CHARACTERISTICS OF A GROUND-WATER PLUME DERIVED FROM ARTIFICIAL RECHARGE WITH RECLAIMED WASTEWATER AT EAST MEADOW, LONG ISLAND, NEW YORK

by Paul M. Heisig and Keith R. Prince

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CONTENTS

Page

Abstract 1
Introduction 1
  Purpose and scope 3
  Previous investigations 3
  Methods of sampling and analysis 3
  Acknowledgments 4
Hydrogeologic setting 4
  Regional hydrogeology 4
  Hydrogeology at the East Meadow recharge site 5
  Ground-water flow 10
Chemical quality of ambient ground water 12
Recharge facility and quality of reclaimed wastewater 14
  Design 14
  Operation 15
  Chemical quality of reclaimed wastewater 15
Factors that affect definition of ambient ground water and delineation of the recharge plume 17
  Meadowbrook sewage-treatment plant 19
  Road-salt stockpiles 20
  Storm runoff to Nassau County recharge basin 62 20
  Injection wells. 21
Distribution of chemical constituents and physical properties of the recharge plume in the three depth zones 21
  Specific conductance 21
  Chloride and sodium 23
  Sulfate 23
  Boron 24
  Nitrate + nitrite 26
  Calcium 27
  Magnesium 27
  Potassium 28
  Alkalinity 29
  pH 29
Chemical processes most likely to affect reactive cations, alkalinity, and pH 30
  Potential for cation exchange 30
    Unsaturated zone 31
    Saturated zone 32
  Potential biological processes 33
Extent, movement, and chemical evolution of the recharge plume 34
  Horizontal movement 35
  Vertical movement 36
  Effects of chemical retardation 36
  Longitudinal geochemical section through the recharge plume 39
  Water-quality evolution beneath the recharge site 39
  Fate of the recharge plume 42
Suggestions for future studies 42
Summary and conclusions 43
References cited 44

CONTENTS (continued)

Page

Glossary 46

Appendix I: Observation-well designations and average screen depths below water table 47

Appendix II: Box plots showing concentration ranges of selected constituents in ambient ground water; grouped by depth below water table 50

ILLUSTRATIONS
(Plate is in pocket)

Plate 1. Vertical section A - A´ showing distribution of selected chemical constituents.

Figure 1. Map of central Long Island showing location of the East Meadow artificial-recharge site and other pertinent features. 2

2. Map of East Meadow area showing locations of observation wells sampled in March-April 1987 4

3. Generalized hydrogeologic section showing relative positions of major aquifers on Long Island 5

4. Representative gamma log from well 24A depicting the upper glacial, intermediate, and Magothy zones 6

5. North-south hydrogeologic section A-A´ through study area showing relative position of upper glacial, intermediate, and Magothy zones and map view of trace of section A-A´ showing locations of wells with gamma-log data 7

6. Maps showing thickness of the upper glacial zone and intermediate zone south of the recharge site, based on natural gamma logs 8

7. Maps showing areas with high silt and clay content in the intermediate zone and Magothy zone as indicated by high natural gamma radiation 9

8. Generalized hydrogeologic section showing ground-water flow paths on Long Island under predevelopment conditions. 10

9. Map showing water-table altitude in East Meadow, May 1987 11

10. Map showing locations of observation wells used to define ambient water quality 13

11. Map of the East Meadow artificial recharge site 14

12. Graph showing cumulative volume of reclaimed wastewater transmitted through seven recharge basins and five injection wells 15

13. Map showing locations of local sources of influence on ground-water quality in relation to the East Meadow artificial-recharge site 18

14. Trilinear and Stiff diagrams showing chemical quality of ambient ground water, reclaimed water, and water affected by three manmade solute sources at East Meadow 19

15. Map showing areas affected by local influences on ground-water quality in relation to the recharge plume, March 1987 20

ILLUSTRATIONS (continued)

Page

16-18. Maps showing distribution of selected constituents, March 1987:
  16. Specific conductance in the intermediate zone. 22
  17. Boron in the upper glacial zone 25
  18. Potassium in the upper glacial zone 28

19. Extent of recharge plume within all three depth zones, March 1987 34

20. Graph showing concentration of chloride and major cations at well 47B as the leading edge of the recharge plume moves through the area 35

21. Box plots of selected constituents of ambient water, plume water, and reclaimed water 37

22. Hydrogeologic section showing chemical quality of plume water in the three depth zones along section A-A´ 40

23. Trilinear and Stiff diagrams showing changes in ground water from well 2C, screened in the upper glacial zone beneath the recharge site, before, during, and after recharge 41

TABLES

Table 1. Summary of inorganic chemical analyses of ambient ground water from wells in East Meadow, N.Y., 1978-87 12

2. Recharge schedule for basins 1-7 and wells A-E, from October 6, 1982 through January 9, 1984 16

3. Physical properties and inorganic constituents of reclaimed water from the Cedar Creek water-pollution-control facility, recharge basins, and plume water from three observation wells. 17

4. Chemical changes associated with cation exchange in selected constituents of reclaimed water between basin 3 and a lysimeter 11 feet beneath it at the start of a 3-day recharge test, June 20, 1983 32

5. Longitudinal movement of selected constituents of plume water, expressed as a percentage of the longitudinal extent of chloride, within the upper glacial, intermediate, and Magothy zones, March 1987 36

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	*By*	*To obtain*
	Length	
inch (in)	2.54	centimeter
inch (in)	25.40	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
foot per mile (ft/mi)		
	Area	
acre	0.4047	hectare
	0.09294	square meter
square mile (mi^2)	2.59	square kilometer
	Volume	
gallon (gal)	3.785	liter (L)
	Flow	
foot per second (ft/s)	0.3048	meter per second
foot per day (ft/d)	0.3048	meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06308	liter per second
gallon per day (gal/d)	0.003785	cubic meter per day
million gallons per day (Mgal/d)	0.04381	cubic meter per second

Other Abbreviations

microsiemens per centimeter (ms/cm)
milliequivalents per liter (meq/L)
milligrams per liter (mg/L)
grams per cubic centimeter (g/cm^3)
gram (g)
milliequivalents per gram (meq/g)

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.

CHARACTERISTICS OF A GROUND-WATER PLUME DERIVED FROM ARTIFICIAL RECHARGE WITH RECLAIMED WASTEWATER AT EAST MEADOW, LONG ISLAND, NEW YORK

by

Paul M. Heisig and Keith R. Prince

Abstract

Artificial-recharge experiments were conducted at East Meadow, N.Y., from October 1982 through January 1984. About 720 million gallons of reclaimed wastewater (tertiary-treated effluent) was applied to the upper glacial aquifer through seven recharge basins. An observation-well network was installed during 1985-87 to examine the physical and chemical properties of the plume derived from recharge water within the local flow system.

Aquifer material in the study area was divided into three depth zones (upper glacial, intermediate, and Magothy) on the basis of plume chemistry and natural gamma-log data. Water-quality data indicate that the permeability of the intermediate zone varies locally, and gamma-log data indicate that the Magothy zone and parts of the intermediate zone within the study area have a higher clay content and, thus, lower and more locally variable permeability than the upper glacial zone .

Delineation of the recharge plume was based on chemical differences among recharge water, ambient ground water, and water affected by three other local influences. By March 1987, the recharge plume extended 6,500 feet downgradient from the recharge site and had a maximum width of 2,250 feet; its maximum depth below the water table was between 53 and 164 feet. The plume is more extensive in the upper glacial aquifer than in the underlying, less permeable Magothy aquifer.

Chemical constituents of plume water were classified as either conservative or reactive. Chloride, a conservative solute, was used to indicate the maximum distance of recharge-plume movement and the relative reactivity of the other solutes. Sodium, sulfate, and boron were transported 80 to 100 percent as far as chloride. Calcium, magnesium, potassium, and alkalinity were transported 30 to 60 percent as far as chloride, and their movement appears to have been retarded by cation-exchange and sorption processes. Data from the unsaturated and saturated zones suggest that cation species in reclaimed water are exchanged primarily for hydrogen ion onto aquifer material. Sharp increases in hydrogen ion through this process are initially buffered by bicarbonate in the effluent. After the bicarbonate is exhausted, pH may decrease to less than 4 .

Biological processes, such as nitrification, appear to affect nitrate concentrations as well as pH and alkalinity in the area affected by secondary-treated effluent from a sewage-disposal facility. Decomposition of organic matter may also affect pH in this area.

Ground-water velocities within each depth zone, calculated from the distance traveled by chloride, were 3.4 ft/d in the upper glacial and intermediate zones, and 0.8 ft/d in the Magothy zone. These values are somewhat higher than those that would occur under natural conditions because recharge operations caused ground-water mounding and, thus, increased hydraulic gradients near the site. Velocities within the upper glacial zone, calculated from aquifer-test data and the distribution of road-salt leachate, were 2.0 to 3.2 ft/d.

The recharge plume has migrated by advection and dispersion within the upper glacial zone, and conservative and minimally reactive components have begun to move ahead of and separate from the reactive components along the ground-water flowpath.

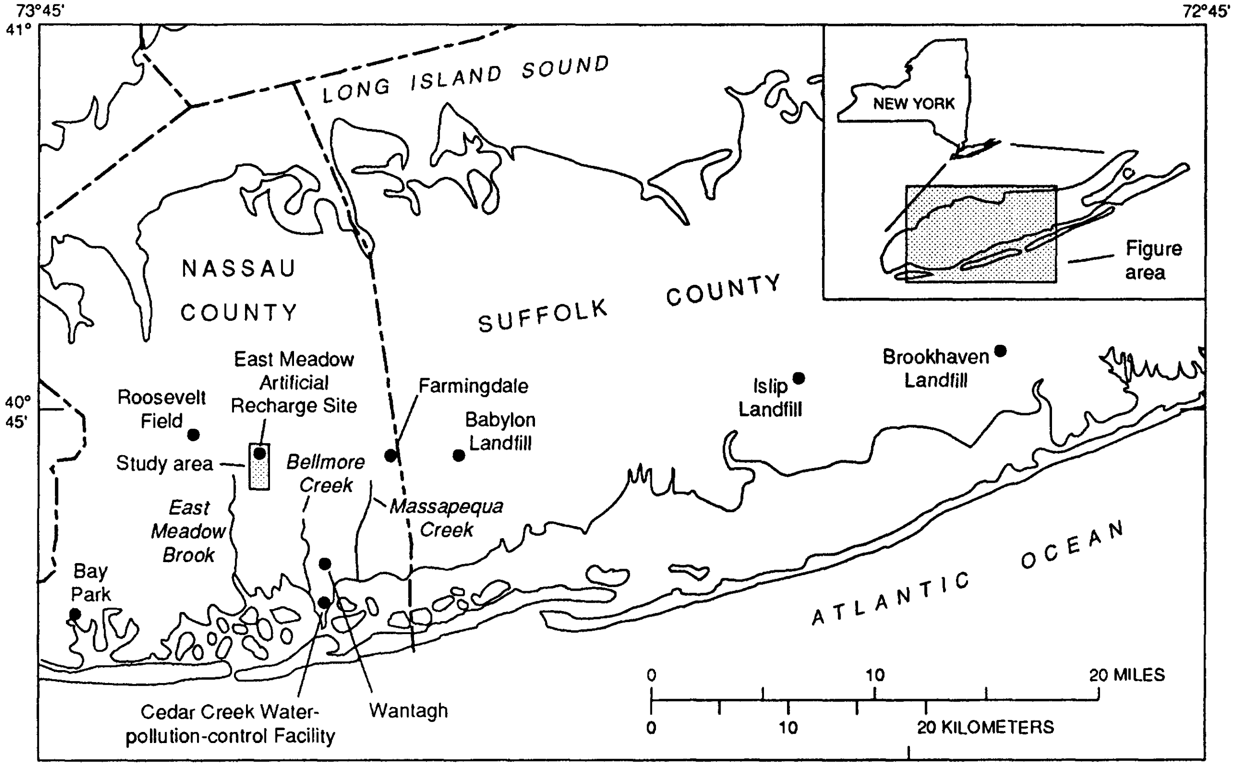
INTRODUCTION

The ground-water system of Long Island, N.Y., is constantly at risk of contamination through the effects of human activity and of depletion through overdevelopment. The surge in population since the 1950's and the attendant residential and industrial development have caused concern over the quantity and quality of the island's ground water. Large-scale sanitary sewers have been constructed to transport raw wastewater to treatment plants, which discharge their treated effluent to tidewater and thus protect the ground-water system from contamination by cesspools and septic systems. This discharge causes a significant loss of recharge to the aquifer system, however, and has caused a lowering of ground-water levels and an attendant decrease in streamflow and subsurface discharge to the surrounding saltwater bodies (Franke, 1968; Garber and Sulam, 1976; Kimmel and others, 1977; Pluhowski and Spinello, 1978; Sulam, 1979; Reynolds, 1982; and Simmons and Reynolds, 1982). Numerical model simulations of the effects of sanitary sewers on ground-water levels have predicted water-table declines of as much as 18 ft in central Nassau County (Reilly and Buxton, 1985).

To minimize ground-water depletion, several methods of augmenting recharge to the ground-water system have been implemented. Since the 1930's, storm runoff from developed areas has been routed to stormwater basins, from which it infiltrates to the water table or to nearby streams, where some of it infiltrates the water table through the streambeds. Artificial recharge through injection of spent cooling water has also been used, and recycling treated wastewater through injection wells and recharge basins has been studied.

The most recent artificial-recharge studies on Long Island were done at East Meadow, in central Nassau County, where tertiary-treated (reclaimed) wastewater from the Cedar Creek water-pollution-control facility in Wantagh (fig. 1) was used, as described by Schneider and others (1987). These studies, which were conducted for 16 months from October 1982 through January 1984, focused on the hydraulic feasibility of applying reclaimed wastewater to the ground-water system through shallow basins and injection wells. The efficiency of the basins and wells was evaluated in terms of application rates and amount of head buildup. Water-level rises and water-quality changes in the unsaturated zone also were documented. Schneider and others (1987) included a brief discussion of the extent of the recharge plume within the ground-water system and the effects of recharge water on the chemical quality of ground water.

Full evaluation of the technical feasibility of using reclaimed wastewater to recharge the ground-water system would require knowledge of how the wastewater moves through the system and interacts chemically with the aquifer material and native ground water. To this end, a study of the water-quality



Base from U.S. Geological Survey
State base map, 1974, 1:500,000 scale

Figure 1.—Location of the East Meadow recharge site and other pertinent features, Long Island, N.Y.

changes and movement of reclaimed waste water in the shallow ground-water system was begun 6 months after the cessation of recharge experiments.

The study, which was conducted by the U.S. Geological Survey (USGS) from October 1984 through September 1988, in cooperation with the Nassau County Department of Public Works, assessed the hydrologic and chemical processes that affect the transport of the recharge water after infiltration through the recharge basins. The objectives were to (1) delineate the extent of the plume 4 years after the cessation of artificial recharge, (2) evaluate the geologic and geochemical factors that affect the rate of plume migration, (3) calculate the rate of movement of the leading edge of the plume, and (4) obtain information on the effects of reclaimed wastewater on the chemical quality of water in the upper glacial and Magothy aquifers.

Reclaimed water that was applied through the injection wells was not investigated because the injection wells, although spaced such that they would be considered separate sources, had zones of influence that would interfere with one another and hamper interpretation of chemical data. The closely spaced recharge basins formed, collectively, a more discrete source and a more efficient means of recharge.

Purpose and Scope

This report presents results of water-quality sampling and well logging in East Meadow by the USGS during 1985-88. The first part describes the hydrogeology and ambient ground-water quality of the study area and briefly discusses the recharge facility design and operation. The second part describes the chemical quality of reclaimed water and discusses (1) characteristics and delineation of the recharge plume; (2) the effect of cation exchange on plume-water chemistry; (3) the location, movement, and chemical evolution of the recharge plume, and (4) the state of reclaimed water 4 years after recharge. Plate 1 shows the distribution of pH, field specific conductance, total alkalinity, and concentrations of eight selected solutes in longitudinal sections of the plume. Appendix I lists the local well-identification numbers and the corresponding numbers used herein, the well diameter, and the average depth of the screened interval of wells in the study area and appendix II shows box plots of ambient ground-water quality, grouped by depth below the water table.

Previous Investigations

Previous investigations at East Meadow have described ambient geochemical conditions, hydrogeology, and the design and results of artificial-recharge experiments. Katz and Mallard (1980) described ambient geochemical conditions near the facility before recharge. Aronson and others (1983) described the hydrogeology at the site. Schneider and Oaksford (1986) described the design and monitoring capabilities of the site and present preliminary results of recharge tests. Schneider and others (1987) discussed the movement and chemical quality of reclaimed water in the unsaturated zone at the recharge facility, the recharge experiments and their hydrologic effects, and a preliminary delineation of the recharge plume.

Studies of the movement of ground-water solutes on other parts of Long Island include investigations of landfill-leachate plumes at Babylon and Islip (Kimmel and Braids, 1980) and at Brookhaven (Wexler, 1988a, 1988b, and Wexler and Maus, 1988). Locations are shown in figure 1. One of the first studies of solute movement on Long Island described a plume of plating waste in Farmingdale (fig. 1) (Perlmutter and Lieber, 1970). The movement and chemical quality of a secondary-treated sewage plume on Cape Cod, Mass., was described by LeBlanc (1984).

Methods of Sampling and Analysis

The chemistry, extent, and movement of ground water derived from recharge with reclaimed wastewater were defined by sampling and analysis of ground water from an observation-well network in the study area. The final network (March-April 1987) is illustrated in figure 2; well diameters and screened depths are listed in appendix I. The observation-well network installed before this study had been designed to monitor the local hydraulic and water-quality effects of recharge operations, and data from previous sampling prompted the installation of additional observation wells during three periods of drilling to define the extent of the recharge plume within the local hydrologic system. All wells were sampled during November-December 1985, March-April 1986, August 1986, and March-April 1987. Unless specified otherwise, all data presented here are from the March-April 1987 sampling.

Water samples were obtained by submersible pump in accordance with standard USGS sampling procedures and analyzed for major inorganic constituents by the USGS Central Laboratory (Fishman and Friedman, 1989). About 10 percent of the samples collected in the study were sent to the Nassau County laboratory at the Cedar Creek water-pollution-control facility and analyzed for the same constituents. Both laboratories participate in the standard reference water-sample program administered by the USGS. Estimates of precision associated with inorganic-constituent analyses are given in Feltz and others (1985).

Acknowledgments

The authors thank James F. Mulligan, Peter Witkowski, and Ralph Denton of the Nassau County Department of Public Works for their help in planning and for providing field crews to assist in drilling and well development. We also thank Harold Morgan of the East Meadow Water District, Edward Donahue of the Town of Hempstead Highway Department, and Thomas Palumbo of the Nassau County Department of Public Works for information and access to records and for assistance during well-drilling operations.

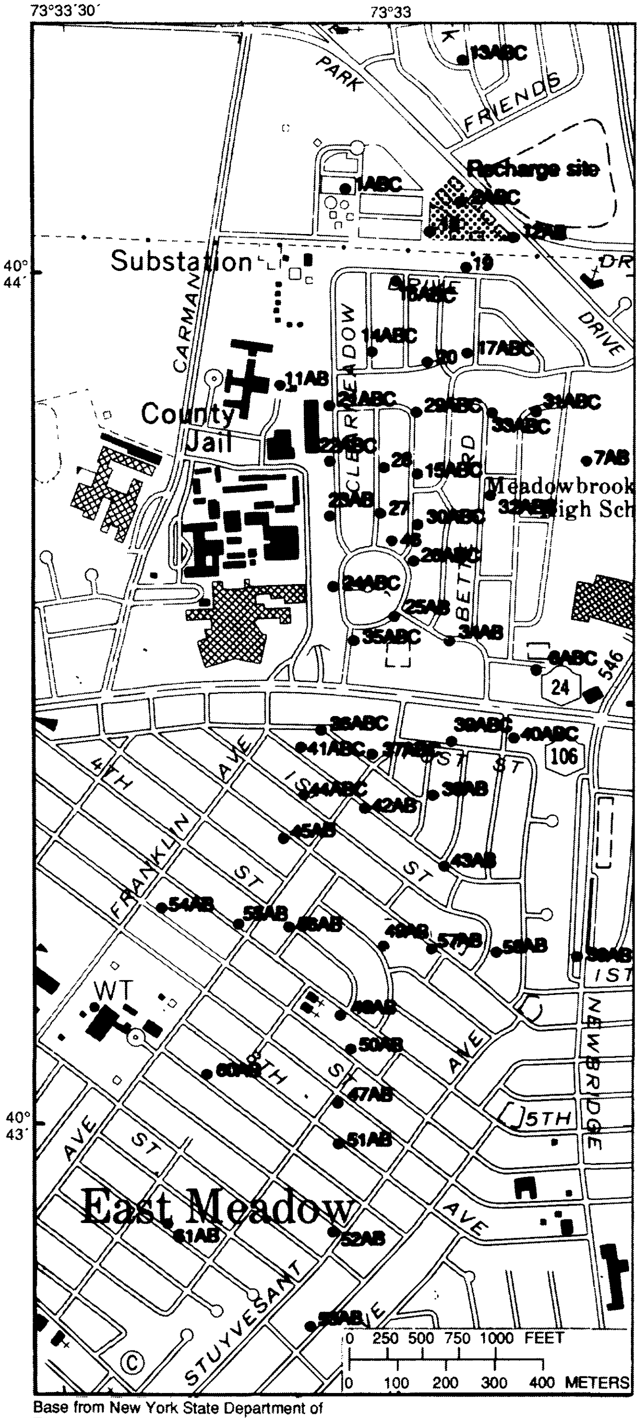
Special thanks are extended to Brian J. Schneider of the Nassau County Department of Public Works for his work during the early stages of the study and for his continued cooperation during the remainder of the study.

HYDROGEOLOGIC SETTING

The hydrogeology of Long Island is discussed in detail in many reports, including those by Cohen and others (1968), McClymonds and Franke (1972), and Franke and Cohen (1972). A discussion of the hydrogeology at Roosevelt Field (fig. 1), a few miles west of the study site, is given in Eckhardt and Pearsall (1989), and the hydrogeology of the East Meadow test site is described in Aronson and others (1983).

Regional Hydrogeology

Long Island is underlain by a sequence of unconsolidated deposits of sand, gravel, and clay of Quaternary and Late Cretaceous age that unconformably overlie bedrock composed of schist, gneiss, and granitic rocks of Precambrian age. A generalized north-south hydrogeologic section of Long Island is given in figure 3. Overlying the bedrock is the Raritan Formation of Late Cretaceous age, which consists of the Lloyd Sand Member (Lloyd aquifer) and the overlying unnamed clay member (Raritan confining unit), which is an effective confining unit. Overlying the Raritan Forma-



Base from New York State Department of Transportation, Freeport, NY, 1:24,000, 1981

EXPLANATION

● 45AB OBSERVATION WELL--number identifies the well site; letters denote more than one well at the site. For example, well 45 consists of wells 45A and 45B. By convention, "A" well is the deepest well at each site

Figure 2.—Locations of observation wells sampled in March-April 1987. (General location is shown in fig. 1).

tion is the Magothy Formation and Matawan Group, undifferentiated (Magothy aquifer), also of Late Cretaceous age. These deposits, which are as much as 1,000 ft thick, consist of clayey and silty, fine-to-medium quartzose sand, some gravel, and clay layers (McClymonds and Franke, 1972). The upper surface of the Magothy aquifer is an erosional surface everywhere in Nassau County and is in hydraulic contact with overlying Pleistocene deposits over much of Long Island.

Overlying the Magothy aquifer are Pleistocene deposits. Along the south shore of Nassau County, these deposits locally include the Jameco Gravel (Jameco aquifer), which overlies the Magothy aquifer, and an overlying confining unit known as the Gardiners Clay. The Jameco aquifer and Gardiners Clay are absent in the study area (fig. 3). The upper glacial aquifer, which consists mostly of sand and gravel, overlies the Gardiners Clay along the south shore and overlies the Magothy aquifer in the study area. The upper glacial deposits are generally less than 100 ft thick but may be much thicker where they fill buried valleys or form morainal deposits.

Holocene deposits of swamp bogs, alluvial deposits, lagoonal sediment, and beach and dune sand overlie the Pleistocene deposits along the margins of Long Island in beds generally less than 20 ft thick, but these do not occur in the study site.

Hydrogeology at the East Meadow Recharge Site

Reclaimed wastewater has affected water quality in the upper glacial aquifer and upper part of the Magothy aquifer; therefore, only the upper glacial and Magothy aquifers are discussed in detail. The upper glacial aquifer is unconfined at the recharge site; the Magothy aquifer ranges locally from unconfined to poorly confined. The degree of confinement in the Magothy generally increases with depth. Geophysical, lithologic, and drillers' logs obtained during the installation of wells in the East Meadow area suggest that the Magothy aquifer consists of a relatively unbroken sequence of interbedded fine to coarse, light-gray to brown sand containing variable amounts of silt and clay. The upper part of the Magothy aquifer contains laterally discontinuous zones of higher clay and silt content. Beneath the recharge site, the Magothy aquifer is about 500 ft thick. Its upper surface dips gently southward at about 25 ft/mi.

