system.--A ground-water reservoir and its contained water. Also, the collective hydrodynamical and geochemical processes at work in the reservoir.

Head.--*See* Hydraulic head.

Hydraulic conductivity.--A measure of the ease with which a fluid will pass through a porous earth material, determined by the size and shape of the pore spaces in the material and their degree of interconnection as well as by the viscosity of the fluid; a term replacing "field coefficient of permeability." Hydraulic conductivity may be expressed as cubic feet per day per square foot or cubic meters per day per square meter; hydraulic conductivity is measured at the prevailing water temperature.

Hydraulic gradient.--In an aquifer, the rate of change of head per unit of distance in the direction of most rapid change.

Hydraulic head.--The height above a datum plane of a column of water. In a ground-water system it is composed of elevation head and pressure head.

Infiltration.--The movement of water into soil or porous rock.

Interface.--In hydrology, the contact zone between two fluids of different chemical or physical makeup.

Leachate.--A solution obtained by leaching, as in the downward percolation of water through soil or solid waste and containing soluble substances.

Percolation.--Slow laminar movement of water through openings within a porous earth material.

Permeability.--The capacity of a rock for transmitting a fluid; a measure of the relative ease of fluid flow in a porous medium.

Plume.--An area of a stream or aquifer containing degraded water resulting from migration of a contaminant.

Potable water.--Water that is safe and palatable for human use.

Potentiometric surface.--An imaginary surface representing the static head of ground water in tightly cased wells that tap a water-bearing rock unit (aquifer); or, in the case of unconfined aquifers, the water table.

Precipitation.--The process whereby water vapor in the air condenses into small particles that accumulate to fall as rain or snow to the land surface.

Pressure head.--Hydrostatic pressure or force per unit area expressed as the height of a column of water that the pressure can support.

Recharge (ground water).--The process of addition of water to the saturated zone.

Recharge area (ground water).--An area in which water infiltrates the ground and reaches the zone of saturation.

Runoff.--That part of precipitation or snowmelt that reaches streams or surface-water bodies.

Saltwater.--Water that generally is considered unsuitable for human consumption or for irrigation because of its high content of dissolved solids. Generally expressed as milligrams per liter (mg/L) of dissolved solids, with 35,000 mg/L defined as sea water.

Saturated zone.--A subsurface zone in which all the interstices or voids are filled with water under pressure greater than that of the atmosphere.

Sea level.--Refers to the National Geodetic Datum of 1929, a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada; formerly called mean sea level.

Sea water.--*See* Saltwater.

Sediment.--Particles derived from rocks or biological materials that have been transported by a fluid.

Sole-source aquifer.--As defined by the U.S. Environmental Protection Agency, an aquifer that supplies 50 percent or more of the drinking water of an area.

Sublimation.--The direct transfer of frozen water molecules (snow or ice) to the air directly as vapor without going through the liquid state.

Transpiration.--The process by which water passes through living organisms, primarily plants, and into the atmosphere.

Unconfined aquifer.--An aquifer whose upper surface is a water table free to fluctuate under atmospheric pressure. *See also* Aquifer and Confined aquifer.

Unsaturated zone.--A subsurface zone in which interstices are not all filled with water; includes water held by capillarity and openings containing air or gases generally under atmospheric pressure. Limited above by land surface and below by the water table.

Water table.--The top water surface of an unconfined aquifer at atmospheric pressure. The water levels in wells that penetrate the uppermost part of an unconfined aquifer mark the position of the water table.

Water-table aquifer.--*See* Unconfined aquifer.