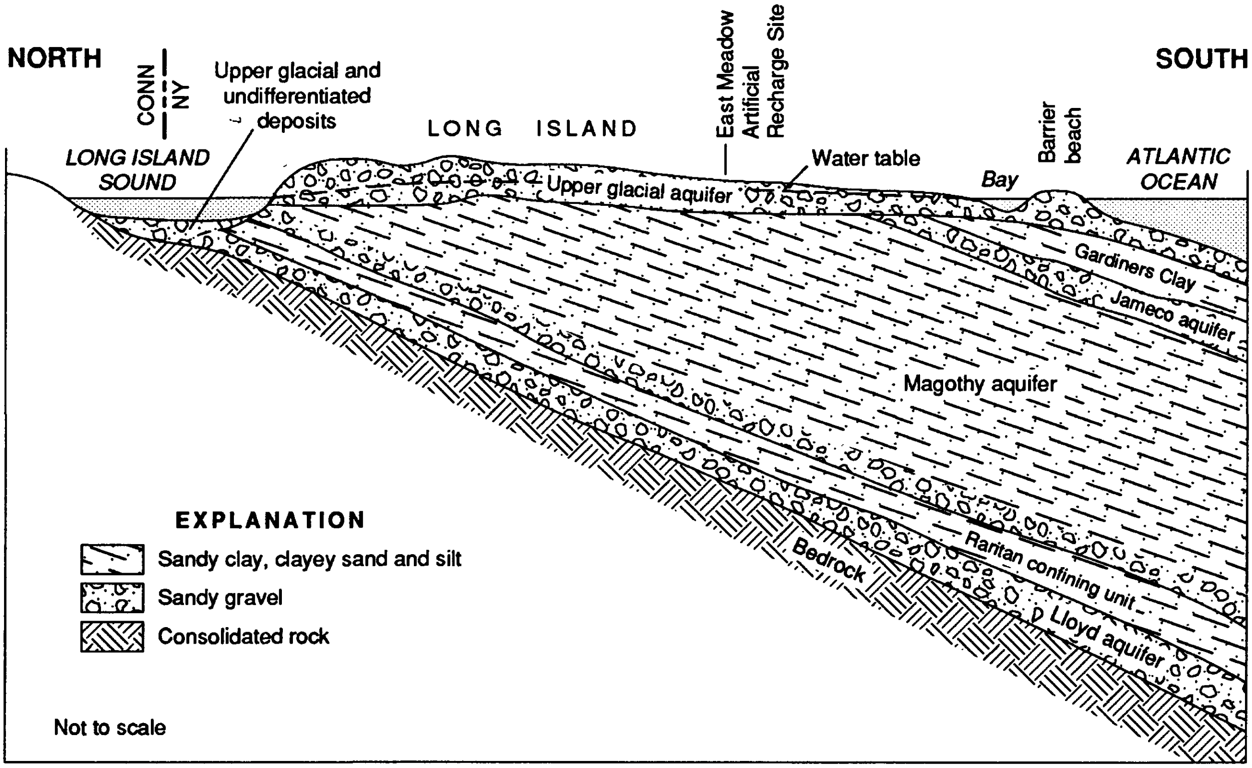


Figure 3.—Generalized hydrogeologic section showing relative positions of major aquifers on Long Island. (Modified from Franke and McClymonds, 1972, fig. 3).

Most of the upper glacial deposits consist of fairly homogeneous, medium to very coarse, brownish-orange (iron oxyhydroxide-coated) sand and gravel containing interbedded lenses of fine to medium silty sand and thin beds of sandy clay. The lower part of the upper glacial aquifer is less homogeneous, with increasing amounts of fine-grained material; therefore, the contact between Pleistocene and Cretaceous materials within the study area is poorly defined. Aronson and others (1983) delineated the contact at 14 observation wells in the study area from the mineralogy and texture. Comparison of geologic logs and natural gamma logs with the contacts indicated by Aronson and others (1983) suggests that the contact or transition zone can be seen in many of the geophysical logs as an increase in gamma radiation. Hydraulic values within the interval from the bottom of the upper glacial aquifer to the top of the Magothy aquifer, about 60 ft below the water table, are indicated by natural gamma logs and water-quality data (presented farther on) to range between those of the upper glacial and those of the Magothy. This zone may consist of reworked Magothy aquifer material into which some upper glacial material has been mixed by glacial action and meltwater erosion and redeposition. As a result, the aquifer material of concern in this report is divided into three zones: the upper glacial, the intermediate, and the Magothy. A representative gamma log in which the three zones are delineated is given in figure 4; the three zones are also depicted in a vertical section through the study area in figure 5.

Gamma-logs and water-quality data were used to delineate the thickness of the three zones. The saturated thickness of the upper glacial zone ranges from 13 to 33 ft (fig. 6A). The most significant aspect is the relatively thin saturated thickness (13 to 19 ft) close to the recharge site.

The intermediate zone is defined as the interval between the bottom of the upper glacial zone and the top of the Magothy zone. Thickness, as indicated by gamma-log and water-quality data, ranges between 24 and 41 ft and is greatest in the north end of the study area (fig. 6B). The top of the Magothy zone (defined as 60 ft below the water table) corresponds to a decrease in permeability and ground-water velocity, as indicated by water-quality data. The bottom of the Magothy zone, defined as 90 ft below water table, is the lower boundary of the area of interest in this study. Well coverage of the Magothy zone does not extend appreciably south of Route 24 (fig. 6) because the recharge plume was not detected more than 1,500 ft downgradient from the recharge site in the Magothy in 1987.

Water-transmitting and storage properties of the upper glacial and Magothy aquifers were estimated by Prince and Schneider (1989), who reported for the upper glacial aquifer a horizontal hydraulic conductivity of 380 ft/d, an anisotropy (ratio of horizontal to vertical conductivity) of 2.5, and a specific yield of 0.15. For the Magothy aquifer, they reported a hydraulic conductivity 100 ft/d, an anisotropy of 5.0, and a coefficient of specific storage of 1.0×10^{-4}. Previously published hydraulic-conductivity estimates for the upper glacial aquifer range from 140 to 380 ft/d, with an anisotropy of 1.8 to 24, whereas estimates for the Magothy aquifer range from 50 to 70 ft/d, with a anisotropy of 30 to 60 (McClymonds and Franke, 1972; Getzen, 1977; Lindner and Reilly, 1983). Estimates based on a Magothy aquifer test by Prince and Schneider (1989) were considerably higher than those published previously, probably because the production well tapped the uppermost 25 to 30 ft

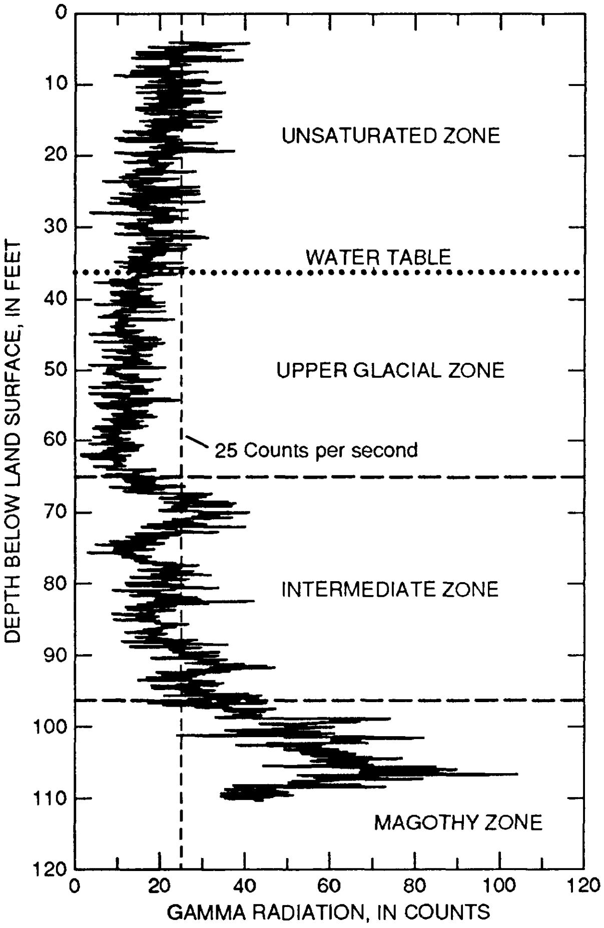
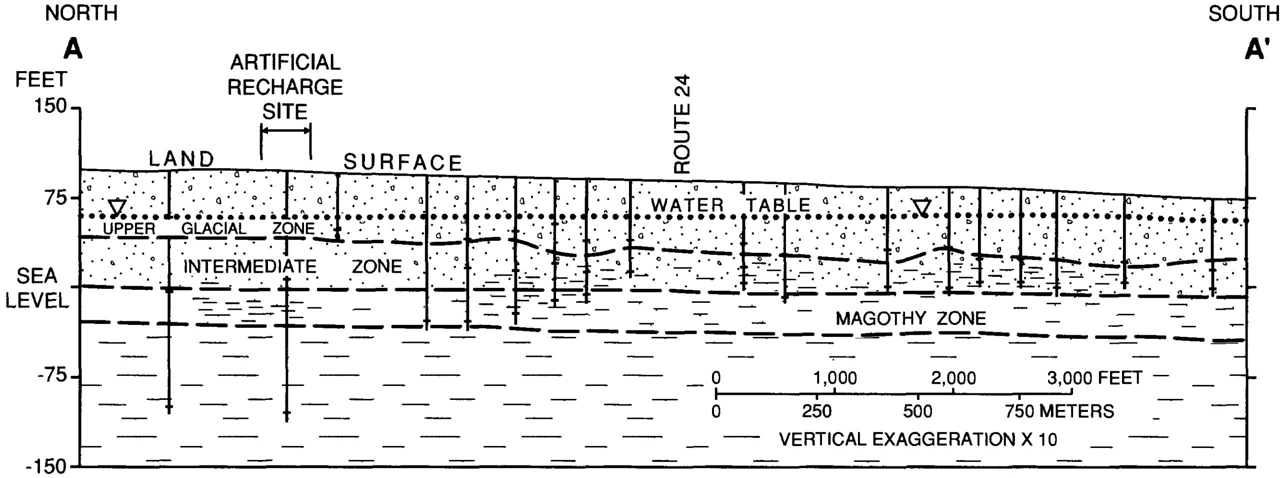


Figure 4.—Representative gamma log from well 24A depicting the upper glacial, intermediate, and Magothy zones. Increases in gamma radiation typically denote increases in clay content. (Well location is shown in fig. 2.)



EXPLANATION

▨ MEDIUM TO VERY COARSE SAND; SOME GRAVEL

▭ MEDIUM TO FINE SAND WITH LENSES OF SILT AND CLAY

↓ OBSERVATION WELLS WITH GAMMA-LOG DATA

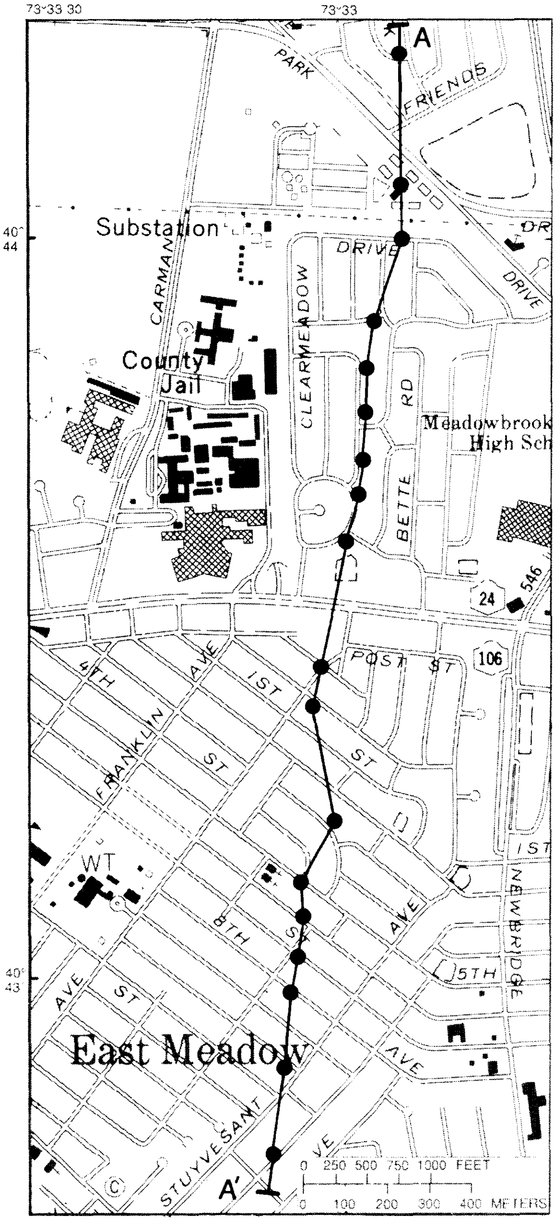
Note: The sediments of the intermediate zone range from upper glacial type to Magothy type

Figure 5.—Above: North-south hydrogeologic section A-A´ through study area showing relative position of upper glacial, intermediate, and Magothy zones. Right: Trace of section A-A´ showing locations of wells with gamma-log data. (Location shown in fig. 1.)

of the Magothy aquifer, which is in the more permeable intermediate zone defined in this study.

Gamma-log data were used to identify areas of elevated clay and silt concentrations within the intermediate and Magothy zones (the upper glacial zone contains little clay and silt within the study area). An increase in gamma radiation generally indicates an increase in fine-grained material and, therefore, lower permeability. In the study area, gamma counts in the upper glacial zone (sand and gravel) typically fall below 25 per second. The percentage of thickness of the intermediate and Magothy zones that exceed 25 cps (counts per second) was calculated to provide a qualitative basis for comparison among well sites in the study area (figs. 7A and 7B). A 30-percent contour line was arbitrarily selected to delineate areas of high silt-clay content.

All gamma-log data used in figures 7A and 7B were logged through hollow-stem augers prior to installation of 2-inch polyvinyl chloride wells. Both of the zones depicted in figures 7A and 7B have incomplete gamma-log coverage, particularly in the southern part of the observation-well network, because the wells were of insufficient depth. As a result, some gamma logs provide only partial coverage of a zone.



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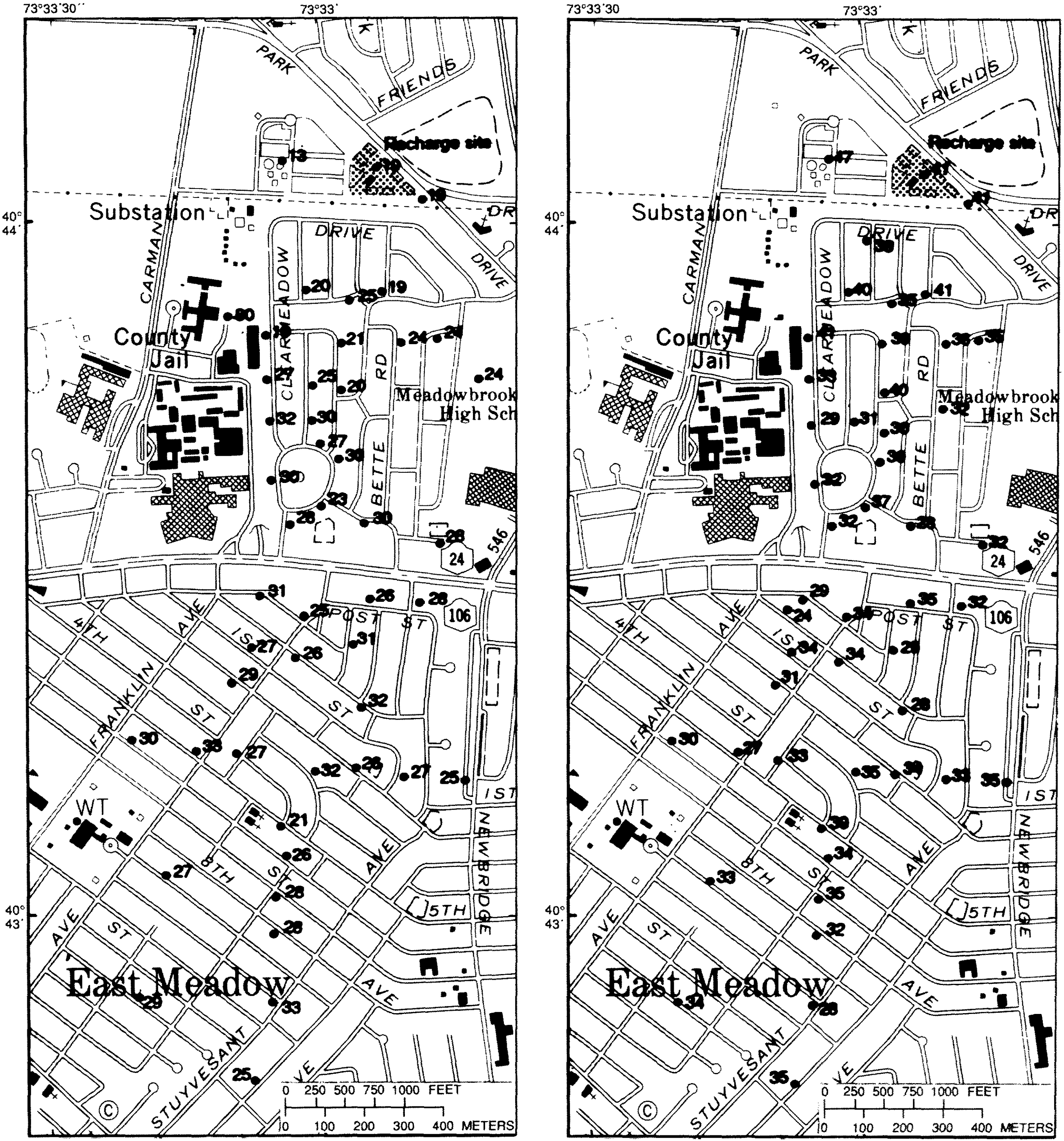


Base from New York State Department of Transportation, Freeport, NY, 1:24,000, 1981

Base from New York State Department of Transportation, Freeport, NY, 1:24,000, 1981

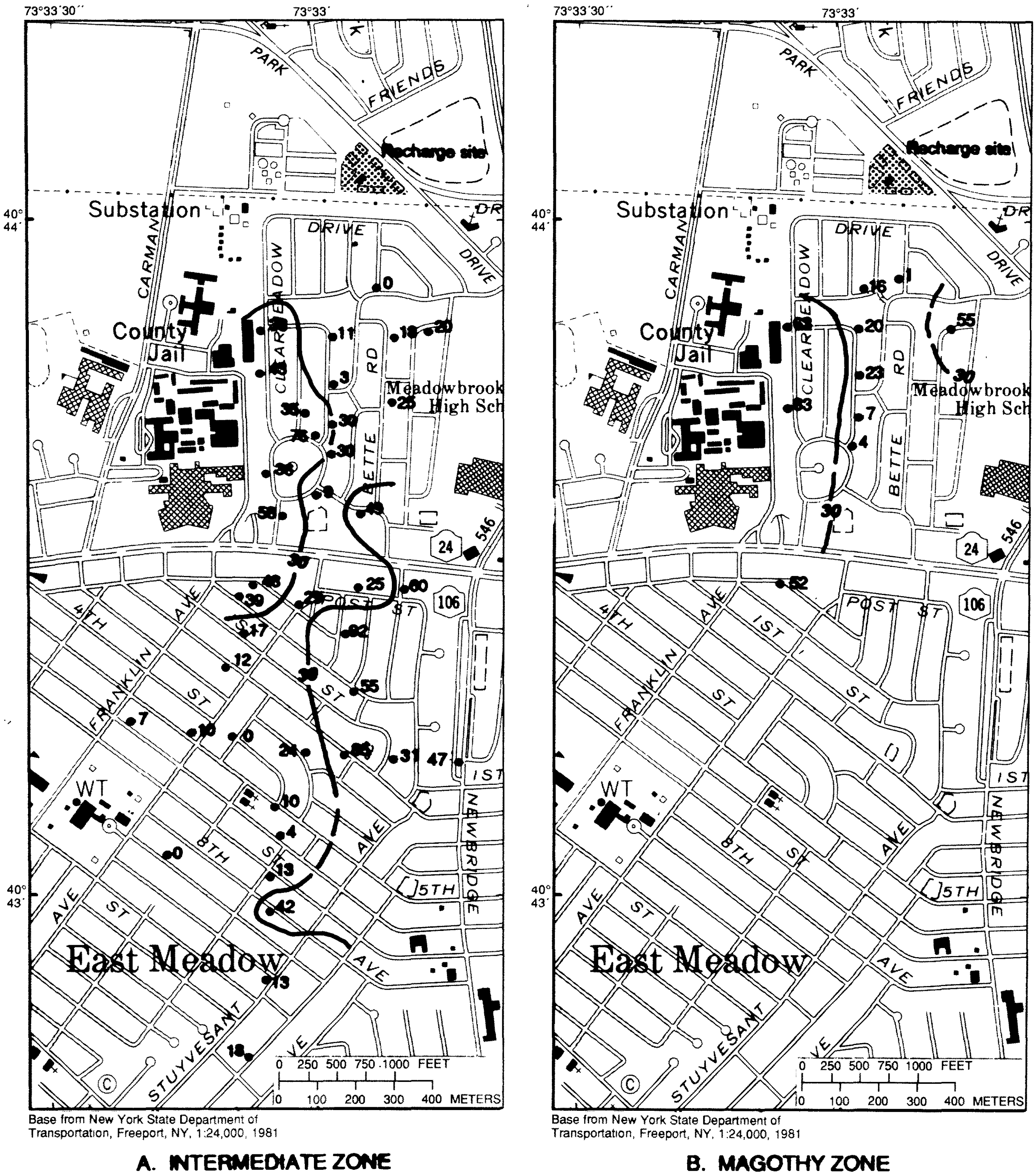
A. UPPER GLACIAL ZONE

B. INTERMEDIATE ZONE

EXPLANATION

●27 WELL SITE--at which thickness of hydrologic zone was estimated from gamma-log data. Number is zone thickness, in feet

Figure 6.—Thickness of (A) upper glacial zone and (B) intermediate zone south of the recharge site, based on natural gamma logs.



Base from New York State Department of Transportation, Freeport, NY, 1:24,000, 1981

A. INTERMEDIATE ZONE

Base from New York State Department of Transportation, Freeport, NY, 1:24,000, 1981

B. MAGOTHY ZONE

EXPLANATION

●24 WELL SITE--where gamma log was taken. Number is percentage of gamma-log data that exceeds 25 counts per second within the zone

30 LINE OF EQUAL PERCENTAGE OF GAMMA RADIATION EXCEEDING 25 COUNTS PER SECOND--number indicates percentage. Dashed where inferred

Figure 7.—Areas with high silt and clay content in intermediate zone and Magothy zone as indicated by high natural gamma radiation. (High gamma radiation is defined as greater than 25 counts per second over at least 30 percent of the zone thickness.)

Ground-Water Flow

The sole source of natural recharge on Long Island is precipitation. The average annual precipitation in the East Meadow area is 44 in/yr (Miller and Frederick, 1969), about half of which is returned to the atmosphere through evapotranspiration or becomes overland runoff. The remainder is available for recharge to the ground-water system.

A generalized north-south vertical section of Long Island (fig. 8) shows the approximate directions of ground-water movement under predevelopment conditions. Near the ground-water divide, flow is predominantly downward to the deeper aquifers, where it then becomes horizontal before curving upward toward discharge areas near the shore. Water that enters the ground-water system away from the divide flows horizontally toward the discharge areas. Ground water north of the divide discharges to Long Island Sound, and ground water south of the divide discharges into the south-shore bays and the Atlantic Ocean.

In the East Meadow area, natural recharge is increased through the use of stormwater basins. Stormwater from impervious surfaces such as roads is piped to the basins, where it percolates to the water table. The Meadowbrook sewage-treatment plant, which borders the west side of the recharge site, was an additional source of recharge (secondary-treated effluent) within the study area during 1951-79.

Discharge from the ground-water system near the site consists of (1) seepage to nearby East Meadow Brook and Bellmore Creek (fig. 1) and (2) ground-water pumpage for municipal public supply, irrigation at nearby Eisenhower Park (fig. 9), and, in the summer, for cooling water for commercial air conditioning. A hospital on Route 24 pumps a small amount for dewatering during periods of high ground-water levels. The municipal water supply is pumped at a town well field on Prospect Avenue (fig. 9), which contains 10 active wells that pump about 5.2 Mgal/d from the Magothy aquifer between 325 and 648 ft below land surface (Harold Morgan, Town of Hempstead, East Meadow Water District, oral commun., 1988).

The water table in the study area ranges from about 46 ft above sea level in the southern part to about 62 ft in the north (fig. 9). Ground-water flow is predominantly horizontal and southward. The potentiometric surface of the Magothy aquifer in this area is nearly the same as the water table. The horizontal gradient in the upper glacial aquifer is about 0.0019 ft/ft. Vertical gradients fluctuate sea-

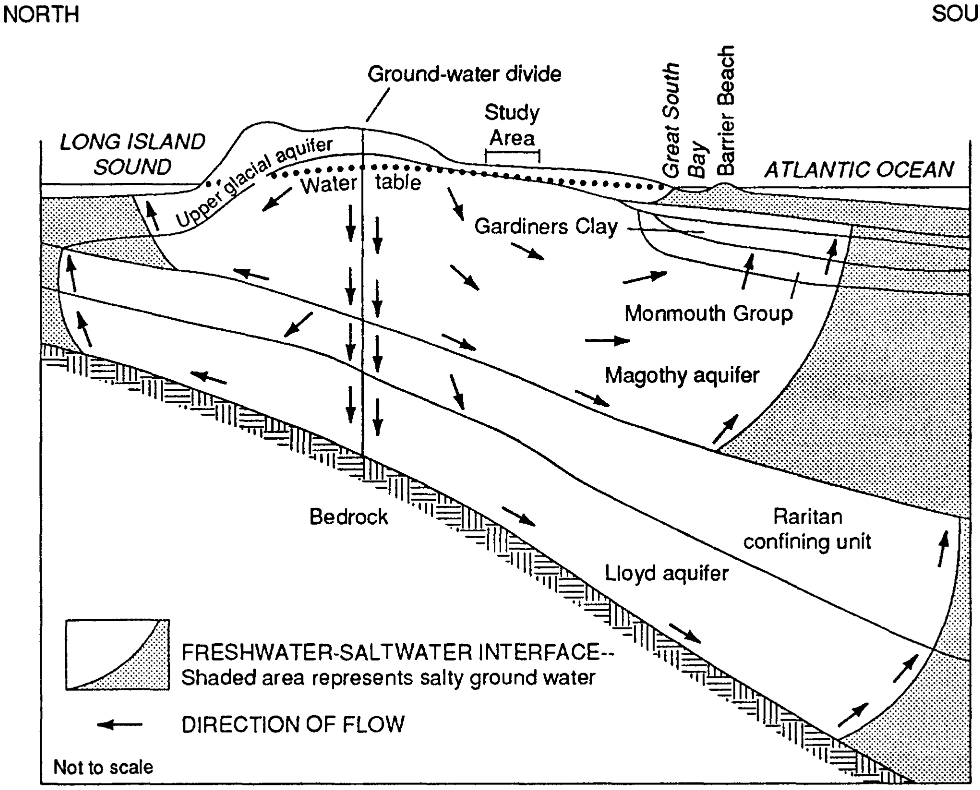


Figure 8.—Generalized hydrogeologic section showing ground-water flow paths on Long Island under predevelopment conditions. (Modified from Franke and Cohen, 1972, fig. 2.)

sonally and areally, depending upon recharge, but generally are less than 0.0026 ft/ft.

The average rate of horizontal ground-water movement in the East Meadow area can be calculated through Darcy's law from the equation:

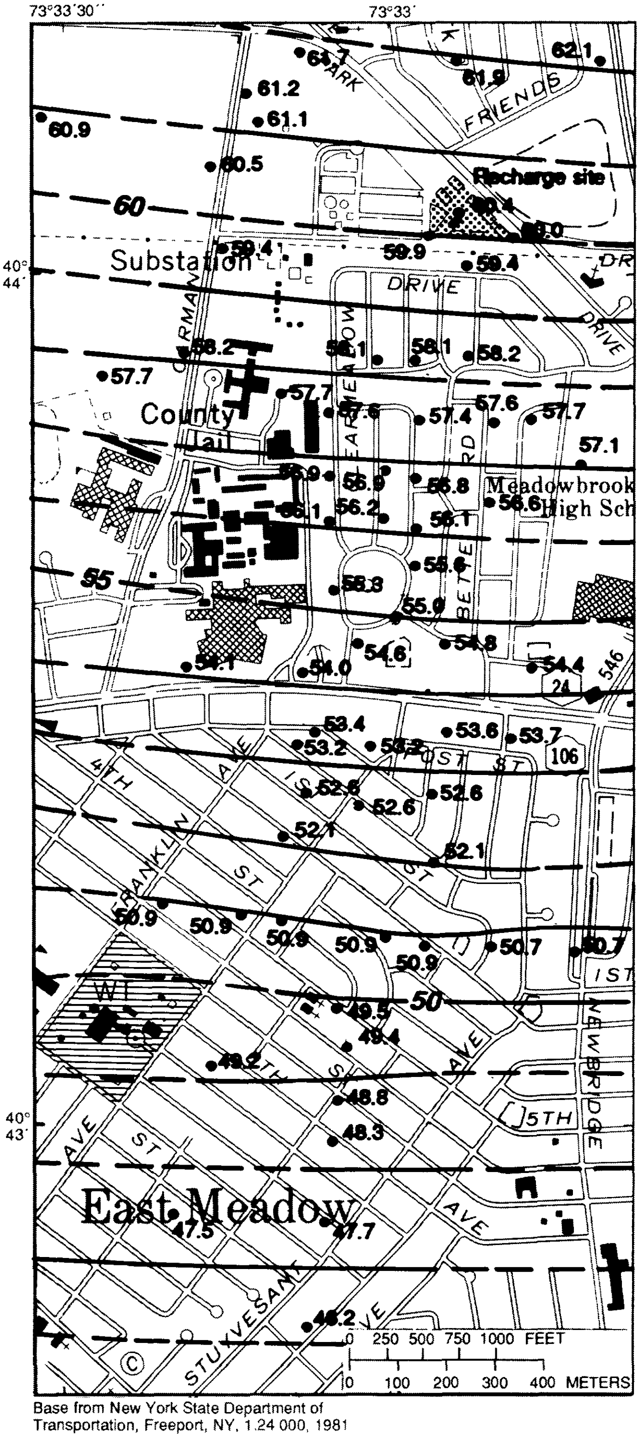
$$V = \frac{KI}{n}$$

where

V = velocity (feet per day),
K = hydraulic conductivity (feet per day),
I = hydraulic gradient (feet per foot), and
n = effective porosity (dimensionless).

Multiplying a hydraulic conductivity of 380 ft/d for the upper glacial aquifer (Prince and Schneider, 1989) by an average gradient of 0.0019 ft/ft and dividing by porosity of 0.32 (E.T. Oaksford, USGS, oral commun., 1989) gives an average velocity of about 2.3 ft/d in the East Meadow area. Actual ground-water velocities would vary in proportion to local variations in hydraulic conductivity and changes in gradient that result from water-table fluctuations due to natural fluctuations in recharge. Perlmutter and Lieber (1970) calculated an average velocity of about 1.5 ft/d for the upper glacial aquifer near Massapequa Creek in Farmingdale (fig. 1) and an average rate of about 1.2 ft/d for a plume of ground water contaminated with plating waste in the same area. Kimmel and Braids (1980) estimated the average velocity of ground water in the upper glacial aquifer in the Babylon area to be about 4 ft/d, and 1.2 to 2.3 ft/d in the Islip area in Suffolk County (fig. 1). Wexler and Maus (1988), using a finite-element numerical model to simulate the movement of a landfill-leachate plume in the upper glacial aquifer in the Brookhaven area (fig. 1), calculated velocities between 0.2 and 4.4 ft/d.

The average velocity of ground water in the upper part of the Magothy aquifer in the study area, based on a hydraulic conductivity of 100 ft/d (Prince and Schneider, 1989), an average gradient of 0.0019 ft/ft, and a porosity of 0.25 (Warren and others, 1968), is about 0.8 ft/d.



Base from New York State Department of Transportation, Freeport, NY, 1:24 000, 1981

Figure 9.—Water-table altitude in East Meadow, July 1987.

EXPLANATION

●57.7 OBSERVATION WELL--number is water-table altitude, in feet above sea level

50 WATER-TABLE CONTOUR-shows water-table altitude in July 1987. Contour interval 5 feet. Dashed where inferred

▤ PROSPECT AVENUE WELL FIELD

CHEMICAL QUALITY OF AMBIENT GROUND WATER

Development on Long Island has been paralleled by increased loading of dissolved constituents into the upper part of the ground-water system. Manmade sources, such as road-salt stockpiles, residential and agricultural fertilizers, sewage-treatment plants, and landfills, have degraded water quality.

Chemical characteristics of *ambient water*[1] were established from water-quality data from 21 observation wells (locations shown in fig. 10). Well selection was based on location, position of well screen below water table, and the availability of recent (post-1978) water-quality data. Data from wells in figure 10 that appear to be affected by the sources discussed later were either screened above or below the affected water or were sampled prior to artificial recharge with reclaimed wastewater. Median concentrations of selected inorganic constituents at each well were calculated. The number of analyses for individual constituents ranged between 1 and 17 per well, depending on the constituent. The overall or population median and the 10th and 90th percentiles of each of the constituents were calculated from the observation-well medians (table 1). The overall median provides a measure of the central tendency of each constituent in ambient water (which is not sensitive to extreme values), and the 10th and 90th percentiles represent the range. Maximum and minimum medians represent the highest and lowest medians for individual wells. The medians in table 1 represent water unaffected by known point sources or artificial recharge in the study area. Point sources in the area are discussed in a later section.

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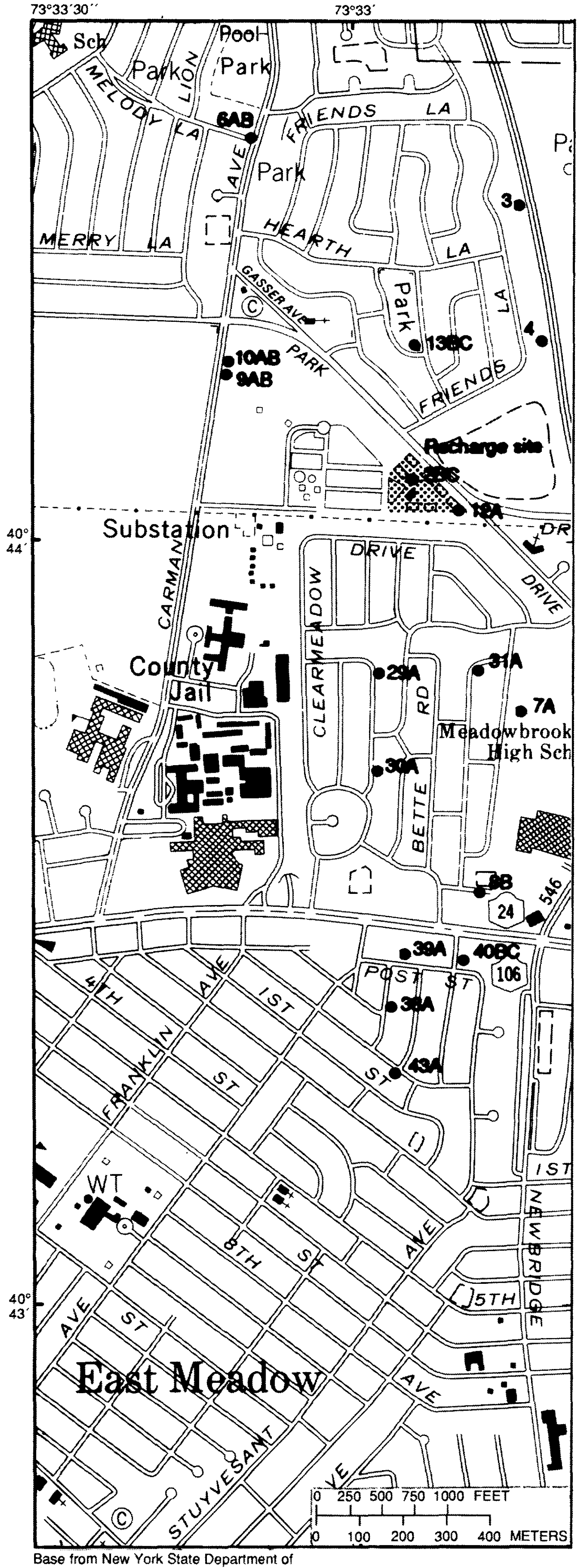
[1] Words in italics are defined in glossary (p. 46).

Table 1.—Summary of inorganic chemical analyses of ambient ground water from wells in East Meadow, N.Y., 1978-87

[Analyses by U.S. Geological Survey, Arvada, Colo. Concentrations in milligrams per liter unless specified. °C, degrees Celsius; µS/cm, microsiemens per centimeter; µg/L, micrograms per liter; <, less than]

Physical property or constituent	Number of observation well medians	Statistics from the population of observation-well medians: Minimum median	10th percentile of medians	Overall median of medians	90th percentile of medians	Maximum median
Residue, dissolved solids at 180°C	17	136	140	179	242	275
Specific conductance (field) (µS/cm at 25°C)	21	230	248	310	379	410
pH (field)	21	4.6	4.8	5.2	5.8	6.0
Alkalinity (as $CaCO_3$)	18	3	3	6	12	27
Chloride	21	19	21	30	35	42
Sulfate	21	14	17	37	42	57
Nitrate plus nitrite (as N)	21	5.5	7.7	9.9	19	24
Ammonium (as N)	18	<.01	<.01	.02	.06	.35
Sodium	21	18	20	26	31	40
Calcium	21	11	14	19	27	31
Magnesium	21	2.3	2.3	3.3	5.6	10
Potassium	21	1.5	2.0	4.8	7.2	7.4
Boron (µg/L)	9	60	60	90	140	140
Silica	21	4.9	5.9	12	15	16
Dissolved oxygen	20	2.0	2.0	4.0	8.0	13



Base from New York State Department of Transportation, Freeport NY, 1:24,000, 1981

Measurement of nitrate-plus-nitrite concentrations (expressed as nitrogen) in ambient water suggest that nitrate commonly exceeds New York State drinking-water standards. Because nitrite is an unstable nitrogen species, most nitrogen occurs as nitrate in the nitrate-plus-nitrite analyses. Of the 21 median $NO_2 + NO_3$ as N values, 48 percent exceeded or equaled the 10 mg/L nitrate standard.

Comparison of median concentrations with well-screen depths indicates that concentrations of some constituents increase or decrease with depth (appendix II). These depth variations are useful in interpreting the differences and similarities between ambient water and *plume water*. Manmade influences, such as road salt, fertilizer, and sewage, as well as differences in composition and permeability among the aquifer zones, probably account for much of the variation. The higher clay content and lower permeability of the Magothy aquifer than of the upper glacial aquifer provides greater surface area and longer contact time for interaction between aquifer material and ground water (such as cation exchange and sorption).

Organic compounds were not used in delineation of the recharge plume because the local variability of concentrations within the ambient water made them poor indicators for this purpose. Data on organic compounds within the study area are reported in Katz and Mallard (1980), Schneider and Oaksford (1986), and Schneider and others (1987).

Figure 10.—Locations of observation wells used to define ambient water quality. (Diameters and screened depths are listed in appendix I.)

EXPLANATION

● 30A **OBSERVATION WELL**--number identifies observation well site; letter denotes the well depth in relation to depth of other wells at site. Well data are given in appendix I

RECHARGE FACILITY AND QUALITY OF RECLAIMED WASTEWATER

Water used at the East Meadow recharge facility underwent tertiary treatment at the Cedar Creek water-pollution-control facility near Wantagh (fig. 1). Detailed descriptions of the plant and the recharge facility are given in Aronson (1980), Schneider and Oaksford (1986), and Schneider and others (1987). Approximately 5 Mgal/d of influent sewage, about half of which was used for recharge, underwent tertiary treatment after initial screening and grit removal. Treatment consisted of a four-step process that included: (1) chemical treatment for removal of phosphorus, suspended solids, heavy metals, and BOD (biochemical oxygen demand); (2) biological treatment for the removal of nitrogen; (3) rapid sand filtration and activated carbon treatment to decrease suspended solids and dissolved organic compounds; and (4) chlorination for disinfection.

The *reclaimed wastewater* (tertiary-treated effluent) used for artificial recharge was pumped 6.25 mi from the treatment facility (fig. 1) to the East Meadow recharge facility, where it was temporarily held in a storage tank before distribution to the recharge basins or the injection wells. The East Meadow recharge facility occupied a 35-acre site at the southeast intersection of Carman Avenue and Salisbury Park Drive (figs. 10, 11).

Design

The recharge facility included an operations building, 11 recharge basins for infiltration of reclaimed water, and five wells for direct injection of reclaimed water into the aquifer. The site also contained a sewage-treatment plant that had been abandoned in 1979 (fig. 11).

Nearly 90 percent of the reclaimed water was applied through the recharge basins; this study focused on reclaimed water from the recharge basins because they represent a more discrete source area and a more successful means of recharge than the injection wells. Injection-well design is discussed in Schneider and Oaksford (1986).

Seven of the 11 recharge basins were 50 ft wide by 100 ft long and 5 ft deep; five of these (basins 1, 4, 5, 6, and 7) had sloping walls to increase the storage area and were lined with impermeable liners to prevent infiltration through the basin sides. Two basins (basins 2 and 3) are also 50 ft by 100 ft and 5 ft deep but have vertical concrete walls that extended 4 ft below the basin floor and an observation manhole that was used for study of flow in the unsaturated zone.

Four other basins were available for temporary storage and disposal of reclaimed wastewater in the event of clogging at the first seven basins. Basin 8

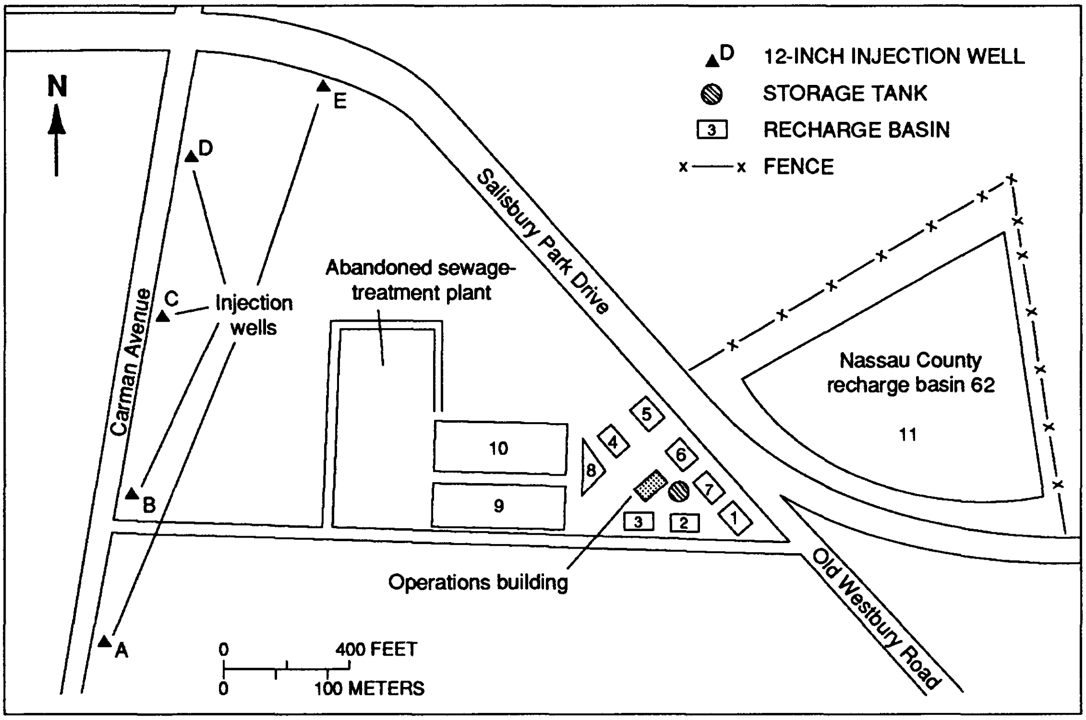


Figure 11.—East Meadow artificial-recharge site. (Modified from Schneider and others, 1987, fig. 4B.)

was designed for deep ponding experiments but was never used because the experiments were terminated earlier than originally planned. Basins 9 and 10 were shallow basins that had been used by the abandoned sewage-treatment plant for disposal of wastewater until June 22, 1979, and also had been used for the disposal of small volumes of reclaimed water during the construction and testing of the East Meadow recharge facility. Basin 62 (fig. 11) is a Nassau County stormwater basin that normally receives highway runoff. This basin was connected to the East Meadow facility and used for emergency storage and disposal of reclaimed wastewater when the primary basins needed to be bypassed for maintenance. This was necessary only a few times, and, even though flow to Basin 62 was not metered, the volume received there is assumed to have been small in relation to the total volume received by the seven primary basins.

Operation

Artificial recharge with reclaimed water continued for 15 months from October 6, 1982 through January 9, 1984. During that 460-day period, nearly 807 Mgal of reclaimed wastewater entered the upper ground-water system. Of this total, about 720 Mgal (89 percent) went to the upper glacial aquifer through the basins, and 87 Mgal (11 percent) to the upper glacial and Magothy aquifers through the injection wells. Dates, locations, and quantities of water applied are summarized in table 2. Cumulative monthly totals of water applied by basins and injection wells are plotted in figure 12. Recharge rates were highly variable; no recharge occurred during November 1982 nor from February through March 1983, and recharge through the injection wells occurred only from October through December 1983. Inflow rates into all basins ranged from about 300 to 800 gal/min, depending on the nature of the experiment and the amount of basin clogging. Recharge was shifted among basins to allow repairs to recharge and monitoring equipment, basin maintenance, and evaluation of several basin-management alternatives. More than 96 percent (694 Mgal) of the water applied to the basins was applied to basins 2, 4, 5, 6, and 7.

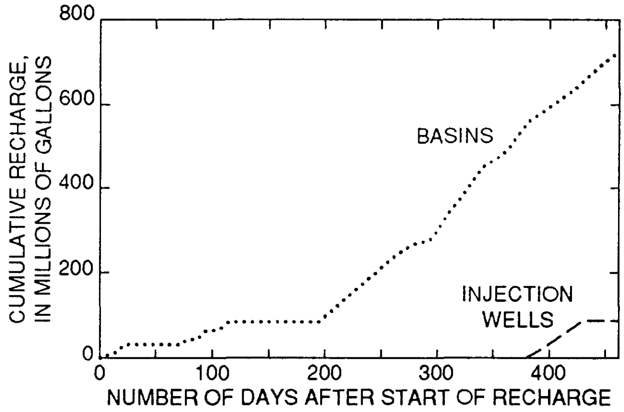


Figure 12.—Cumulative volume of reclaimed wastewater transmitted through seven recharge basins and five injection wells.

Chemical Quality of Reclaimed Water

The chemical quality of reclaimed water is summarized in table 3. The data represent reclaimed water at three locations: the Cedar Creek sewage-treatment plant before recharge, the East Meadow recharge site during recharge, and three observation wells (16B, 17A, 33A) downgradient of the site after recharge.

The concentrations of the chemical constituents of reclaimed water at all three points (table 3) were below New York State drinking-water standards and within the State Pollutant Discharge Elimination Systems permit requirements. Data from the Cedar Creek plant are the medians of median monthly reclaimed-wastewater values; this column is considered most representative of conservative and minimally reactive constituents (chloride, sodium, nitrate + nitrite) because it represents almost the entire period of recharge and includes the largest amount of data. The two other columns (recharge basins and observation wells) are included because the Cedar Creek data set does not include all constituents of interest and is not representative of reactive constituents such as ammonium. The recharge-basin data represent eight composite samples of reclaimed water taken directly from the recharge basins during recharge tests. This data set is not ideal because the number of samples is small and the sampling dates do not represent the entire period of recharge, as evidenced by the differences between median values of constituents common to both data sets.

The observation-well data provide median values of conservative and minimally reactive constituents in plume water. These data are included in table 3 to provide an estimate of the concentration of boron in reclaimed water. The samples are representative of reclaimed water because chloride concentrations indicate the samples to be approximately 95 percent reclaimed water.

Schneider and others (1987) noted relatively

Table 2.—Recharge schedule for basins 1-7 and wells A-E, from October 6, 1982 through January 9, 1984

[From Schneider and others, 1987. All values are in gallons. Basin and well locations shown in fig. 11. Dashes indicate no recharge].

Water-application dates		Duration, in days	Basins						
Start	End		1	2	3	4	5	6	7
10- 6-82	10- 8-82	2	1,100,800	--	--	--	--	--	--
10 -6-82	10-12-82	6	--	--	--	--	3,026,300	3,181,100	3,244,800
10-15-82	10-29-82	14	7,409,500	--	--	--	6,417,600	6,248,700	7,475,900
12-15-82	12-18-82	3	1,732,400	--	--	1,537,800	--	1,580,500	1,608,200
12-22-82	12-24-82	2	1,076,200	--	--	989,800	--	974,800	1,005,200
12-30-82	1- 8-82	9	5,004,000	--	--	4,563,500	--	4,525,200	4,645,400
1-14-83	1-19-83	5	--	--	--	--	--	--	2,848,400
1-17-83	1-29-83	12	6,490,300	--	--	--	--	--	--
1-14-83	1-29-83	15	--	--	--	--	--	6,954,100	--
1-19-83	1-29-83	10	--	--	--	4,844,000	--	--	--
4-18-83	6-20-83	63	--	--	--	31,085,450	41,561,200	30,876,400	37,289,100
6-20-83	6-23-83	3	--	--	2,924,200	--	1,790,700	2,043,000	--
6-23-83	7-10-83	17	--	--	--	7,769,700	6,786,000	7,627,000	10,133,100
7-15-83	7-18-83	3	--	--	--	1,356,000	827,600	--	--
7-18-83	7-26-83	8	--	8,438,400	--	--	--	--	--
7-26-83	9- 6-83	43	--	41,171,100	--	--	36,001,400	37,203,500	40,666,500
9- 6-83	9-12-83	6	--	6,522,600	--	4,064,810	3,592,400	--	5,977,800
9-12-83	10- 3-83	21	--	19,669,560	--	--	--	--	17,968,800
10- 3-83	10-20-83	17	--	15,922,000	--	14,830,100	19,484,250	--	16,804,800
10-20-83	10-30-83	10	--	9,645,060	--	--	--	--	8,998,100
10-31-83	12- 5-83	35	--	33,696,000	--	--	--	--	31,726,080
12- 5-83	12-31-83	26	--	14,826,240	--	[a]2,395,200	20,007,360	14,774,400	[b]6,048,000
12-31-83	1- 9-83	9	--	3,219,840	--	--	8,049,600	7,740,000	--
		Totals	22,813,200	153,110,800	2,924,200	73,436,360	147,544,410	123,728,700	196,440,180

Water-application dates		Duration, in days	Injection wells				
Start	End		A	B	C	D	E
10- 5-83	10- 6-83	1	--	--	--	370,500	480,500
10-20-83	12- 5-83	45	22,724,640	22,366,080	18,691,200	17,028,360	--
12- 7-83	12-11-83	4	--	1,872,000	1,526,400	1,411,200	864,000
		Totals	22,724,640	24,238,080	20,217,600	18,810,060	1,344,500

[a] Operated for 56 hours.

[b] Operated for 6 hours.

little change in the quality of reclaimed water as it moved through the unsaturated zone to the water table during extended periods of recharge but noted changes in the concentrations of several cations and total phosphorus at the start of recharge periods. These changes are attributed to cation exchange and adsorption. Chloride, sodium, sulfate, and nitrate + nitrite as N did not change appreciably as they moved through the unsaturated zone. No data on boron in the unsaturated zone are available.

Table 3.—Physical properties and inorganic constituents of reclaimed water from the Cedar Creek water-pollution-control facility and recharge basins, and plume water from three observation wells.

[All concentrations in milligrams per liter unless specified. °C, degrees Celsius; µS/cm, microsiemens per centimeter; µg/L, micrograms per liter. Dash indicates no data.]

Physical property or constituent	Cedar Creek effluent[1]	Eight recharge basins (composite samples)			Observation wells[2] (3-well composite)
	Median	Minimum	Median	Maximum	Median
Residue dissolved solids at 180 °C	--	410	480	578	--
Specific conductance (field) (µS/cm at 25 °C)	--	700	810	1,040	--
pH (field)	7.5	6.3	6.5	7.1	--
Alkalinity (as $CaCO_3$)	--	144	151	166	--
Chloride	156	110	120	180	150
Sulfate	--	63	74	98	94
Nitrate and nitrite (as N)	.76	.45	.57	1.2	--
Ammonium (as N)	.7	<.01	.03	.05	--
Sodium	110	93	95	160	99
Calcium	--	49	52	56	--
Magnesium	--	6.7	8.3	13	--
Potassium	--	12	12	13	--
Boron (µg/L)	--	--	--	--	220
Silica	--	11	12.5	14	--
Dissolved oxygen	--	4	7	9	--

[1] From Schneider and others (1987)

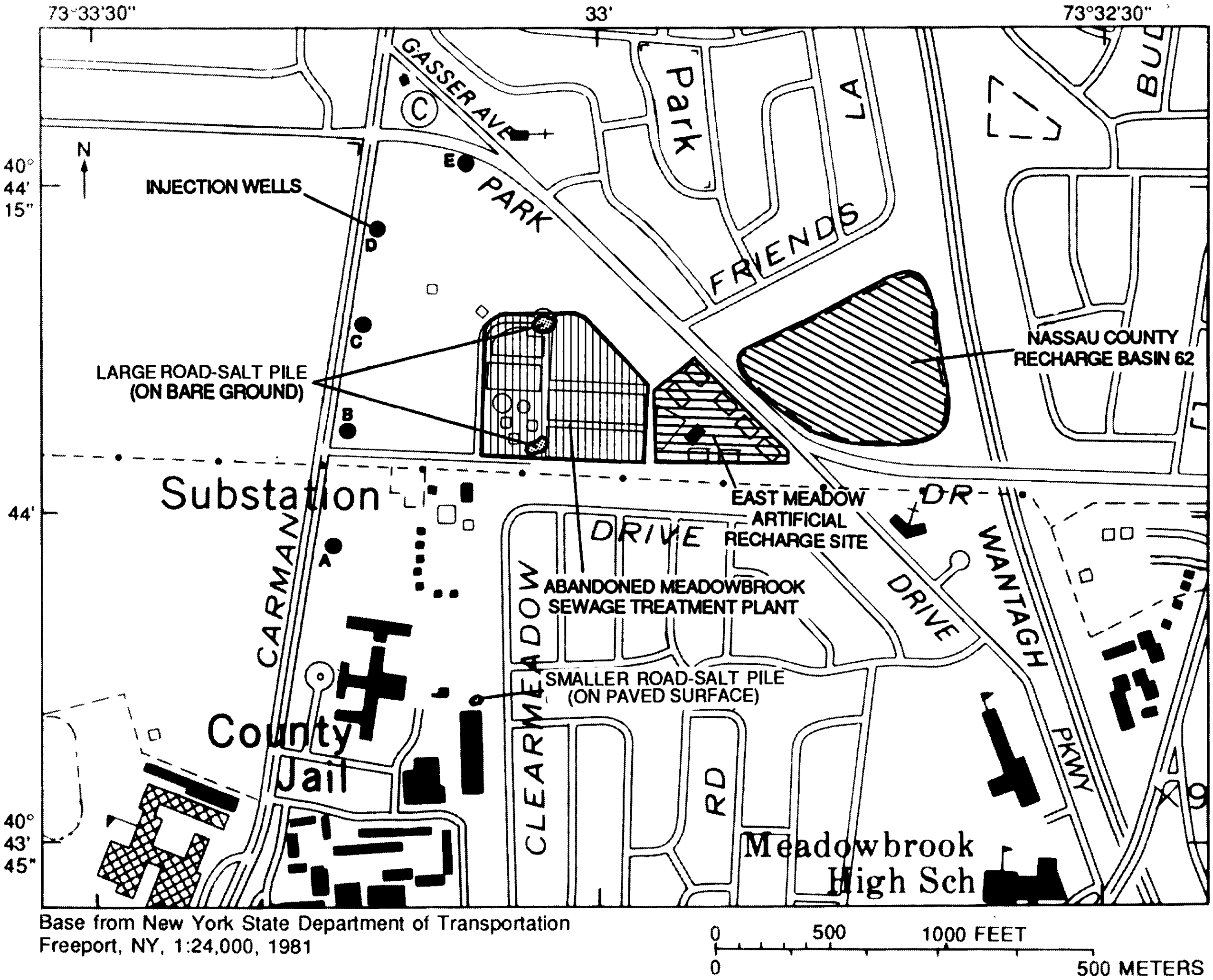
[2] Wells N10517 (33A), N10171 (17A), and N10163 (16B), from March 1987 sampling. (Locations are shown in fig. 2.)

FACTORS THAT AFFECT THE DEFINITION OF AMBIENT GROUND WATER AND DELINEATION OF THE RECHARGE PLUME

Ideally, delineation of plume water in the aquifer system would be based solely on chemical differences between ambient and reclaimed water. In developed areas, such as the study area, however, introduction of solutes from local manmade sources may cause ground-water quality to differ from the ambient conditions described earlier and thereby make delineation more difficult. Four potential interferences have been identified near the recharge site: (1) the abandoned Meadowbrook sewage-treatment plant, (2) uncovered road-salt stockpiles, (3) stormwater basin 62 and other local stormwater basins, and (4) reclaimed water that was applied through the injection wells during the 1982-84 recharge study (fig. 13). Each of these sources affects the ambient water in a specific way that could obscure the boundaries of the recharge plume. Thus, thorough examination of chemical and historical data is essential to distinguish recharge-plume water from ground water affected by these sources.

The differences among waters influenced by differing sources can be illustrated through Stiff and trilinear diagrams. Both are used here because each accentuates a different aspect of water composition. Stiff diagrams allow a direct comparison of concentrations of major constituents within a single sample or among a number of samples. Trilinear diagrams depict the percentage of cations and anions in a sample on trilinear and diamond plots (fig. 14). This type of diagram can group samples of wide-ranging concentrations within a specific area if the proportions of constituents are similar and can indicate the "path" of the chemical evolution of the ground water at a given sampling point. Although the grouping of cations (Ca, Mg, K) and anions (Cl^- and SO_4^{-2}) on the diamond plot may mask some local differences in the concentration of individual constituents, they can usually be detected in the trilinear part of the plot or in corresponding Stiff diagrams. Therefore, the effects of local contaminant sources can often be identified through a combination of these diagrams and historical data (for example, age and nature of the source), and this identification improves the delineation of the plume water. The trilinear and Stiff diagrams in figure 14 depict the chemical composition of ambient water, reclaimed water, stormwater, and waters affected by the abandoned secondary-treatment plant and road salt. (Injected reclaimed water has the same composition as that used during infiltration tests at the recharge basins.)

The data used for these diagrams are considered representative of each source. Ambient- and reclaimed-water data are median values from tables 1 and 3, respectively. Stormwater data are averages from surface water entering five basins in Nassau and Suffolk Counties that were examined by Ku and



Base from New York State Department of Transportation
Freeport, NY, 1:24,000, 1981

Figure 13.—Locations of local sources of influence on water quality with respect to the East Meadow artificial-recharge site. (Location is shown in fig. 10.)

Simmons (1986). Data on secondary-treated effluent from the Meadowbrook sewage-treatment plant are a composite of median chloride concentrations measured at the plant over the last 5 years of operation and other constituents measured in a shallow-ground-water sample from the plant while it was in operation. Road-salt data are from a single sample, collected at the storage site, that was dissolved in distilled water to a specific conductance of 934 µS/cm.

Figure 14 suggests considerable chemical differences among the sources, but, as water from each source moves downgradient, hydrodynamic dispersion and chemical retardation (described further on) alter the composition and obscure the differences. Ground water downgradient will not plot near the representative source position on the trilinear diagram, but rather, somewhere between it and the position of ambient water or plume water.

Meadowbrook Sewage-Treatment Plant

The Meadowbrook sewage-treatment plant discharged secondary-treated effluent to recharge basins during 1951-79. The resulting zone of influence extends downgradient from the recharge basins beyond the southern boundary of the study area (fig. 15). Secondary-treated effluent has significantly higher concentrations of organic carbon, ammonium, and nitrate and lower concentrations of dissolved oxygen and most other major ions than reclaimed water. By 1987, nearly 8 years after the cessation of recharge with secondary-treated effluent, conservative and minimally reactive constituents such as chloride and sodium had been transported beyond the study area, except in zones of low permeability, whereas reactive constituents such as ammonium, potassium, and calcium, remained.

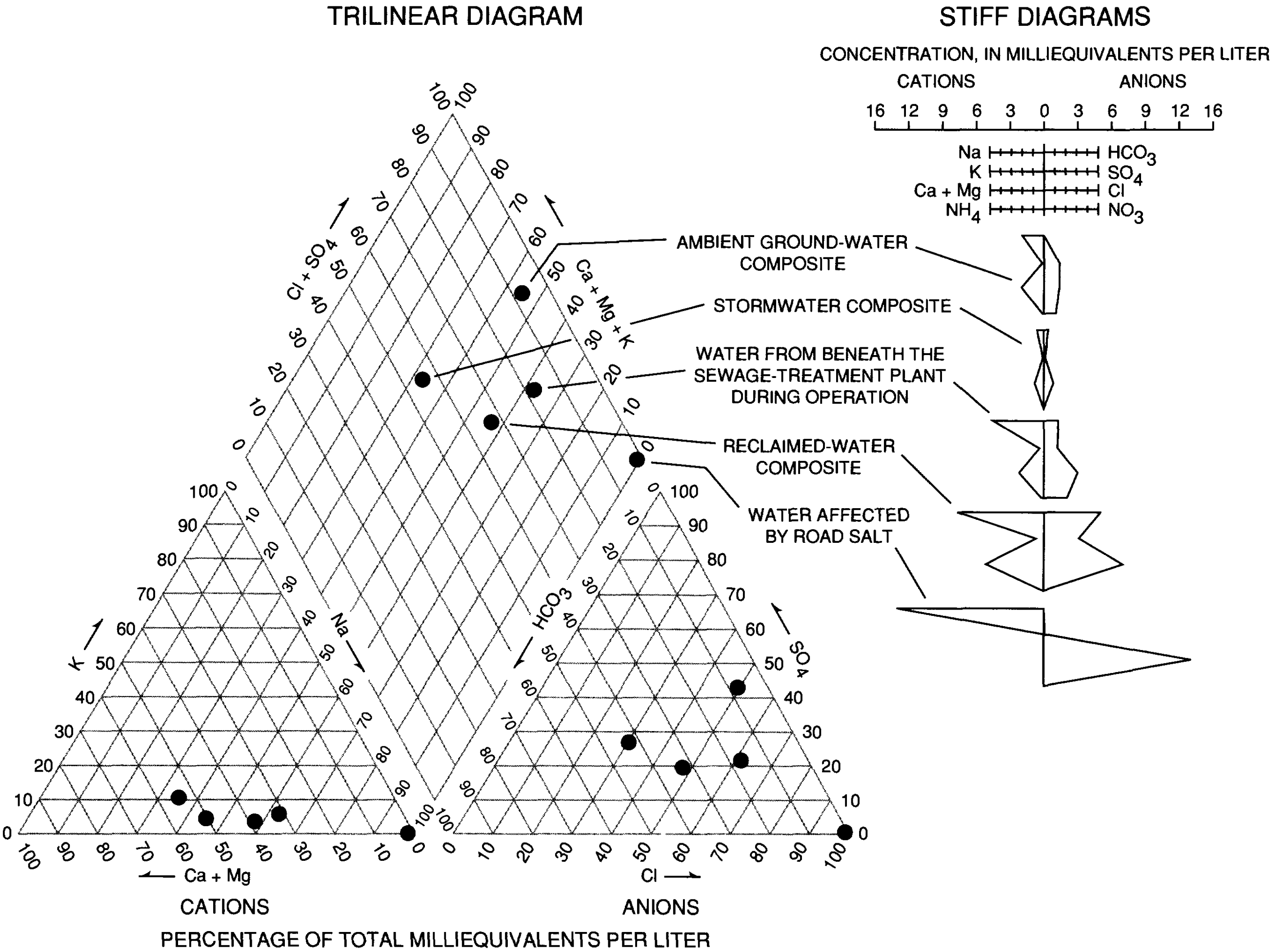


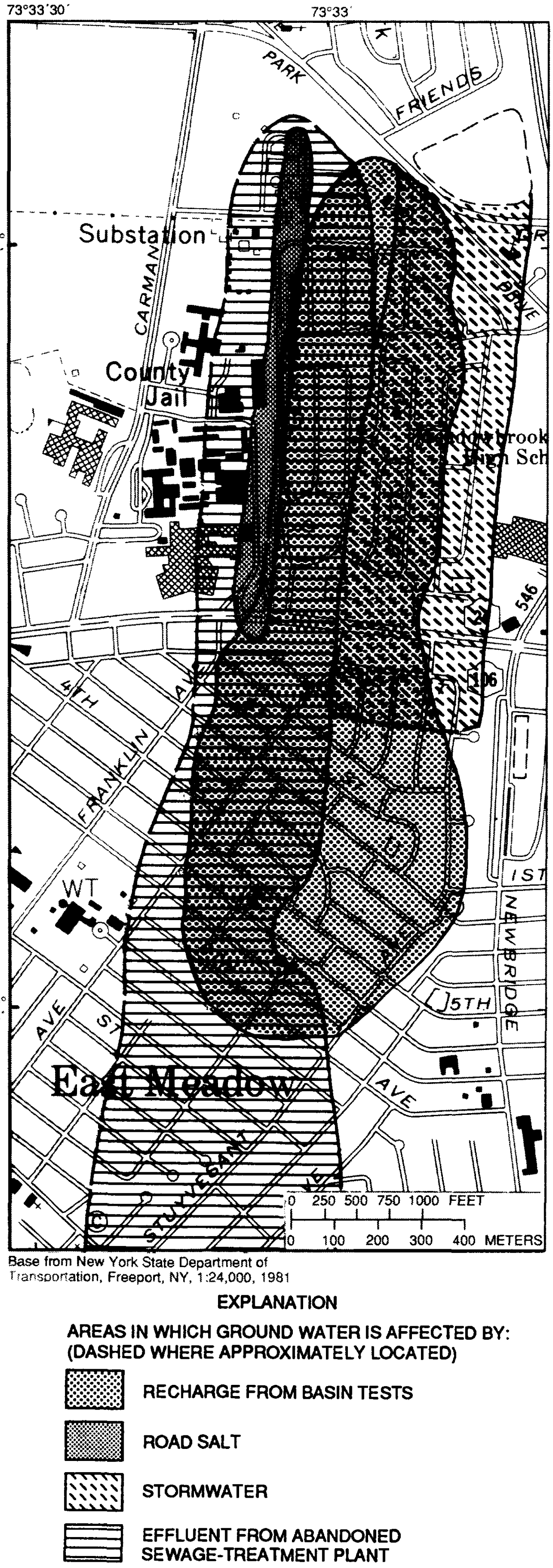
Figure 14.—Trilinear and Stiff diagrams showing chemical quality of ambient ground water, reclaimed water, and water influenced by three manmade solute sources at East Meadow. (Source locations are shown in fig. 13.)

Road-Salt Stockpiles

Road-deicing salt has been stored outdoors and uncovered during winter at two sites within the study area (fig. 13). The larger source is a stockpile that has been stored since the 1984-85 winter on bare, permeable soil at two alternating locations within the abandoned Meadowbrook sewage-treatment plant site (Edward Donahue, Town of Hempstead, oral commun., 1988); the smaller stockpile has been observed on a paved surface about 500 ft downgradient of the larger pile (fig. 13). The larger stockpile is probably the primary source of salt leachate to the ground-water system. Analysis of a salt sample from the larger stockpile revealed it to be relatively pure sodium chloride. Ground water containing road salt can be distinguished from parts of the recharge plume with similar chloride and sodium concentrations by a lack of sulfate. By May 1988, ground water containing road salt extended at least 3,000 ft downgradient of the larger pile (fig. 15).

Storm Runoff to Nassau County Recharge Basin 62

Storm runoff that enters Nassau County recharge basin 62 (fig. 13) affects both the flow patterns and chemistry of ground water within the study area. The drainage area served by this basin is about 420 acres, which includes a section of Wantagh Parkway (fig. 13) (Seaburn and Aronson, 1973). About 71 Mgal of water is routed to this basin each year, according to estimates by Ku and Simmons (1986). A large storm could deliver a "slug" of stormwater exceeding 1 Mgal to this basin. Ku and Simmons (1986) reported lower concentrations of major ions in stormwater than in ambient ground water within the study area, except in winter and early spring, when stormwater may contain elevated concentrations of chloride and sodium from road-deicing salt. Stormwater from basin 62 is characterized by low concentrations of nitrate + nitrite, and sulfate and low specific conductance. When stormwater mixes with the recharge plume, the plume becomes diluted. The extent of stormwater influence, which is limited to the upper glacial zone, is evident for 3,000 ft downgradient from basin 62 (fig. 15).



Base from New York State Department of Transportation, Freeport, NY, 1:24,000, 1981

Figure 15.—Areas affected by local influences on ground-water quality in relation to the recharge plume, March 1987. (Locations of these influences are shown in fig. 13.)

Injection Wells

Reclaimed water that was applied through injection wells during the 1982-84 recharge experiments (fig. 13) could mix with reclaimed water from the basins as it moves downgradient. Both waters had the same chemical composition before recharge. Although data on the extent of the *injected water* are scant, differences between the modes of recharge, the locations, the timing, and the volumes of recharge may be sufficient to enable distinction between the two. Injected water was applied through wells screened between 25 and 55 ft below the water table (intermediate zone), and injection was essentially continuous, in contrast to the basin operations. The injection operations were also of much shorter duration and began near the end of the basin tests (fig. 12). As a result, the plume of injected water should be less diffused in the aquifer than the reclaimed water that was applied through the basins and should be moving more slowly because it is in a zone of lower permeability. Delineation of injected water was beyond the scope of the study, however.

DISTRIBUTION OF CHEMICAL CONSTITUENTS AND PHYSICAL PROPERTIES OF THE RECHARGE PLUME IN THE THREE DEPTH ZONES

The distribution of recharge-plume water is discussed in this section with reference to the north-south vertical sections in plate 1, which depict the longitudinal extent of 11 constituents and physical properties. This section was chosen to focus on plume water and to minimize the discussion on water affected by the local influences discussed in the previous section. Each constituent is discussed in terms of its individual extent within the study area. The maximum extent of the recharge plume, as discussed in a later section, is not defined by the distribution of any single constituent but by the sum or union of several constituent distributions.

Where plume water had higher concentrations of a given constituent than ambient water, the concentration or value used to differentiate ambient water from plume water for each constituent was the average of the overall median and the 90th percentile median of ambient-water from table 1. Conversely, where plume water had lower concentrations of a given constituent (for example, nitrate + nitrite), the concentration or value used to differentiate ambient water from plume water was the average of the overall median and the 10th percentile median of ambient-water from table 1. These cutoff criteria were used rather than the 10th or 90th percentile median values of table 1 because (1) some wells chosen as representative of ambient conditions could be affected by unidentified upgradient source(s), and (2) most wells in highly developed areas are probably affected by transient water-quality conditions. The outermost concentration contour in each vertical section on plate 1, excepting nitrate + nitrite and pH, represents this value and generally encloses the area with concentrations greater than those in ambient water. The nitrate + nitrite contour value encloses the area with concentrations lower than that in ambient water because nitrate + nitrite concentrations in reclaimed water are lower than in ambient water. The wide range of pH values above and below ambient-water levels within the plume water led to the use of unit pH contour values.

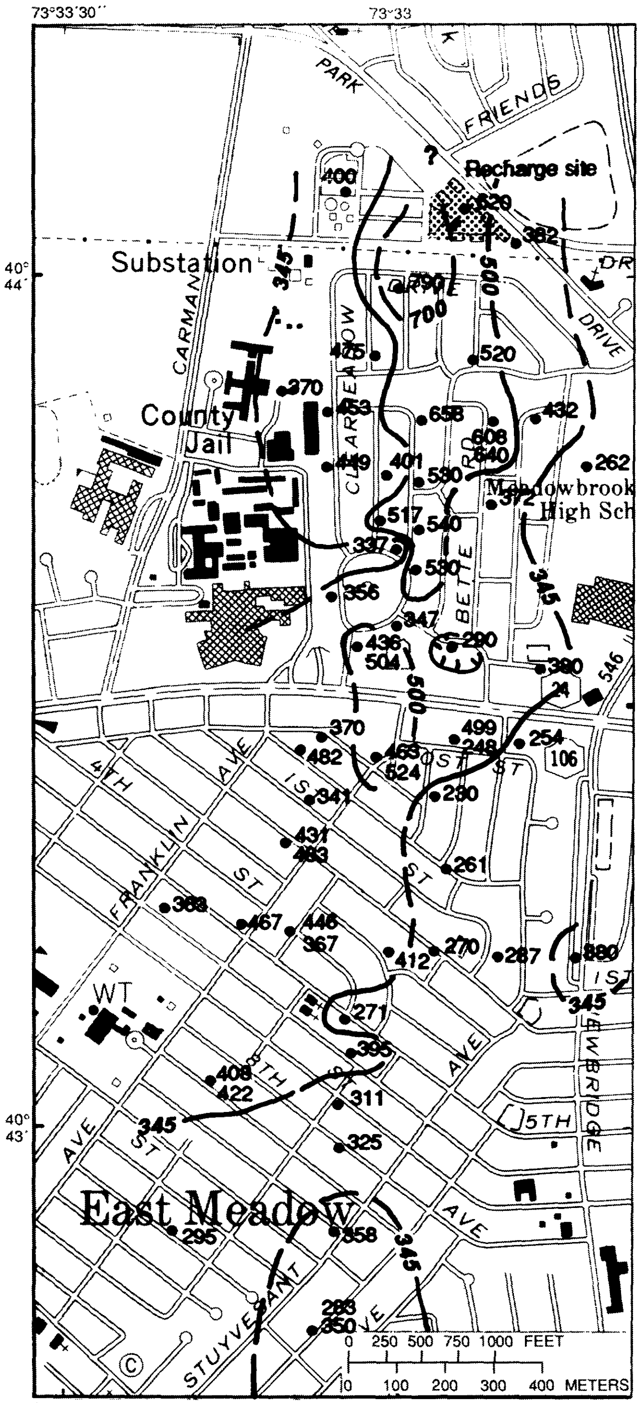
Differentiation of plume water from water derived from local point sources was based on differences in source chemistry, as described in the previous section.

Specific Conductance

Specific conductance is a measure of a solution's ability to conduct electricity. The conductivity is caused by the presence of charged ionic species (Hem, 1986) and, thus, provides an indication of the total ion concentration. Specific conductance is a useful indicator of plume water in the study area because reclaimed water has a median of 810 µS/cm, whereas ambient water has a median of 310 µS/cm. Plume water is defined by conductance values exceeding 345 µS/cm. This definition is not unique to plume water, however, because values greater than 345 µS/cm are common in water affected by other local influences.

Upper Glacial Zone

The leading and trailing edges of plume water with elevated specific conductance in the upper glacial zone extend approximately 6,200 and 1,200 ft downgradient from the recharge site, respectively (pl. 1). Water with specific conductance values greater than 345 µS/cm within the study area extends laterally beyond the observation-well coverage (3,200 ft) because it is affected by other influences. The absence of elevated specific conductance within the first 1,200 ft downgradient from the recharge site reflects the transport of conservative constituents



Base from New York State Department of Transportation, Freeport, NY, 1:24,000, 1981

EXPLANATION

●325 OBSERVATION WELL--number is specific conductance, in microsiemens per centimeter

345 LINE OF EQUAL SPECIFIC CONDUCTANCE, in microsiemens per centimeter. Dashed where approximately located

Figure 16.—Distribution of specific conductance in the intermediate zone, March 1987.

within the highly permeable upper glacial zone. The slightly elevated values beneath and upgradient from the recharge site are probably due to another influence, such as road salt.

Intermediate Zone

The leading edge of specific conductance values associated with plume water in the intermediate zone closely matches that in the upper glacial zone, which further suggests that parts of the intermediate zone are nearly as permeable as the upper glacial zone. The distribution of specific conductance within the intermediate zone differs from that in the upper glacial zone in three respects (fig. 16): the primary difference is the persistence of high values directly beneath and immediately downgradient of the recharge site, which indicates little movement or dilution of plume water as a result of the lower permeability (higher clay-silt content) here than in the upper glacial zone, particularly beneath the recharge site. The second difference, which reflects the intermittent nature of recharge, is the irregular distribution of specific conductance values with depth in the intermediate zone. The third difference is that the downgradient section of water with high specific conductance in this zone is much narrower (about 2,000 ft wide) than in the upper glacial zone and trends more toward the southwest (fig. 16)in response to permeability differences.

Local areas of low permeability in the intermediate zone (fig. 7A) appear to cause ground water from two sources—the abandoned plant and the recharge basins—to move into the same area at the downgradient end of the longitudinal section. The zone of elevated specific conductance at the south end of the study area (fig. 16) is attributed to lingering secondary-treated effluent from the abandoned sewage-treatment plant because it contains elevated concentrations of ammonium, nitrate + nitrite, and boron. The elevated specific conductance along the eastern side of the study area is from an unidentified source.

Magothy Zone

Specific-conductance distribution within the Magothy zone is characterized by an area of high values beneath the recharge site and within an area about 1,300 ft wide that extends 1,100 ft downgradient. The small size of the area with elevated conductance values suggests that only a small amount of reclaimed water reached this zone, and the limited downgradient extent and high conductance values reflect the lack of significant movement through the Magothy zone. The presence of elevated ammonium concentrations at wells 29A and 15A in association with high conductance values indicates that the high conductance in this area is associated with recharge from the abandoned sewage-treatment plant.

Chloride and Sodium

Ambient ground water typically contains less than 33 mg/L chloride and less than 29 mg/L sodium; the elevated chloride and sodium concentrations within the study area can be attributed to plume water as well as water affected by several identified and unidentified local influences. The distribution of chloride and sodium values associated with plume water is similar within each of the three depth zones. The conservative nature of chloride and the similarity in location and shape of the chloride distribution to that of sodium indicate that sodium is only slightly reactive, in accordance with findings of Wexler and Maus (1988), LeBlanc (1984), Nicholson and others (1983), Kimmel and Braids (1980), and Kaufman and Orlob (1956).

Upper Glacial Zone

Within the upper glacial zone, sodium is transported at a slightly slower rate than chloride, probably as a result of cation-exchange processes (pl. 1). The leading edges of elevated chloride and sodium are 6,500 ft and 6,250 ft downgradient of the recharge site, respectively, and the trailing edges are 900 to 2,300 ft and 900 ft downgradient, respectively. The range of downgradient distance values of the trailing edge of the chloride distribution reflects the uncertainty as to the source of slightly elevated chloride concentrations in the area. The maximum lateral (east-west) extent of chloride and sodium associated with the recharge plume in the upper glacial zone is masked by outside influences, and slightly elevated chloride concentrations beneath the recharge site and elevated chloride and sodium concentrations upgradient of the site indicate the presence of an outside source.

Intermediate Zone

In the intermediate zone, local variations in permeability confine chloride and sodium to a southwest-trending plume south of Route 24. The area of elevated concentrations close to the recharge site is wider than in the downgradient section, and its shape is similar to that of specific conductance. Chloride and sodium concentrations in ground water beneath the recharge site are well above those in ambient water. Although the concentrations have been decreasing through time, they still contrast markedly with the low values in the upper glacial zone. The maximum downgradient extent of sodium and chloride is similar to that in the upper glacial zone, but the area of highest concentrations in the intermediate zone remains close to the recharge site because the local areas of low permeability that prevent rapid movement. Overall, concentrations of both constituents are higher in the intermediate zone than in the upper glacial zone as a result of the greater dilution and more rapid flow in the upper glacial zone.

The irregular distribution of concentration and depth of influence of conservative and slightly reactive constituents such as chloride and sodium ions, particularly in the intermediate zone, is probably the result of two factors. First, local differences in clay-silt content in the two lower zones influence the velocity and direction of flow, and second, the application of reclaimed water was neither continuous nor at a constant rate (fig. 13 and table 2), and thereby resulted in local variations of the plume-water component within the system.

Magothy Zone

The extent of elevated chloride and sodium concentrations within the Magothy zone resembles the extent of elevated specific conductance. The elevated sodium and chloride concentrations at well 16A (pl. 1) are not attributed to plume water, but, like specific conductance, to recharge from the former sewage-treatment plant. The elevated chloride and sodium values within the recharge plume extend about 1,000 ft downgradient from the artificial-recharge site and are about 1,000 ft wide.

The distribution of sodium in the Magothy zone is virtually identical to that of chloride, either because the effects of cation exchange are insignificant within the short distance in which they have traveled, or because the concentrations of more reactive cations, such as potassium, calcium, and magnesium, are sufficient to inhibit significant adsorption of sodium.

Sulfate

Sulfate concentrations of 40 mg/L or more in the upper glacial and intermediate zones typically denote the presence of plume water or secondary-treated wastewater. The sulfate concentrations in ambient water in the Magothy zone are higher than in the other two zones, otherwise the distribution of sulfate associated with plume water in each zone is similar to that of chloride.

Upper Glacial Zone

The downgradient extent of elevated sulfate concentrations in the upper glacial zone is the same as the extent of elevated chloride concentrations, about 6,500 ft, but sulfate concentrations are only 2 mg/L greater than the ambient-water "cutoff" concentration for nearly 1,000 ft upgradient from the leading edge of the recharge plume, whereas chloride concentrations increase steadily over the same distance. Mechanisms for sulfate attenuation include sulfate reduction, precipitation of sulfate minerals, and anion exchange. Sulfate reduction here, though, does not appear to be an important attenuation mechanism because the ground water contains measurable oxygen as well as nitrate, which is reduced before sulfate. Precipitation of sulfate minerals is not considered likely because analysis of ground-water chemistry by WATEQ (Plummer and others, 1976) does not indicate saturation with respect to any sulfate minerals. The most plausible explanation for sulfate attenuation is anion exchange. The ferric oxyhydroxide coatings on the aquifer particles and the acidic ground water (pH 3.8 to 4.0), particularly at the leading edge of the recharge plume, are conducive to anion exchange (Nicholson and others, 1983; Wood, 1978; Stumm and Morgan, 1981; and Drever, 1982). A similar attenuation of sulfate downgradient of a landfill in similar hydrogeologic settings has been observed by Nicholson and others (1983) and Apgar and Langmuir (1971).

The trailing edge of sulfate associated with the recharge plume is about 2,000 ft downgradient of the recharge site, which indicates minimal reactivity of sulfate under slightly acidic (pH 5.3 to 6.6) conditions. The maximum width of the elevated sulfate body associated with the recharge plume is at least 3,000 ft. Delineation of the actual width of the elevated sulfate body is hampered, however, by sulfate from an unidentified source along the west side of the plume.

Ground water from two wells that tap the upper glacial and intermediate zones north of the artificial-recharge site has sulfate concentrations above ambient levels, but these are attributed to an outside influence because chemical data show no evidence of plume water at this site.

Intermediate Zone

The sulfate distribution within the recharge plume in the intermediate zone is similar to that of chloride and sodium in that concentrations are highest close to the recharge site, and movement is constrained downgradient by clay-silt zones and trends southwestward. The distribution of sulfate in this zone differs from that of sodium and chloride in that the concentrations downgradient of the leading edge of the recharge plume are elevated, whereas those of sodium and chloride are not. Sulfate in this location is probably derived from secondary-treated water from the abandoned sewage-treatment plant. The persistence of sulfate in this area suggests that it is more attenuated than sodium.

Magothy Zone

The extent of elevated sulfate within the Mag-othy zone resembles that of elevated specific conductance. Elevated concentrations at wells 15A and 29A (pl. 1) are probably derived from secondary-treated sewage. The elevated concentrations downgradient of these wells may reflect ambient ground water; the median sulfate concentration at the only deep observation well that represents ambient water in the Magothy zone was 46 mg/L (appendix I), which is higher than the overall ambient "cutoff" value (40 mg/L).

Boron

Boron is a common trace element in both reclaimed water and secondary-treated wastewater and was introduced into the shallow ground-water system in Nassau County through cesspools before the installation of sanitary sewers. Boron is derived primarily from detergents (LeBlanc, 1984; Kimmel and Braids, 1980).

Data on boron in reclaimed water are lacking, but concentrations as high as 220 µg/L were recorded in plume water from wells immediately downgradient of the recharge site after the cessation of recharge (table 3). Boron concentrations in the range of 400 to 500 µg/L have been recorded in secondary-treated effluent from a facility on Cape Cod similar to the Meadowbrook plant (LeBlanc, 1984). Boron derived from the reclaimed and secondary-treated waters is defined by concentrations exceeding 115 µg/L.

The median boron concentration in ambient water is 90 µg/L. Data in appendix II indicate a substantial increase in boron concentrations from the shallowest ground water in the study area (0 to 10 ft below water table) to the deepest (50 to 65 and 86 ft below water table).

Upper Glacial Zone

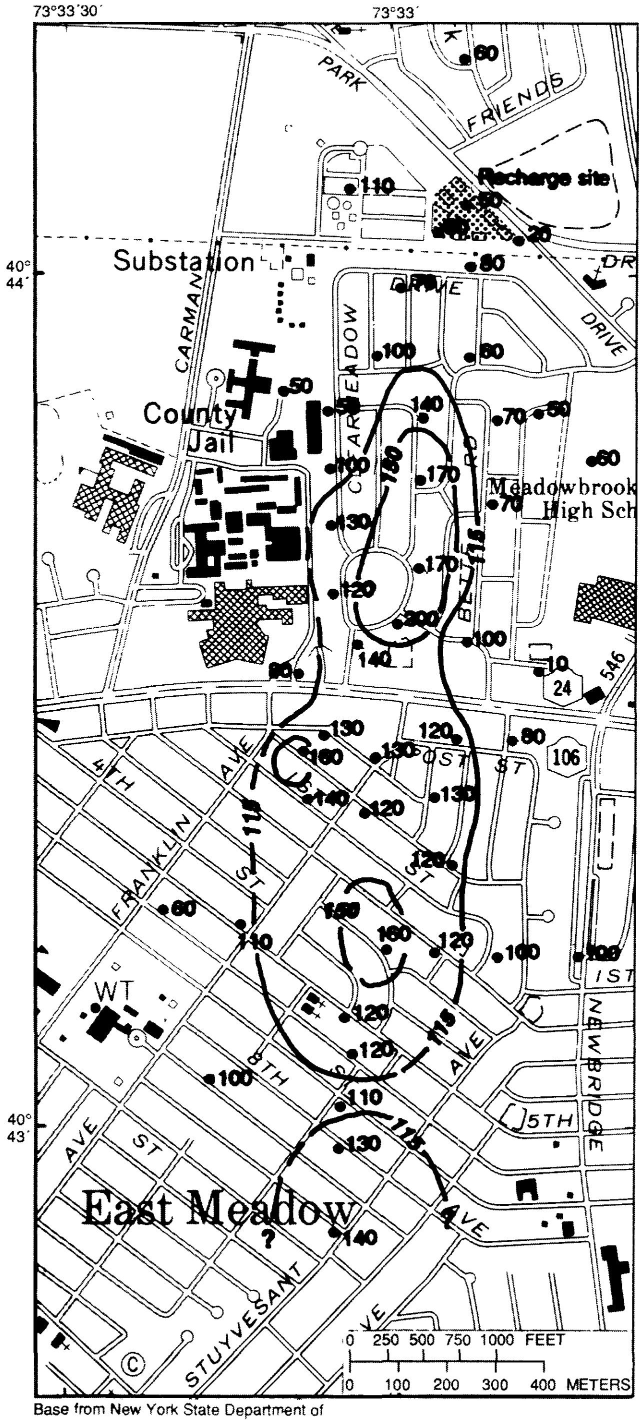
The distribution of boron in the upper glacial zone is depicted in figure 17. Boron is a good indicator of the dimensions of the recharge plume because it is not characteristic of any of the local water-quality influences discussed earlier except secondary-treated water. Boron associated with the recharge plume is represented by the larger contoured area in figure 17. The maximum downgradient extent of boron is about 5,900 ft; the maximum width is about 1,500 ft, and the trailing edge is about 900 ft downgradient of the artificial-recharge site. The low precision of the measurements (±10 μg/L) and the small differences in concentration around the leading edge of the plume limit confidence in the downgradient limit of boron associated with the recharge plume. The extent of boron associated with the recharge plume, with high concentrations at the upgradient end, indicate that boron is more reactive than sodium or sulfate. The attenuation of boron in similar hydrogeologic settings was not reported by LeBlanc (1984) or Kimmel and Braids (1980) but has been observed in soils containing clay and iron oxides (Elrashidi and O'Connor, 1982; Keren and Gast, 1981; Goldberg and Glaubig, 1985).

Boron associated with secondary-treated sewage was detected in samples from the two southernmost upper glacial-zone wells (51B, 52B, fig. 17). This interpretation is supported by ammonium concentrations of at least 0.04 mg/L and elevated nitrate + nitrite concentrations in the same samples. The presence of elevated boron concentrations and the absence of elevated chloride, sodium, and sulfate concentrations at this location suggest that boron is being transported at a slower rate than the latter constituents in this zone.

Intermediate Zone

The downgradient extent of boron associated with the recharge plume within the intermediate zone is slightly less than that in the upper glacial zone (pl. 1). The zones of highest boron concentration and the shape of the boron body associated with the recharge plume reflect local variations in silt-clay content and are similar to those of chloride, sodium, and sulfate.

Elevated concentrations of boron from secondary-treated wastewater persist in the intermediate zone downgradient of the recharge plume and parallel those in the upper glacial zone. The higher concentrations in the intermediate zone result from lower permeability and less mixing in this zone.



Base from New York State Department of Transportation Freeport, NY, 1:24,000, 1981

EXPLANATION

●120 OBSERVATION WELL--number is boron concentration, in micrograms per liter

115 LINE OF EQUAL BORON CONCENTRATION, in micrograms per liter. Contour interval variable. Dashed where approximately located

Figure 17.—Distribution of boron within the upper glacial zone, March 1987.

Magothy Zone

Elevated boron concentrations observed throughout the Magothy zone correspond to general increase in ambient boron concentrations with depth, as illustrated by box plots in appendix II. The lowest value of boron in the Magothy zone (140 µg/L) is greater than the "cutoff" concentration for ambient water (115 µg/L), but the concentration at the deepest well and several intermediate-depth wells used in the ambient-ground-water data set was 140 µg/L. When this concentration is contoured, the distribution of elevated boron concentrations associated with the recharge plume and secondary-treated water is similar to that of sulfate.

Nitrate + Nitrite

Unlike other constituents, nitrate + nitrite characteristically has lower concentrations in reclaimed water than in most ambient water and all secondary-treated water (table 1; appendix I) as a result of the denitrification step during the advanced wastewater-treatment process. Low nitrate + nitrite concentrations in ambient ground water are occasionally observed in the shallowest zone, as shown in the box plot in appendix II. The "cutoff" concentration for nitrate + nitrite is 8.8 mg/L as N. The poor distinction between plume water and ambient water is probably due to the relatively small difference between median values for the two and, in areas affected by secondary-treated effluent, the addition of nitrate through biologically mediated oxidation of residual ammonium (nitrification). Nitrate + nitrite concentrations associated with the recharge plume are anomalously high (5 to 7 mg/L as N), given the low concentrations in the reclaimed water (table 3). In areas not affected by secondary-treated effluent, the only plausible explanations appear to be local variation in reclaimed-water chemistry or nitrate influx from an unidentified source. Because nitrate + nitrite values within the west half of all three depth zones were influenced by secondary-treated wastewater, the delineation of recharge plume water from nitrate + nitrite data is questionable.

Nitrate + nitrite concentrations below 8.8 mg/L are considered to represent plume water unless they are from shallow observation wells (less than 10 ft below the water table). In an environment with measurable dissolved oxygen, such as ambient water or plume water, nitrate is relatively stable (Behnke, 1975) and would be expected to move conservatively unless nitrification is occurring within the aquifer material.

Upper Glacial Zone

The maximum longitudinal extent of plume water in the upper glacial zone, as indicated by a lack of nitrate + nitrite, is about 5,900 ft downgradient of the recharge site. The downgradient extent of low nitrate + nitrite concentrations is less than that of elevated chloride concentrations. The trailing edge and lateral dimensions of plume water with low nitrate + nitrite concentrations are obscured by the low values associated with stormwater recharge (basin 62) to the east and low values in ambient water to the west and north.

A high nitrate + nitrite concentration at the southernmost well (52B) indicates the influence of secondary-treated effluent or ambient ground water. The distribution of elevated nitrate + nitrite values is similar to those of other constituents that are characteristic of secondary-treated effluent, such as boron and ammonium.

Intermediate Zone

The plume of low nitrate + nitrite concentrations in the intermediate zone extends as far downgradient as in the upper glacial zone. Concentrations are elevated at several wells where ambient water or secondary-treated effluent are present; however, all other minimally reactive and conservative constituents at the wells indicate plume water (wells 2B, 25A, 26B, pl. 1). The elevated nitrate + nitrite concentration at well 2B, beneath the recharge site, strongly suggests that the concentrations in the recharge water may not have been consistently as low as indicated by the data. Elevated nitrate + nitrite concentrations (≥ 14 mg/L) downgradient from the recharge plume are attributed to secondary-treated sewage by their association with ammonium, boron, and sulfate.

Magothy Zone

The recharge plume in the Magothy zone as delineated by the low nitrate + nitrite concentrations extends about 900 ft downgradient of the recharge site and is about 1,100 ft wide. The nitrate + nitrite concentrations within the recharge plume contrast sharply with those in ambient water and secondary-treated water, which range from 13 to 20 mg/L. Ground water affected by secondary-treated effluent, as indicated by specific conductance, sulfate, and ammonium data, is present at at least two wells directly downgradient of the toe of the recharge plume.

Calcium

Calcium has a shorter downgradient extent (pl. 1) than any other constituent discussed thus far. Elevated concentrations still prevail beneath the recharge site and extend less than 3,000 ft downgradient. The limited extent of calcium is attributed to cation-exchange processes, as discussed later in the report.

Upper Glacial Zone

The body of elevated concentrations of calcium associated with the recharge plume within the upper glacial zone is 2,900 ft long and 900 ft wide. The ambient "cutoff" concentration is 23 mg/L. Concentrations are highest within the upper glacial zone; those at two shallow wells near the recharge site exceed 40 mg/L (not shown in pl. 1), and concentrations greater than 30 mg/L are common elsewhere.

Intermediate Zone

The distribution of calcium in the intermediate zone shows the influence of secondary-treated water as well as reclaimed water. The elevated concentrations of calcium derived from reclaimed water extends about 2,500 ft downgradient from the recharge site and has a maximum width of about 900 ft. Elevated calcium concentrations downgradient of the recharge plume are interpreted to be a remnants of secondary-treated water from the abandoned sewage-treatment plant.

Magothy Zone

The distribution of elevated calcium values near the recharge site in the Magothy zone is defined by data from wells outside, but within 250 feet of, section A-A′ (pl. 1). The recharge plume as defined by calcium is about 1,000 ft long and 1,000 ft wide. The elevated concentration at well 29A does not indicate plume water because it is downgradient of the leading edge of chloride in this zone. The lowest calcium concentrations associated with the recharge plume are within the Magothy zone.

Magnesium

The maximum downgradient extent of elevated magnesium concentrations is similar to that of calcium. The greatest difference between the calcium and magnesium distributions is within the Magothy zone, where anomalously high magnesium concentrations occur. The "cutoff" concentration for magnesium is 4.5 mg/L. Like calcium, magnesium is involved in cation-exchange processes.

Upper Glacial Zone

The distribution of elevated magnesium concentrations within the recharge plume in the upper glacial zone is similar in extent and location to that of calcium. Low magnesium concentrations close to the recharge site may reflect the influx of stormwater from basin 62 (fig. 13). Like calcium, concentrations are elevated just west of section A-A′, near the site. The highest magnesium concentration in the study area (12 mg/L) is at the leading edge of the elevated magnesium concentrations in the recharge plume.

Intermediate Zone

The distribution of elevated magnesium concentrations in the intermediate zone is similar in shape and extent to that of calcium. A slightly elevated magnesium concentration downgradient of the recharge plume probably corresponds to the high calcium concentration in this area and is consistent with the low (slightly above ambient) concentrations associated with secondary-treated sewage. Elevated magnesium concentrations upgradient of the artificial-recharge site result from either an unknown outside source or anomalously high ambient concentrations.

Magothy Zone

The magnesium distribution in the Magothy zone shows an area of elevated concentrations between and downgradient from the artificial-recharge and secondary-treatment sites. The concentrations are above those expected from either reclaimed or secondary-treated water; therefore this anomaly cannot be attributed to either source. One explanation is suggested by the box plots for magnesium, calcium, and potassium in ambient ground water in appendix II. The magnesium concentration at the deepest well is much higher than those at wells within the intermediate and shallow-well groupings, whereas calcium and potassium concentrations at the same deep well are within the expected range. Additionally, the magnesium concentration at well 31A, downgradient from the recharge site, is above the "cutoff" concentration, whereas chloride, a conservative constituent, is at ambient levels. This, as well as the distribution of elevated magnesium concentrations, suggests that the ambient concentrations of magnesium are greater in the Magothy zone at depths exceeding 70 ft below the water table than in the upper zones.

Potassium

Potassium within the study area reacts strongly with the aquifer material, as evidenced by the small area of elevated concentrations associated with the recharge plume beneath and immediately down-gradient from the recharge site as well as the isolated downgradient slugs, which are attributed to secondary-treated water and road salt. The effect of cation exchange on potassium is discussed in a later section.

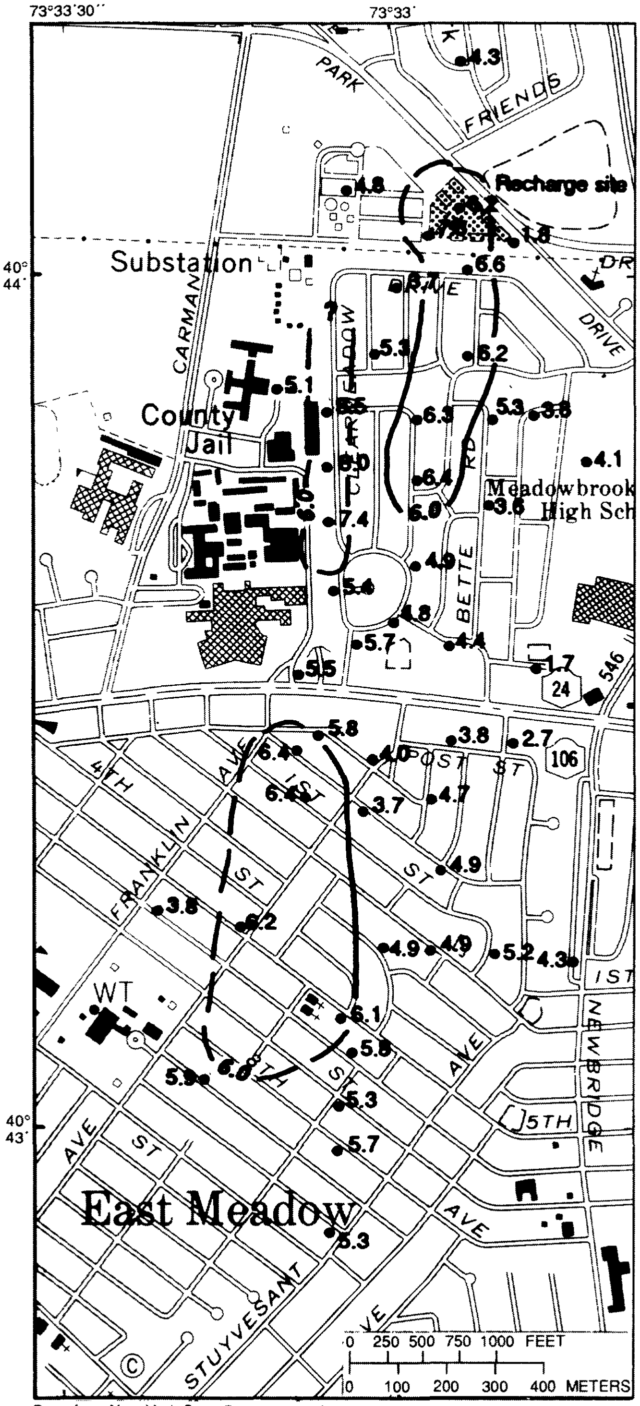
Upper Glacial Zone

Concentrations of potassium in the upper glacial aquifer are delineated in figure 18 and in plate 1. The "cutoff" concentration of potassium is 6.0 mg/L. The elevated potassium concentrations extend about 1,900 ft downgradient from the recharge site and are 600 ft wide.

Two other zones of elevated potassium concentration are indicated figure 18. One is west of the recharge plume and trends north-south along Clearmeadow Drive. Ground water here has been affected by road salt, as discussed earlier. Apparently the high concentrations of sodium have resulted in reequilibration of cation-exchange conditions, where sorbed potassium and other cations have been exchanged in favor of sodium. The second area of elevated potassium concentrations is near well 48B (pl. 1), downgradient from the area affected by road salt. This body is attributed to the effects of secondary-treated water at the abandoned sewage-treatment plant. Potassium is interpreted to be lagging behind the conservative and minimally reactive constituents of secondary-treated water.

Intermediate Zone

Elevated potassium concentrations in the intermediate zone are derived from both reclaimed and secondary-treated waters (pl. 1). Potassium concentrations related to reclaimed water extend downgradient about the same distance here as in the upper glacial zone. Elevated concentrations at the leading edge and downgradient from the elevated potassium body associated with the recharge plume are probably related to secondary-treated water, as suggested by their location and the presence of ammonium. Significant retardation of potassium and ammonium during transport through a sandy aquifer has been observed by Ceazan and others (1987).



Base from New York State Department of Transportation, Freeport, NY, 1:24,000, 1981

EXPLANATION

● 8.0 OBSERVATION WELL--number is potassium concentration, in milligrams per liter

6.0 LINE OF EQUAL POTASSIUM CONCENTRATION, in milligrams per liter. Dashed where approximately located

Figure 18.—Distribution of potassium within the upper glacial zone, March 1987.

Magothy Zone

In the Magothy zone, potassium derived from reclaimed water extends about 1,000 ft downgradient from the recharge site. The width of this distribution is obscured by the elevated concentrations near the abandoned sewage-treatment facility.

Alkalinity

The area of elevated alkalinity (≥ 9.0 mg/L as $CaCO_3$) along section A-A′ is attributed to plume water except at wells 13B, 13C, and 53A, which lie outside the recharge plume. Elevated alkalinity values west of section A-A′ are attributed to secondary-treated water. The similarity between alkalinity and calcium distributions (pl. 1) suggests that alkalinity, too, may be affected by cation-exchange processes. Alkalinity within the aquifer may also be decreased by biological processes such as nitrification in areas affected by secondary-treated wastewater.

Upper Glacial Zone

The alkalinity associated with plume water in the upper glacial zone extends about 3,900 ft downgradient from the recharge site, but the width is obscured by alkalinity levels associated with the influence of secondary-treated water. The most striking characteristic of the alkalinity distribution in the upper glacial zone is its similarity to those of calcium and magnesium. In plan view, the contoured area with a value of 30 mg/L as CaCO3 or greater is almost identical to the corresponding areas for calcium and magnesium.

Intermediate Zone

The alkalinity distribution within the intermediate zone is similar to that in the upper glacial zone. The largest difference is the decrease in values in the intermediate zone with distance from the recharge site. This decrease roughly parallels the decrease in pH from the upper glacial to the intermediate zone.

Magothy Zone

Except for the anomalously high alkalinity at well 20 (pl. 1), alkalinity within the Magothy zone does not exceed 22 mg/L as $CaCO_3$. The alkalinity distribution within the plume near the recharge site is similar to that of calcium. The reason for the high value at well 20 is unknown but is probably the result of sampling or analytical error. The pH at this site is too low (4.5) for an elevated alkalinity value.

pH

The reactive nature of hydrogen ion is reflected by the wide range of pH values (pl. 1). pH of reclaimed water ranges between 6.3 and 7.5; the lower values in plume water indicate the addition of hydrogen ions to the ground water by some means. Possible mechanisms of hydrogen ion release include cation exchange and nitrification.

Upper Glacial Zone

pH values in the upper glacial zone range between 3.8 and 6.7. The values greater than or equal to 6.0 are within an area that extends 2,000 ft downgradient from the recharge site. This area corresponds roughly to the areas of elevated calcium, magnesium, potassium, and alkalinity in the recharge plume. Beneath and immediately downgradient from the recharge site, pH values between 5.0 and 6.0 may indicate the influx of stormwater from basin 62.

Farther downgradient and toward the leading edge of the recharge plume (as defined by chloride), pH decreases to a low of 3.8, which represents a sharp increase in the hydrogen-ion concentration over a relatively short distance. pH values downgradient from the leading edge of the recharge plume remain below 5.0, perhaps as a result of nitrification of residual ammonium associated with secondary-treated water.

Intermediate Zone

The pH distribution in the intermediate zone is, in many respects, similar to that in the upper glacial zone. pH values near the recharge site are generally greater than 6.0 and decrease to less than 5.0 at the southern end of the study area (pl. 1). pH distribution in the intermediate zone differs from that in the upper glacial zone in that (1) high pH values persist beneath the recharge site, (2) the decrease from pH ≥ 6.0 to <5.0 is closer to the recharge site and more abrupt, and (3) the lowest pH value at the toe of the recharge plume (4.3) is not as low as in the upper glacial zone (3.8).

Magothy Zone

The extent of elevated pH in this zone is smaller than in the upper two zones. Although pH values are highest near the recharge site, none of them exceeded 5.7 in 1987. Downgradient, pH values between 4.4 and 4.7 are most common. The elevated pH (5.56) at well 15A is probably related to the abandoned sewage-treatment plant because ammonium is also present at that site.

CHEMICAL PROCESSES MOST LIKELY TO AFFECT REACTIVE CATIONS, ALKALINITY, AND pH

Within each depth zone, the chemical composition of the recharge plume varies with distance from the recharge site. The changes in water composition indicate chemical processes whose net result includes loss of potassium, calcium, magnesium, and alkalinity and gain of hydrogen ion and nitrate.

Field data suggest that cation exchange accounts for much of the observed change in potassium, calcium, magnesium, alkalinity, and pH. Biological processes such as nitrification may affect nitrate concentrations, pH, and alkalinity within the recharge plume in areas where secondary-treated effluent has been. Decomposition of organic matter derived from secondary-treated effluent may also affect pH. The potential for these processes is discussed in the following sections.

Potential for Cation Exchange

Cation exchange is a dynamic process that involves adsorption and desorption of cations between porous aquifer or soil material and pore water (Freeze and Cherry, 1979). The most common minerals that participate in cation-exchange processes are clay minerals, which may be present as coatings or weathering rinds on larger particles. The adsorption and release of cations is caused by charge imbalances on the mineral surfaces that result from imperfections or ionic substitutions within the crystal lattice, and (or) from chemical-dissociation reactions at the particle surface (Freeze and Cherry, 1979).

The imbalance of charge, which results in a net negative charge on the clay minerals, is balanced by a surface accumulation of ions of opposite charge (counterions) (Freeze and Cherry, 1979). Counterions are the exchangeable ions within the aquifer material, and the degree of exchange is controlled by (1) the concentrations of ions adsorbed on mineral surfaces and in the pore water, (2) each ion's affinity for adsorption, and (3) pH conditions (Drever, 1982).

WATEQ (Plummer and others, 1976) was used to compute aqueous speciation and mineral saturation indices at several locations in the study area; the results suggest that only quartz and amorphous silica species can be precipitated under the water-chemistry conditions within the area. Additionally, because the upper glacial aquifer does not contain carbonates, cation exchange appears to be the most probable mechanism controlling the distributions of calcium, magnesium, potassium, alkalinity, and pH.

The cation-exchange capacity (CEC) of the upper glacial aquifer material is about 0.60 meq/100 g (Faust, 1963; K. A. Pearsall, U.S. Geological Survey, written commun., 1988). The cation-exchange capacity of Magothy sediments generally exceeds that of the upper glacial aquifer as a result of the greater proportion of clay- and silt-size particles, but the heterogeneous nature of Magothy sediments results in wide local variations of CEC values (K. A. Pearsall, U.S. Geological Survey, written commun., 1988).

Calcium, magnesium, and potassium distributions in the ground water indicate that cation exchange is important within all three depth zones, but its effects are accentuated in the highly permeable upper glacial zone, which received reclaimed water directly from the unsaturated zone and has higher ground-water velocities. The following discussion focuses on the upper glacial zone because it provides the simplest example for discussion of cation exchange. The intermediate and Magothy zones probably are subject to similar processes, but only after transport through the overlying material.

Calculation of aquifer reactivity reveals the potential effect of cation-exchange processes on ground-water chemistry. A comparison of the reservoir of exchangeable cations in the aquifer material with those in ambient ground water and reclaimed water illustrates the reactive nature of the aquifer material. The sample computation below assumes the following values:

1. CEC representative of upper glacial aquifer material = 0.60 meq/100 g
2. bulk density of aquifer material = 1.80 g/cm^3
3. porosity = 0.32

The concentration (in milliequivalents [meq]) of cations in aquifer material associated with 1 L of ground water is calculated as follows:

1. $\dfrac{1.0\text{ L aquifer material}}{0.32\text{ L ground water}} = \dfrac{3.13\text{ L of aquifer material}}{1\text{ L ground water}}$
2. 3.13 L aquifer material = 3,130 cm^3
3. 3,130 cm^3 x 1.80 g/cm^3 = 5,634 g aquifer material in contact with 1 L ground water
4. 5,634g x $\dfrac{0.60\text{ meq}}{100\text{ g}}$ = 34 meq exchangeable cations per liter ground water

In contrast, total concentrations of major cations in ambient and reclaimed water are 2.5 and 7.7 meq/L, respectively. Thus, the exchangeable cations on aquifer material exceed the concentrations in ambient water about 14 times and those in reclaimed water about 4 times. Even if the estimated cation-exchange capacity associated with the aquifer is halved, the aquifer material still has the potential to exert a strong effect on the distribution of cation species within the ground water.

The most reactive constituents within the recharge plume are calcium, magnesium, potassium, alkalinity, and hydrogen ion. Concentrations of the first four are elevated from the recharge site to about 3,000 ft downgradient (pl. 1), in contrast to that of hydrogen ion, which increases by nearly 3 orders of magnitude over the longitudinal extent of elevated chloride (pl. 1). Near the recharge site, pH values greater than or equal to 6.0 coincide roughly with the elevated concentrations of calcium, magnesium, potassium, and alkalinity. At the toe of the plume is a "front" or "halo" of elevated hydrogen-ion concentrations (pH = 3.8). Such high hydrogen-ion concentrations are not characteristic of reclaimed water, which suggests that the source of excess hydrogen ion is the aquifer material.

Reclaimed water typically has low concentrations of ammonium and organic matter, which rules out their oxidation products as a significant source of acidity to the ground-water system.

Unsaturated Zone

Although data on cation exchange in the three zones within the study area are lacking, cation-exchange data from the unsaturated zone during recharge tests are available (Schneider and Oaksford, 1986). Cation-exchange capacities ranged from 0.85 to 3.45 meq/100 g with a median value of 1.15 meq/100 g. Before the recharge tests, the base saturation of unsaturated-zone material ranged from 10 to 47 percent with a median of 37 percent. The order of abundance of major adsorbed species was hydrogen>calcium>potassium>sodium>magnesium. The abundance of adsorbed hydrogen reflects the acidity of Long Island soils.

Cation exchange within the unsaturated zone is indicated by chemical changes in recharge water as it infiltrated through the bottom of basin 3 (fig. 11) to a lysimeter 11 ft below basin floor at the start of a recharge test on June 20-23, 1983 (table 4 and Schneider and others, 1987). Data from the saturated zone were not used for calculation of concentration changes because the water would be mixed with ground water affected by recharge from other basins. Concentrations of all major cations except hydrogen ion in recharge-water samples decreased over the 11-ft depth; hydrogen ion concentration increased by 2 orders of magnitude and was accompanied by a sharp decrease in alkalinity. If bicarbonate (HCO_3) is assumed to be the primary source of alkalinity, the decrease in alkalinity may be viewed as the following reaction:

$$HCO_3^- + H^+ \rightleftharpoons H_2CO_3 \qquad (1)$$

In this context, hydrogen ions released by the sediments and the high bicarbonate concentration associated with recharge water will force the reaction to the right (formation of carbonic acid) by the law of mass action. The loss of alkalinity (bicarbonate) can then be viewed as an equivalent gain in hydrogen ions from the unsaturated-zone material. If cation exchange is responsible for these changes, a balance of charge between adsorbed species (hydrogen ion) and released species (calcium, magnesium, potassium, sodium) must be maintained. Charge-balance calculations support this hypothesis (table 4). The difference between cations lost from solution and equivalent hydrogen ions gained is about 5 percent.

Another check on this interpretation is a budget calculation to determine whether an 11-ft-thick section of the unsaturated zone contains enough adsorbed hydrogen ion to produce the observed effect. Consider a column 11 ft (335.3 cm) long with an area of 1 cm^2.

Given:

1. median CEC of the unsaturated zone = 1.15 meq/100 g dry weight
2. median exchangeable acidity = 63 percent of total CEC
3. porosity = 0.32
4. density of solid material = 2.65 g/cm^3
5. volume of column = 335.3 cm x 1 cm^2

Then:

bulk density of unsaturated zone = 2.65 g/cm^3 x 0.68 = 1.80 g/cm^3
total dry weight of column = 1.80 g/cm^3 x 335.3 cm^3 = 603.5 g
total CEC of column = 1.15 meq/100 g dry weight x 603.5 g dry weight = 6.94 meq
total exchangeable $[H^+]$ = 6.94 meq x 0.63 = 4.37 meq available as $[H^+]$
total $[H^+]$ exchanged by sediments under basin ≈ 3 meq (from table 4)

The budget calculation suggests that the amount of hydrogen ion absorbed on the aquifer material is sufficient for the proposed interpretation.

Table 4.—Chemical changes associated with cation exchange in selected constituents of reclaimed water between basin 3 and a lysimeter 11 feet beneath it at start of 3-day recharge test, June 20, 1983

[Modified from Schneider and others, 1987. mg/L, milligrams per liter; meq/L, milliequivalents per liter.]

	Concentration				
	Basin		Lysimeter		Change
Constituent	mg/L	meq/L	mg/L	meq/L	(meq/L)
Loss of positive charge					
Calcium	49	2.445	30	1.497	-0.948
Magnesium	6.7	.551	1.3	.107	-0.444
Potassium	12	.307	6.8	.174	-0.133
Sodium	96	4.176	61	2.654	-1.522
Total					-3.047
Gain of positive charge					
pH (hydrogen ion)	$10^{-7.3}$	.00005	$10^{-5.4}$	.004	+0.004
Alkalinity (as $CaCO_3$)	148	2.960	3	.060	-(-2.900)
Total					+2.904

Saturated Zone

The calcium, magnesium, potassium, alkalinity, and pH distributions in the saturated zone appear to be affected by the same cation-exchange processes that occur within the unsaturated zone. During continuous recharge, equilibrium is eventually reached in the unsaturated zone, and essentially no changes in cation concentrations, pH, or alkalinity occur (Schneider and others, 1987). Thereafter, relatively unaltered reclaimed water recharges the upper glacial zone, which appears to cause further desorption of hydrogen ions and adsorption of calcium, magnesium, and potassium. Hydrogen desorption from saturated-zone sediments upon injection of reclaimed water into the Magothy aquifer was noted by Faust and Vecchioli (1974) and Ragone (1977) at Bay Park (fig. 1). As hydrogen ions are released, they would be expected to combine with the bicarbonate ions in the reclaimed water to form carbonic acid. Once the bicarbonate supply is exhausted, excess hydrogen remains in solution, causing a decrease in pH downgradient from the recharge site that culminates in the "hydrogen halo" mentioned earlier at the leading edge of the plume (pl. 1). Similar "hardness" or "calcium halos" have been reported by Griffin and others (1976) and Dance and Reardon (1983) in ground water associated with landfills. The increase in hydrogen ions causes alkalinity to decrease to nearly zero, whereas calcium, magnesium, and potassium at the toe of the plume remain at ambient levels.

The high pH and elevated concentrations of calcium, magnesium, potassium, and alkalinity in ground water beneath and immediately downgradient from the artificial-recharge site (pl. 1) suggest that the supply of exchangeable hydrogen in this part of the aquifer system has been exhausted.

Within the upper glacial zone, conservative constituents, such as chloride and sodium, have mvoed away from the recharge site with regional ground-water flow since the cessation of recharge (pl. 1). As ambient water mixes with remaining plume water, the aquifer material would be expected to shift toward prerecharge conditions through exchange of calcium, magnesium, and potassium in the aquifer material for hydrogen ion. The magnitude of this shift on the water quality in the upper glacial zone is unknown, but calcium concentrations in several samples from the upper glacial zone near the recharge site were the highest in the study area (not shown in pl. 1).

Charge-balance calculations for adsorbed and released cationic species in ground water near the recharge site and at the leading edge of the plume appear to indicate cation-exchange processes in the upper glacial zone. Ground water near the recharge site suggests reequilibration of the aquifer material to ambient conditions after cessation of recharge, whereas water at the leading edge of the recharge plume reflects the initial response of the aquifer material to recharge.

As in the unsaturated zone, the net change in cation concentrations from one point to another in the saturated zone ideally should be opposite to, but of equal magnitude as, the net changes in hydrogen-ion concentration and in alkalinity. The situation in the upper part of the saturated zone is complicated by dispersion and mixing during transport, however.

For example, sodium, which has a low affinity for adsorption, can be an important factor in cation-exchange processes at high concentrations, but at lower concentrations, after dispersion and mixing, it probably exerts only a minor influence. (The similarity between sodium and chloride in terms of distribution and relative concentration support this interpretation.) As a result, sodium was not included in the charge-balance calculations because the decrease in concentration through dilution outweighs any decrease through cation exchange .

Dilution and dispersion are sources of discrepancy in charge-balance calculations for all other adsorbed and released constituents as well. Several pairs of well data showed charge-balance differences of less than 20 percent between equivalent hydrogen ions and cations.

The relative adsorption affinities of the major cations, based on distributions within the upper glacial zone (pl. 1), are potassium>calcium ≈ magnesium>sodium. Similar relations have been observed by Nicholson and others (1983) for potassium, magnesium, and sodium in a sand aquifer. In contrast, Ceazan and others (1989) reported no attenuation of calcium and magnesium in a plume derived from secondary-treated effluent in a sand and gravel aquifer on Cape Cod. A lack of information on the downgradient extent of the plume does not rule out the possibility of retardation of these constituents, however.

Potential Biological Processes

Changes in nitrate concentration, alkalinity, and pH within the recharge plume may be partly controlled by bacterially mediated processes. The most likely processes, nitrification and decomposition of organic matter, would be associated with the earlier discharge of secondary-treated effluent followed by the influx of oxygenated ground water. In addition, decomposition of organic matter may be possible where stormwater inputs of organic matter are significant. Otherwise, only the western half of the recharge plume, which overlaps with the area affected by secondary-treated effluent, would be subject to these processes.

Nitrification is the bacterially mediated oxidation of ammonium, a reduced nitrogen species, to nitrate, a stable oxidized species. A generalized equation (R. L. Smith, U.S. Geological Survey, written commun., 1991) for the process would be:

$$NH^+_4 + 2O_2 + HCO^-_3 \rightarrow$$
$$NO_3^- + \begin{bmatrix}\text{organic carbon as} \\ \text{increased biomass}\end{bmatrix} + H^+ + H_2O \qquad (2)$$

In the study area, ammonium is present in ground water of the two deepest aquifer zones downgradient from the former sewage-treatment plant. The amount of ammonium retained by the aquifer material is unknown, but Ceazan and others (1989) report significant ammonium sorption in a sand and gravel aquifer on Cape Cod. Influx of oxygenated ground water (ambient or reclaimed) after the cessation of sewage-treatment operations could stimulate growth of nitrifying bacteria, which were reported in water from about 50 percent of the wells in the East Meadow area (Katz and Mallard, 1980).

Equation 1 predicts a loss of alkalinity and gains in hydrogen ion and nitrate. Low alkalinity and relatively high hydrogen ion concentration are observed in the downgradient part of the study area, which includes the recharge plume and water downgradient from and west of the toe of the plume. This suggests that the nitrification process is not unique to the recharge plume. Nitrate concentrations within the upper glacial and intermediate zones of the plume (fig. 19) are higher than those in recharge water. Concentrations in the western half of the plume in the upper glacial zone (affected at one time by secondary-treated effluent, fig. 15) are higher than those in the eastern half (partly affected by stormwater, fig. 15). Although nitrification appears to explain elevated nitrate in the western half of the plume (if the amount of sorbed ammonium was sufficient), it does not account for the less elevated concentrations (3 to 5 mg/L as N) in the eastern half. Ku and Simmons (1986) report < 1 mg/L nitrate as N concentrations in storm runoff on Long Island.

Nitrate concentrations within the recharge plume in the Magothy zone are consistent with those in reclaimed water. Presumably, lower levels of dissolved oxygen than in the shallower zones and a lack of ammonium have prevented formation of additional nitrate.

Bacterial decomposition of organic matter could potentially alter the pH of water affected by secondary-treated effluent. A sample of shallow ground water collected immediately downgradient from the infiltration beds at the sewage-treatment plant during its operation yielded a total organic carbon concentration of 10 mg/L. Total organic carbon in recharge water directly below recharge basins ranged from 1.6 to 2.7 mg/L (Schneider and others, 1986). Retention of dissolved or particulate organic matter by the aquifer material, followed by the influx of oxygenated water after cessation of operations, could result in the simplified reactions:

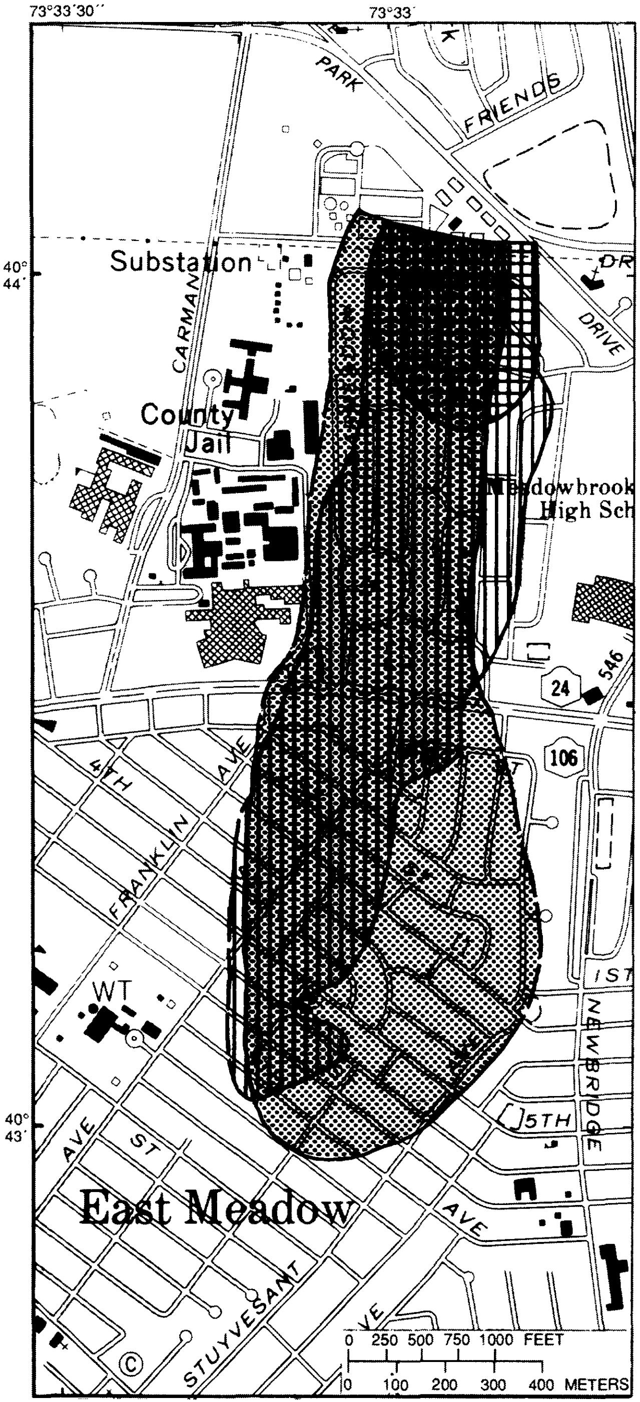
$$O_2\,(g) + CH_2O \rightarrow CO_2\,(g) + H_2O + H_2CO_3 \qquad (3)$$
$$\text{and} \qquad H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$$

The decrease in pH generated by this process would likely affect the same area as nitrification.

EXTENT, MOVEMENT, AND CHEMICAL EVOLUTION OF THE RECHARGE PLUME

The extent of plume water within the upper glacial, intermediate, and Magothy zones in 1987 is depicted in figure 19. The distributions in this map are a composite of all constituents used to delineate plume water. For example, within the upper glacial zone, chloride, a conservative solute, has been transported at least 900 ft away from the site, whereas potassium, the most reactive solute, persists at elevated concentrations beneath the site. Thus, chloride alone does not define the plume's entire area of influence. The maximum downgradient extent of the recharge plume in both the upper glacial and intermediate zones is 6,500 ft, and that in the Magothy zone is 1,300 ft. The plume width in the upper glacial zone downgradient from the recharge site, based in part on the extent of boron, is about 2,000 ft. (Sodium, sulfate, and chloride are subject to outside interferences on the west side of the study area, which prevents reliable lateral definition.)

The plume decreases in size with increasing depth as a result of the sharp decrease in vertical hydraulic conductivity (from 150 ft/d in the upper glacial aquifer to 20 ft/d in the Magothy) and a corresponding decrease in ground-water velocity (Prince and Schneider, 1989). The plume's distribution also is affected by the influx of stormwater and the distribution of clay and silt. The east side of the plume in the upper glacial zone is constricted downgradient from recharge basin 62, presumably by the influx of stormwater, whereas the plume in the intermediate and Magothy zones extends farther east and is apparently unaffected by it. The distribution of clay and silt within the intermediate and Magothy zones represents areas of low permeability (fig. 7) that correspond to areas where plume water is limited or not evident. The first such area extends about 2,000 ft downgradient from the abandoned secondary-treatment site and is present in both the intermediate and Magothy zones; the second starts about 3,000 ft downgradient from the recharge site and affects the intermediate zone. The upper glacial zone contains plume water in both areas (fig. 19).



Base from New York State Department of Transportation, Freeport, NY, 1:24,000, 1981

EXPLANATION

▒ UPPER GLACIAL ZONE

▥ INTERMEDIATE ZONE

▤ MAGOTHY ZONE

— — PLUME BOUNDARY--dashed where inferred

Figure 19.—Extent of recharge plume within all three depth zones, March 1987.

Horizontal Movement

The maximum downgradient extent of the recharge plume in the upper glacial, intermediate, and Magothy zones in 1987 is delineated from concentrations of the conservative constituent (chloride) within the ground-water system. The movement of this solute is due to two physical transport processes—advection and hydrodynamic dispersion.

Advection.—Advection is the bulk movement of solutes by the movement of water at the rate of regional ground-water flow. It is evidenced at this site by the presence of the recharge plume downgradient from the recharge site. This process alone would cause the leading edge of the plume to move at the average linear velocity of ground water and to have a sharp boundary because no mixing with ambient water occurs during this process.

Hydrodynamic dispersion.—Hydrodynamic dispersion spreads out solutes laterally and longitudinally from the path expected from advective transport. The gradual increase of the chloride concentrations (the "breakthrough" curve) at well 47B as the toe of the recharge plume passed (fig. 20) indicates that, in addition to advection, hydrodynamic dispersion is affecting the movement of this water. Chloride concentration would increase as a step function from ambient level to that in reclaimed water if advection were the only process causing an increase in chloride concentrations.

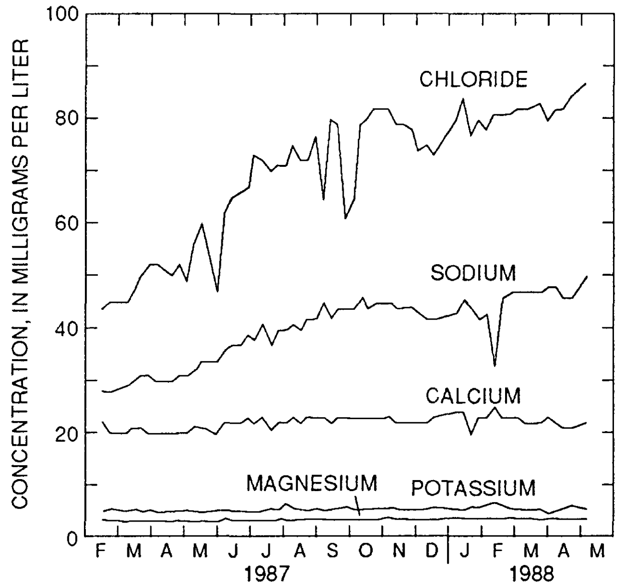


Figure 20.—Concentration of chloride and major cations at well 47B as the leading edge of the recharge plume moves through the area. (Well location is shown in fig. 2.)

Hydrodynamic dispersion entails mechanical mixing and molecular diffusion during advective movement. Mechanical mixing of ambient water with reclaimed water occurs at the micro and macro scales. Mixing on a micro scale occurs as ground water moves through torturous, interconnecting flow-paths, where variation in the geometry and size of the flowpath and friction at the pore surfaces facilitate mixing. Mixing on a macro scale occurs as water travels in and around zones of differing permeability. Localized changes in permeability are particularly common within the intermediate and Magothy zones.

Molecular diffusion, unlike mechanical mixing, is independent of water movement. It is important at the micro scale at low ground-water velocities, where it is driven by concentration gradients of the solutes. At higher velocities, such as those in the study area, it is insignificant in relation to mechanical dispersion.

Ground-water velocities can be calculated from hydraulic conductivity values derived from aquifer tests and from water-quality data. Prince and Schneider (1989) analyzed two aquifer tests within the upper glacial aquifer and upper part of the Magothy aquifer about 1,500 ft west of the artificial-recharge site. Horizontal hydraulic conductivities were calculated at 380 ft/d for the upper glacial aquifer and 100 ft/d for the Magothy aquifer. These values, combined with representative hydraulic gradients and porosities, indicate that the ground-water velocity in the upper glacial aquifer to be about 2.2 ft/d, and that of the Magothy 0.8 ft/d. These values represent average rates over the area stressed during the tests. In both tests, the production wells were screened close to the transition between aquifers.

Horizontal velocities within the upper glacial aquifer were also calculated from chloride data from the leachate plume associated with the road-salt stockpiles discussed earlier, as well as from the extent of the recharge plume (fig. 19). Velocities calculated from the road-salt data range from 2.5 to 3.2 ft/d, and those calculated from recharge-plume water were about 3.4 ft/d. The values for the intermediate and Magothy zones based on recharge-plume water were 3.4 and 0.8 ft/d, respectively. One reason why the recharge-plume data gave higher values than aquifer-test and road-salt data is that high recharge rates in the basins caused 6 to 7 ft of mounding of the water table (Schneider and others, 1987), and the elevated hydraulic gradients increased the average horizontal ground-water velocities near the recharge site.

The average horizontal velocity in the upper glacial zone under natural gradients was calculated from breakthrough curves of chloride concentration at successive wells (47B and 51B, fig. 2) as the leading edge of the recharge plume moved downgradient. Both wells are screened at the base of the upper glacial zone. The resulting average velocity was about 1.0 ft/d, which suggests that the permeability of aquifer material at one or both of these well screens is similar to that of the Magothy zone.

Vertical Movement

Recharge operations caused as much as 7 ft of water-table mounding (Schneider and others, 1987), and the resulting vertical gradients forced the reclaimed water to flow downward and radially away from the recharge site into the aquifer system. Presumably, the recharge water would reach its greatest depth below the water table during the longest sustained period of recharge. Water-quality data from deep observation wells at the site indicate that recharge water moved to depths between 90 and 160 ft below the water table.

Once the recharge ceased, plume water was acted upon by the prevailing gradients in the natural flow system. To assess the vertical component of natural flow, water samples were collected every 5 ft below the water table during the installation of well 46 in 1986 (fig. 2). Specific-conductance measurements indicated that the upper limit of plume water was about 10 ft below the water table. Because the density of plume water does not differ significantly from that of ambient ground water, this indicates a downward flow component in the local ground-water system. This component is probably controlled by intermittent recharge from precipitation and by the distribution of permeability within the unsaturated and saturated zones. The time elapsed between the application of reclaimed water and sample collection at well 46 is not known exactly, but the position of this well with respect to the chloride distribution in the upper glacial zone suggests that the sampled water was applied during the last third of the recharge period. If this period is used as a basis for calculations, a vertical velocity between 0.0096 and 0.011 ft/d is estimated. The depth of the toe of the plume below the water table, estimated from the vertical velocity data, should be between 15.5 and 17.8 ft.

Effects of Chemical Retardation

Chemical retardation is an important influence on the transport of many constituents in plume water. Unlike chloride, which is unreactive and subject to only physical transport processes, nearly all other constituents of interest are affected by chemical retardation. Exchange reactions between the aquifer material and the dissolved constituents are the most common means of chemical retardation. For example, under acidic conditions, sulfate may be subject to anion-exchange processes involving metal oxide coatings on sand grains, particularly within the upper glacial aquifer, and calcium, magnesium, potassium, and hydrogen ion concentrations are affected by cation-exchange reactions with clay minerals. Sodium is only slightly affected by cation exchange at the concentrations measured in recharge water. Carbonate speciation (bicarbonate alkalinity) is affected by the hydrogen ion concentration. Although nitrate is assumed to be stable under oxidizing conditions, low concentrations characteristic of plume water lag behind the leading edge of chloride in the upper glacial zone. The reason for the apparent increase in nitrate+nitrite is unknown. Boron also shows apparent retardation, which may be caused by sorption or variation in the source water.

The effects of chemical retardation and mixing on the movement of plume water in all three depth zones are summarized in table 5, where the longi-

Table 5.—Longitudinal movement of selected constituents of plume water, expressed as a percentage of the longitudinal extent of chloride within the upper glacial, intermediate, and Magothy zones, March 1987

[Dashes indicate insufficient data or interference from an outside source]

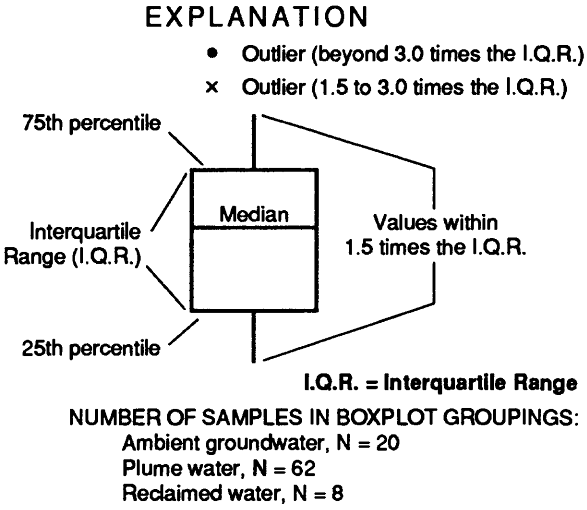
Constituent	Depth zone		
	Upper glacial	Intermediate	Magothy
Chloride	100	100	100
Sodium	94	~100	95
Sulfate	98	--	105
Boron	88	94	--
Nitrate + nitrite	91	84	85
Alkalinity	57	43	85
Calcium	44	30-42	80
Magnesium	47	33-46	--
Potassium	31	29-42	75

tudinal extent of each constituent is expressed as a percentage of the longitudinal extent of chloride. (Chloride is used as the standard because it is conservative and thus represents transport only by advective and hydrodynamic-dispersion processes.) Transport distances in the intermediate zone were measured along section A-A′ as far as route 24; distance measurements downgradient from route 24 were made along a line trending west of section A-A′ because flow was inhibited by less permeable material. Chemical retardation results in a value lower than 100 percent. The constituents undergoing the greatest chemical retardation are those involved in or affected by cation-exchange processes. The least reactive constituents are sodium, sulfate, boron and nitrate + nitrite. Among the three depth intervals, the Magothy zone shows the least chemical retardation, and the intermediate and upper glacial zones show significant amounts. The range of percentages given for the reactive cations in the intermediate zone indicates uncertainty in the transport distances. The apparent lack of retardation in the Magothy zone is attributed to the short distance travelled by the plume water.

The effect of cation exchange at the toe of the plume within the upper glacial zone is depicted in figure 20. This plot of chloride and major cation concentrations through time shows that chloride and sodium were approaching maximum concentrations by May 1988, whereas calcium, magnesium, and potassium showed no significant change in concentration over background levels.

The reactivity of any constituent can also be examined with box plots. Figure 21 depicts concentrations of selected constituents in ambient water, plume water, and the reclaimed water. The plume-water population represents wells within the area of the recharge plume shown in figure 18. The concentration range of each constituent differs substantially between the ambient- and reclaimed-water populations. The most conservative and least reactive constituents of plume water—chloride and sulfate, sodium, and nitrate + nitrite, —span but do not exceed the difference between the two end-point populations. These distributions can be viewed as continuous mixing lines between the ambient-water and reclaimed-water populations.

When ambient water, plume water, and reclaimed water are depicted in box plots, the most reactive constituents differ from the conservative and minimally reactive ones in one of two ways: (1) the range of the plume-water population is similar to or only slightly above that of the ambient water, and all are below the interquartile range of reclaimed water, as in the case of calcium, or (2) the plume-water population range extends outside the bounds of the ambient-water populations, as with pH.



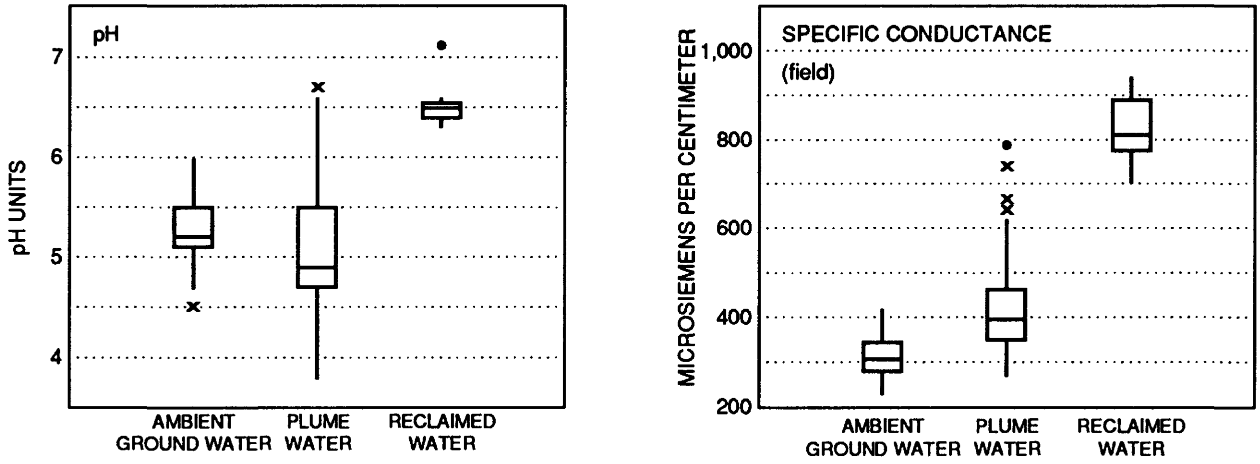


Figure 21.—Box plots of selected constituents of ambient water, plume water, and reclaimed water.

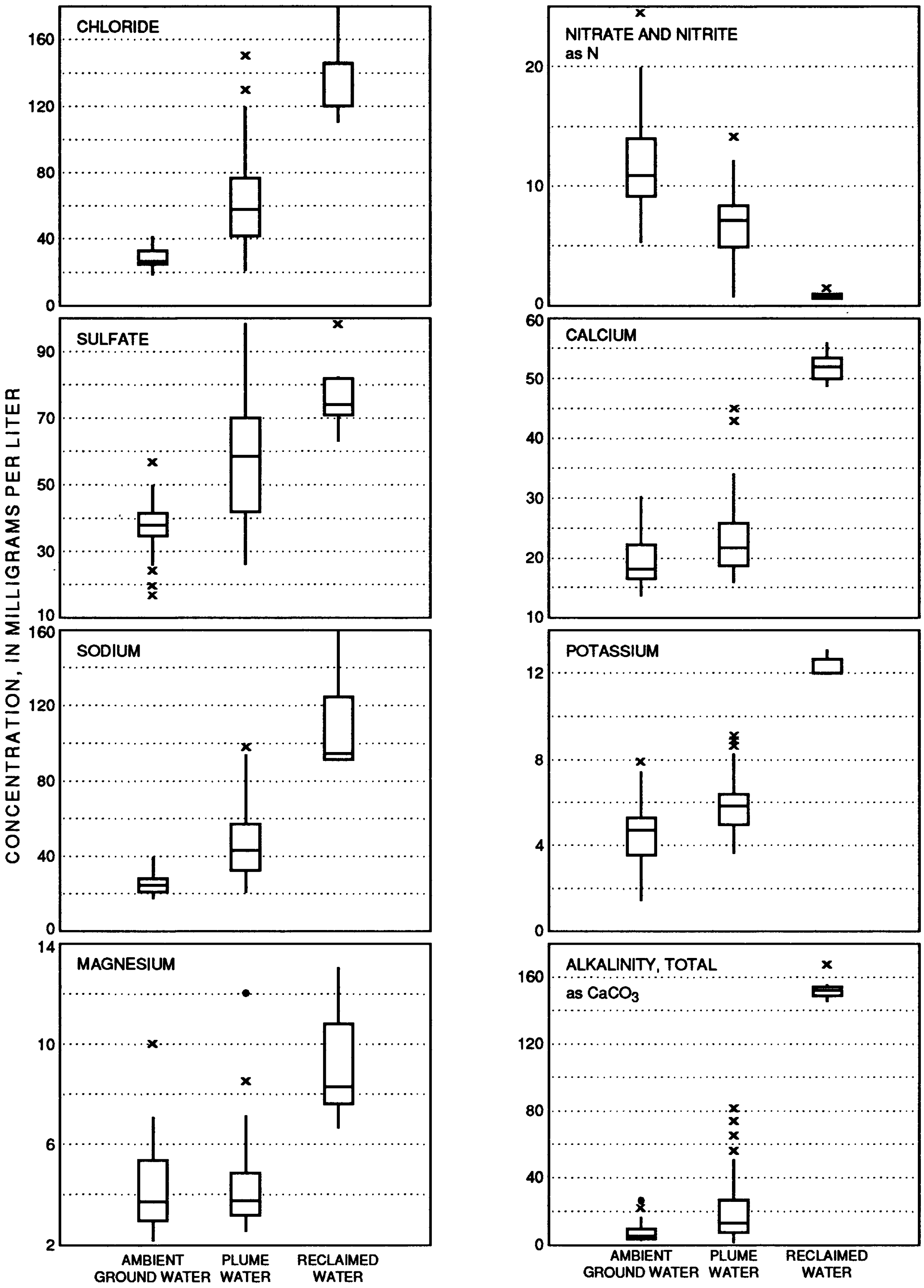


Figure 21.—Box plots of selected constituents of ambient water, plume water, and reclaimed water (continued.).

The first difference (similarity between ambient and plume waters) is characteristic of the reactive cations (calcium, magnesium, potassium) and alkalinity and reflects the strong control that cation-exchange processes exert on these constituents. The second difference (plume-water range extending outside the lower bound of ambient water) is exemplified by pH. The plume-water population encompasses the pH ranges of both ambient and reclaimed water, but the median value and lower range fall below the interquartile range of ambient water (fig. 21). This distribution also reflects the effect of cation exchange on ground-water chemistry. The pH box plot does not indicate enough hydrogen ion in either the ambient or the reclaimed water to explain the low pH values in the plume water but, if the aquifer material is considered to be a source of hydrogen ions, the interpretation of the box plot becomes more plausible.

Longitudinal Geochemical Section through the Recharge Plume

The location and general chemistry of plume water are depicted in longitudinal vertical section in figure 22, which shows a composite of the plume within all three depth zones. The plume is divided into four general areas represented by Stiff diagrams that characterize water quality by shape to facilitate comparison. Stiff diagrams of ambient water from nearby observation wells are included to illustrate the range of differences between ambient water and plume water.

The plume water in area I, which is mainly in the intermediate and Magothy zones beneath and immediately downgradient from the recharge site but includes a small section of the upper glacial zone, is most similar to reclaimed water. The primary differences are the lower concentrations of calcium, magnesium, alkalinity, and lower pH, all of which are affected by cation exchange.

Compared to the other areas of plume water, area I contains the highest concentrations of conservative and minimally reactive constituents as well as high concentrations of alkalinity, calcium, magnesium, and potassium. The highest concentrations of conservative constituents occur where little transport and, thus, minor dispersion have occurred, and the highest concentrations of reactive constituents occur where exchangeable acidity has been exhausted. These conditions are met in the Magothy zone and in the less permeable areas of the intermediate zone beneath and proximal to the recharge site. The part of the upper glacial zone classified as area I represents o-verlap of the trailing edge of conservative and minimally reactive constituents and the leading edge of more reactive constituents. Area I in the upper glacial zone is small because high ground-water velocities in the upper glacial zone have transported the con-servative and minimally reactive solutes farther down-gradient.

Area II of figure 22 represents water directly downgradient from area I, beyond the maximum downgradient extent of the reactive plume constituents except hydrogen ion, and extends to the toe of the plume. Area II is primarily in the intermediate and upper glacial zones but extends locally into the Magothy zone. Plume water in this area is identified by elevated concentrations of conservative and minimally reactive constituents and hydrogen ion.

The effects of chemical retardation and hydrodynamic dispersion, or mixing, on plume water in this area are illustrated by Stiff diagrams. Chemical retardation is indicated by the lack of elevated concentrations of calcium, magnesium, and potassium, and hydrodynamic dispersion is illustrated by a progressive downgradient change in Stiff diagram shape toward that of ambient ground water. This change indicates mixing and dilution of the conservative and minimally reactive solutes in plume water with ambient ground water.

Area III represents plume water downgradient from the recharge site and upgradient of area I within the upper glacial zone. It is characterized primarily by elevated concentrations of reactive constituents (calcium, magnesium, potassium, alkalinity) that have persisted in this area, and by ambient levels of conservative or minimally reactive solutes. The conservative and minimally reactive constituents associated with the plume in the upper glacial zone have been transported downgradient to areas I and II. Area III can be interpreted as the reactive part of plume water in the upper glacial zone.

Area IV represents the last stage of influence by plume water on ambient water. This area, which lies within the upper glacial zone and is closest to the recharge site, continues downgradient to area III. As ambient ground water flows into this area, all but the most reactive constituents of the plume reach or approach ambient levels. The water is characterized by ambient levels of all constituents except potassium, which is consistent with the relative cation-adsorption affinities described in the section on cation exchange, in which potassium is considered the most reactive cation.

Water-Quality Evolution Beneath the Recharge Site

Well 2C, screened in the upper glacial zone beneath the recharge site, was sampled several

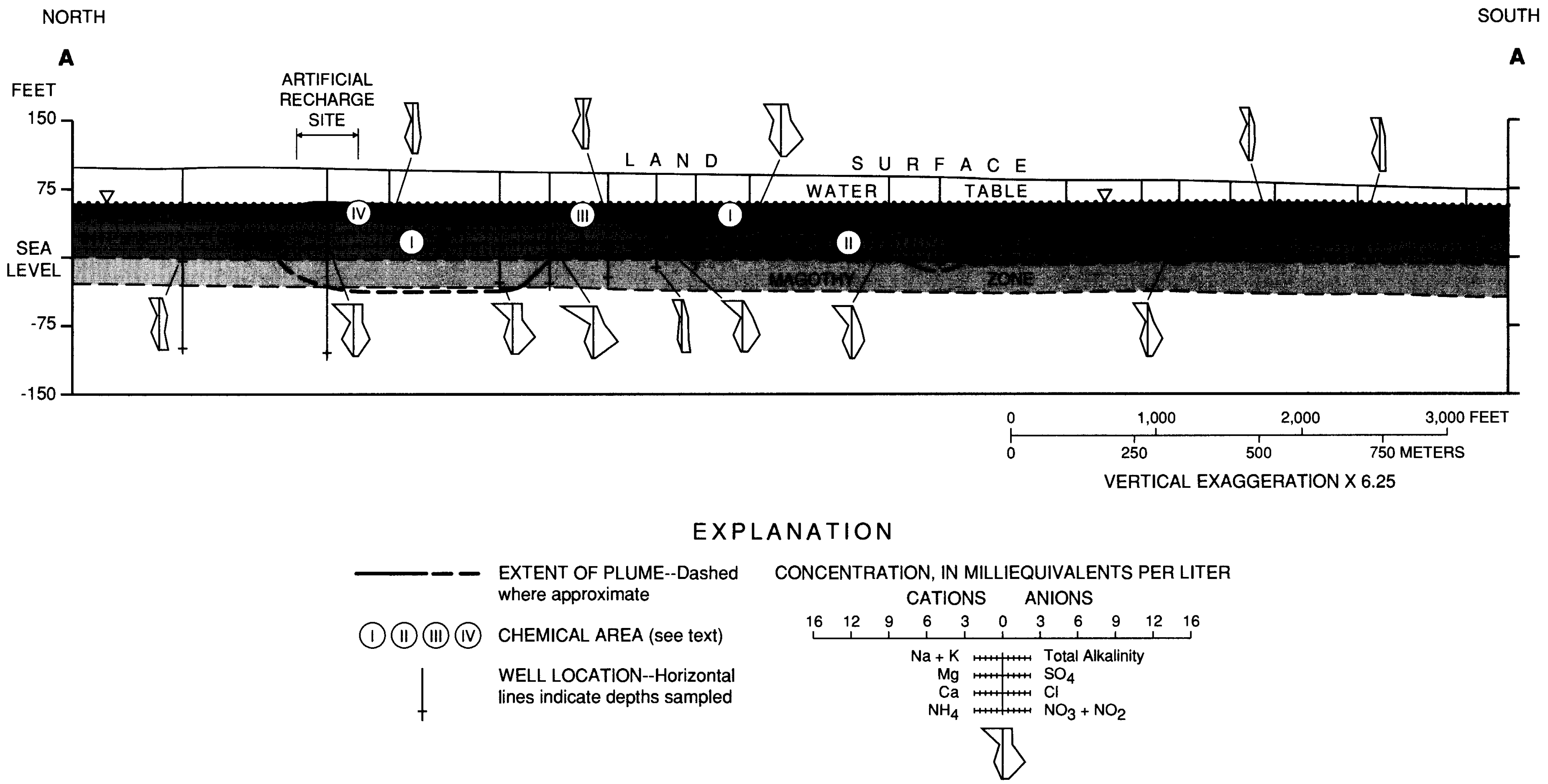


Figure 22.—Chemical quality of plume water in the three depth zones along section A-A′. (Location of section is shown in fig. 5.)

times before, during, and after the recharge tests. The water-quality data from this well are plotted on trilinear and Stiff diagrams in figure 23. Data illustrate several points. First, the pre-recharge samples show temporal variability in the chemistry of ambient ground-water , where the anion sides of the diagrams show the widest fluctuations. These fluctuations are also evident on the corresponding points in the trilinear diagram.

The Stiff diagram of plume water at well 2C during recharge operations is nearly identical to that of reclaimed water from the treatment plant in figure 14. These data, along with data from Schneider and others (1987), indicate that cation-exchange equilibrium was achieved (probably after several days) in the unsaturated zone during recharge.

After the cessation of recharge, the conservative and least reactive constituents of recharge water flow downgradient while ambient water replaces them beneath the recharge site. The Stiff diagrams for the post-recharge period are similar to those for areas III and IV of figure 22. Stiff diagrams that resemble those in area III indicate chemical proportions of the major ions that differ most from those in ambient water and illustrate the effects of cation exchange in this system. From this date (3/12/85),

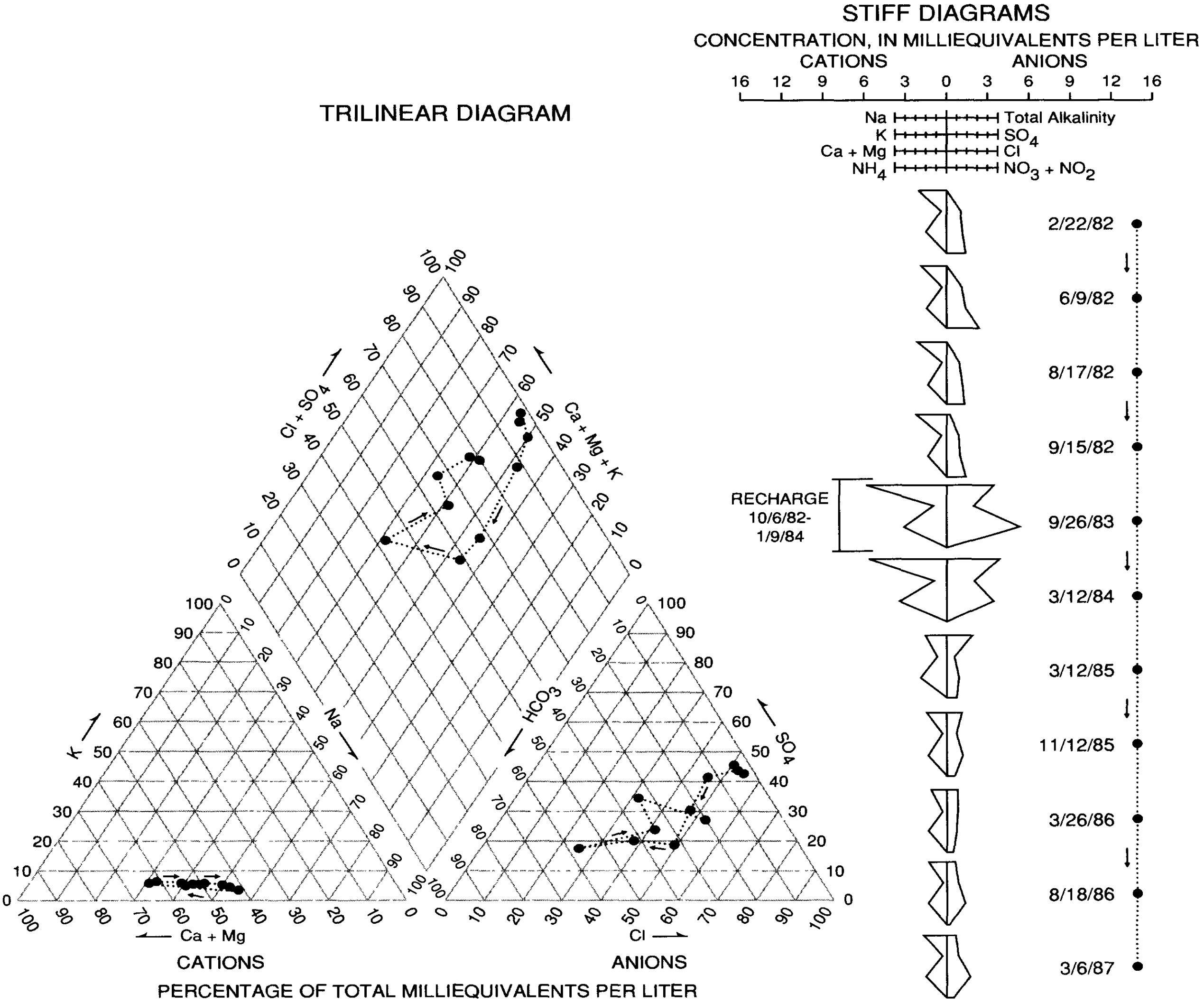


Figure 23.—Trilinear and Stiff diagrams showing changes in ground water from well 2C, screened in the upper glacial zone beneath the recharge site, before, during, and after recharge.

the influx of ambient ground water slowly brings concentrations back toward ambient levels. The trilinear diagram in figure 23 indicates that water at well 2C has not completed this process because the proportions of alkalinity and calcium, magnesium, and potassium differ from those in ambient water.

Fate of the Recharge Plume

In 1987, the distribution of plume water within the ground-water system reflected (1) the duration, areal distribution, and discontinuous nature of the 1982-84 artificial-recharge operations, (2) regional ground-water flow patterns, (3) local ground-water flow patterns resulting from vertical and lateral variations in permeability, (4) hydrodynamic dispersion, and (5) the effects of the chemical-retardation processes such as ion exchange and adsorption.

Chloride and the least reactive constituents, such as sodium, sulfate, nitrate, and boron, which characterize the downgradient part of the plume (area II, fig. 22), will continue to migrate downgradient at or near the local ground-water velocities, and the body of a given constituent within each depth zone will eventually separate from that in the other two zones because the ground-water velocity varies with depth. This becomes especially apparent through comparison of upper glacial distributions with Magothy distributions. In addition, dispersion will continue to lower the concentrations in the plume water toward ambient levels. The greatest amount of mixing will occur in the upper glacial zone, where the flow velocities are greatest.

Reactive constituents such as the cations (other than sodium) and alkalinity will disperse at a slower rate than the conservative and minimally reactive constituents because their movement is retarded by exchange reactions and adsorption. One result of chemical retardation is that the conservative and minimally reactive constituents within a given zone will, in time, separate from the reactive constituents, as evidenced by the 1987 chloride and potassium distributions within the upper glacial aquifer.

The hydrogen "halo" associated with the plume can be expected to dissipate through dispersion and cation-exchange processes with time. As the reactive cations quickly decrease to ambient levels downgradient from the recharge site and sodium disperses gradually as it moves downgradient, less hydrogen ion will be driven into solution from the aquifer material at the leading edge of the plume. The transport of calcium, magnesium, and potassium may cause continued desorption of hydrogen ion from aquifer material at their leading edge, although the process would slow as the concentrations of these cations diminish during transport.

The position of the leading edge of a given constituent at a specific future date in the upper glacial zone can be estimated as the ground-water velocity (2.5 to 3.4 ft/d) multiplied by the percentage of chloride transport (from table 5 and divided by 100) multiplied by the amount of time since the March 1987 measurements, plus the distance traveled before March 1987:

$$\begin{bmatrix}\text{Distance of leading edge}\\ \text{of constituent from}\\ \text{recharge site}\end{bmatrix} = \begin{bmatrix}\text{Ground water}\\ \text{velocity}\end{bmatrix} \times \begin{bmatrix}\dfrac{\begin{array}{c}\text{Percentage of chloride}\\ \text{transport (table 5)}\end{array}}{100}\end{bmatrix} \times \begin{bmatrix}\text{time (in days)}\\ \text{since March 1987}\end{bmatrix} + \begin{bmatrix}\text{distance from recharge}\\ \text{site in March 1987}\end{bmatrix}$$

The same procedure may be used for the intermediate zone but with less accuracy because the ground-water velocity is more variable. Magothy zone estimates would not be reliable for reactive constituents because estimated percentages of chloride transport from the limited well coverage and the short distance of transport would be only general (table 5).

SUGGESTIONS FOR FUTURE STUDIES

Further examination of the behavior and movement of solutes within the shallow ground-water system would improve understanding of water/ aquifer interactions. Laboratory sorption studies and column experiments could provide information on the role of upper glacial and Magothy sediments in cation-exchange processes and (or) adsorption reactions. Field studies might include an examination of geochemical conditions at the toe of the plume in the upper glacial aquifer because the low pH associated with this part of the plume might cause dissolution and mobilization of trace metals from aquifer material to levels that exceed drinking-water standards.

SUMMARY AND CONCLUSIONS

A pilot study examined the effects of artificial-recharge with reclaimed (tertiary-treated) wastewater at East Meadow, N.Y. The study began in October 1982 and continued for 16 months, during which about 720 Mgal of reclaimed effluent was applied through recharge basins, and 80 Mgal through injection wells. This study investigated the movement, extent, and chemistry of ground water affected by effluent from the recharge basins.

The extent of the recharge plume in the upper glacial aquifer and the uppermost part of the Magothy aquifer was delineated. Three hydrogeologic zones were established from water-quality and gamma-log data—the upper glacial zone and the Magothy zones, which represent the upper glacial aquifer and the uppermost part of the Magothy aquifer, and the intermediate zone, which represents the transition between them. Water-quality data suggest that the intermediate zone has some of the hydraulic characteristics of each aquifer. Gamma-log and water-quality data define locally variable amounts of silt and clay in the Magothy and intermediate zones that may retard or deflect ground-water flow. The upper glacial zone is predominantly sand and gravel.

Three local sources of solutes other than the artificial-recharge experiments were identified from water-quality data collected during the study—(1) secondary-treated sewage that was applied to infiltration beds adjacent to the artificial-recharge site from 1951 through 1979; (2) leachate from uncovered road-salt stockpiles stored at the secondary-treatment site; and (3) storm runoff that enters local stormwater basins, particularly Nassau County recharge basin 62, adjacent to the artificial-recharge site. The latter two sources affect mainly the upper glacial zone, whereas the former was detected in all three depth zones. An attempt was made to delineate the areas affected by each of these sources because, if unaccounted for, they could skew data on the chemical quality of ambient water and cause misinterpretation of the extent of the recharge plume. Historical data, Stiff and trilinear diagrams, and box and scatter plots were used in conjunction with maps of horizontal distribution to identify the areas affected by these sources.

Differentiation of plume water from ambient water was based on "cutoff" concentrations, which in turn were based on conservative estimates of the upper or lower concentration ranges for each constituent in ambient water. Median concentrations of all reclaimed-water constituents exceeded the corresponding concentrations in ambient water with the exception of nitrate + nitrite and hydrogen ion.

Chloride is the only conservative (unreactive) constituent of the plume, although several constituents were transported more than 80 percent of the distance that chloride had been transported by 1987. These include sodium, sulfate, boron, and nitrate + nitrite. The most likely mechanisms of retardation are cation exchange for sodium; anion exchange, biological sulfate reduction, or mineral reactions for sulfate, and sorption or source variation for boron. Mixing with ambient ground water, source variation, or biological processes might cause increases in nitrate + nitrite concentration.

Most reactive constituents had been transported between 30 and 60 percent as far as chloride in the upper glacial and intermediate zones in 1987. Distances travelled by the same constituents were greater with respect to chloride in the Magothy (deep) zone because they had migrated a shorter distance from the recharge site.

Cation-exchange processes are the most important control on the migration the reactive constituents. Cation-exchange capacities of unsaturated-zone material are generally less than 3 meq/100 g, and exchangeable acidity ranges between 1 and 2 meq/100 g (Schneider and Oaksford, 1986). Although these values are relatively small, the volume of aquifer material in contact with the effluent is large and, thus, has a significant effect on concentrations of the aforementioned constituents. The deepest aquifer zone has higher cation-exchange capacities than the upper zones. Data from the unsaturated zone suggest that hydrogen ions were driven off the aquifer material by the high cation concentrations in the effluent and were converting the bicarbonate portion of alkalinity to carbonic acid by the reaction

$$H^+ + HCO_3 \rightleftharpoons H_2CO_3$$

The toe of the plume within the upper glacial zone is characterized by (1) ambient concentrations of all major cations except sodium, (2) pH values as low as 3.8, and (3) alkalinity values less than 5 mg/L as $CaCO_3$. Near and beneath the recharge site, exchangeable hydrogen ions have been depleted, and the concentrations of calcium, magnesium, potassium, and alkalinity are above ambient levels but will return toward normal through exchange equilibria as ambient water continues to flow through this area.

Nitrification appears to be a primary control on nitrate concentration and an additional control on pH and alkalinity in areas affected by secondary-treated effluent. Decomposition of organic matter may also contribute to decreases in pH in this area.

The maximum longitudinal extent of plume water in 1987 was 6,500 ft in the upper glacial and intermediate zones and 1,300 ft in the Magothy zone. The high permeability and the relatively uniform texture of the upper glacial zone in this area is consistent with the absence of conservative and minimally reactive plume-water constituents beneath the recharge site and their extensive, reg-ular distribution downgradient from it. The intermediate zone is characterized by: (1) an extensive body of plume water whose irregular shape is due to variations in permeability, and (2) the persistence of conservative and minimally reactive constituents beneath the recharge site. The Magothy zone contains by a small body of plume water beneath and immediately downgradient from the recharge site that reflects the fine texture (low permeability) of the aquifer material at this depth. The maximum depth of the bottom of the plume is between 53 and 164 ft below the water table, as indicated by two observation wells that bracket this depth range beneath the recharge site. The maximum depth of the top of the plume is estimated to be 15 to 18 ft below the water table at the toe of the plume.

Chloride, a conservative constituent, was used to estimate horizontal ground-water velocity within each depth zone. The velocities calculated from the leading edge of chloride within the upper glacial, intermediate, and Magothy zones were 3.4, 3.4, and 0.8 ft/d, respectively. These velocities represent maximum values for each zone because recharge operations steepen the gradients. Chloride data from road-salt stockpile leachate suggest that the ground-water velocity within the upper glacial aquifer under natural gradients ranges from 2.5 to 3.2 ft/d.

Four years after cessation of recharge, distributions of conservative and reactive chemical constituents within the permeable upper glacial zone give an indication of processes that affect the fate of reclaimed water in the ground-water system. Chloride has moved much farther downgradient than the most reactive constituents, and the chloride and potassium distributions associated with the recharge plume in the upper glacial zone had separated from each other by 1987. The velocity variations among the conservative and reactive constituents can be expected to continue to alter the composition of the plume water, and hydrodynamic dispersion will continue to decrease the concentrations of all constituents.

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GLOSSARY

ambient water.—ground water whose quality is not affected by solutes from any known point source in the study area. The quality of this water reflects background conditions and is typically affected by nonpoint or diffuse influences common in developed areas such as cesspools, road salt, fertilizers, and possibly unidentified point sources upgradient.

injected water.—reclaimed water used for aquifer recharge through injection wells.

plume water (or recharge-plume water).—ground water derived from the infiltration of reclaimed wastewater through recharge basins. Interaction with aquifer material and physical transport away from the recharge site results in a variety of water compositions that range between the extremes of reclaimed-water and ambient-water composition.

recharge plume (or plume).—the body of water in the shallow ground-water system that has been affected chemically by constituents of reclaimed water.

reclaimed wastewater (or recharge water).—tertiary-treated wastewater from the Cedar Creek water-pollution-control facility used for the recharge experiments at the East Meadow recharge site.

Appendix I.—Identification numbers, diameters, and average screened depths of observation wells used in this study.

[Locations shown in figs. 2 and 10. Letters associated with well designations used in this report denote relative well depths for multiple wells at a single site: A = deepest, B = intermediate, C = shallowest]

Local number	Well number used this report*	Diameter (inches)†	Average screen depth below water table (feet)
9193	1A	6	152
9194	1B	6	53
9195	1C	6	3
9196	2A	6	164
9197	2B**	6	53
9198	2C**	6	4
9217	3**	6	7
9218	4**	6	3
9225	5	6	5
9235	6A**	6	61
9236	6B**	6	6
9247	7A**	6	59
9248	7B	6	7
9252	8A	6	157
9253	8B**	6	61
9254	8C	6	9
9361	9A**	6	58
9362	9B**	6	5
9363	10A**	6	65
9364	10B**	6	5
9365	11A	6	54
9366	11B	6	4
9367	12A**	6	59
9368	12B	6	2
9449	13A	6	156
9450	13B**	6	66
9451	13C**	6	3
10153	14A	4	81
10152	14B	4	46
10151	14C	4	13
10156	15A	4	81
10155	15B	4	46
10154	15C	4	13
10164	16A	4	80
10163	16B	4	45
10162	16C	4	13
10171	17A	4	79
10172	17B	4	44
10173	17C	4	11
10065	18	2	7

* These designations do not correspond to those cited in Schneider and others (1987).

** Samples from these wells were used to determine ambient water quality.

† 6-inch-diameter wells were installed with a fiberglass casing and a 5-ft section of stainless steel screen. 4-inch-diameter wells were installed with a steel casing and a 10-ft section of stainless steel screen. 2-inch-diameter wells were installed with a polyvinyl-chloride casing and a 4- to 5-ft section of PVC screen.

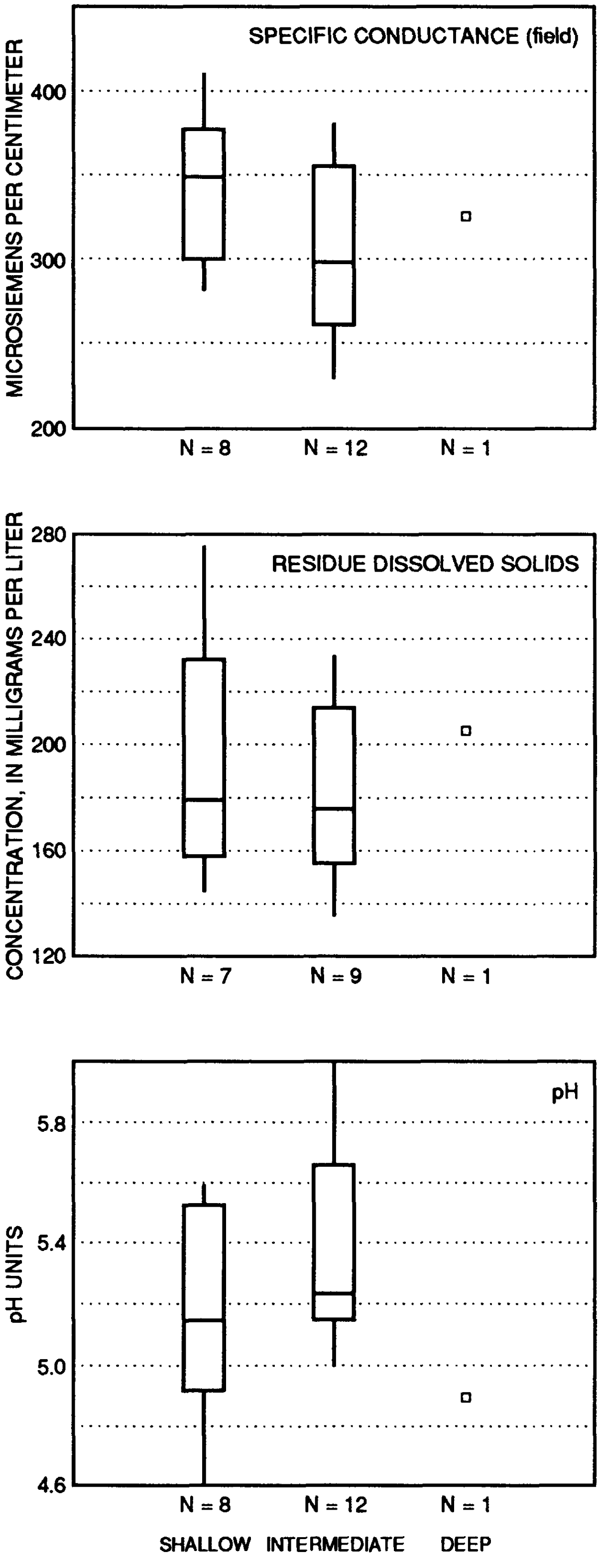
Appendix I.—Identification numbers, diameters, and average screened depths of observation wells used in this study (continued).

Local number	Well number used this report*	Diameter (inches)†	Average screen depth below water table (feet)
10069	19	2	13
10348	20	2	88
10349	21A	2	83
10350	21B	2	45
10351	21C	2	19
10352	22A	2	49
10353	22B	2	8
10354	23A	2	89
10355	23B	2	17
10356	24A	2	69
10357	24B	2	44
10358	24C	2	8
10359	25A	2	44
10360	25B	2	17
10361	26A	2	64
10362	26B	2	45
10363	26C	2	19
10364	27	2	44
10365	28	2	28
10366	29A	2	86
10367	29B	2	43
10368	29C	2	18
10369	30A	2	68
10370	30B	2	37
10371	30C**	2	3
10372	31A**	2	86
10373	31B	2	44
10374	31C	2	16
10375	32A	2	43
10376	32B	2	17
10517	33A	2	56
10518	33B	2	35
10519	33C	2	20
10520	34A	2	57
10521	34B	2	27
10522	35A	2	57
10523	35B	2	36
10524	35C	2	22
10525	36A	2	69
10526	36B	2	46
10527	36C	2	24
10528	37A	2	51
10529	37B	2	37
10530	37C	2	17
10531	38A**	2	54
10532	38B	2	31
10533	39A**	2	58
10534	39B	2	36
10535	39C	2	23
10536	40A**	2	64

Appendix I.—Identification numbers, diameters, and average screened depths of observation wells used in this study (continued).

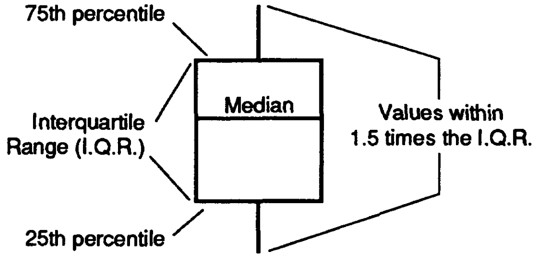
Local number	Well number used this report*	Diameter (inches)†	Average screen depth below water table (feet)
10537	40B	2	637
10538	40C	2	24
10539	41A	2	75
10540	41B	2	44
10541	41C	2	24
10542	42A	2	61
10543	42B	2	25
10544	43A**	2	53
10545	43B	2	27
10546	44A	2	67
10547	44B	2	543
10548	44C	2	34
10549	45A	2	59
10550	45B	2	35
10582	46	2	36
10770	47A	2	46
10771	47B	2	27
10772	48A	2	53
10773	48B	2	20
10774	49A	2	51
10775	49B	2	21
10776	50A	2	47
10777	50B	2	28
10778	51A	2	51
10779	51B	2	27
10780	52A	2	45
10810	52B	2	29
10782	53A	2	49
10783	53B	2	33
10784	54A	2	47
10785	54B	2	26
10786	55A	2	42
10787	55B	2	25
10788	56A	2	50
10789	56B	2	30
10790	57A	2	51
10791	57B	2	26
10792	58A	2	52
10793	58B	2	25
10794	59A	2	49
10795	59B	2	26
10852	60A	2	46
10853	60B	2	27
10854	61A	2	51
10855	61B	2	35

Appendix II. —Box Plots showing concentration ranges of selected constituents in ambient ground water; grouped by depth below water table.



EXPLANATION

- ● Outlier (beyond 3.0 times the I.Q.R.)
- × Outlier (1.5 to 3.0 times the I.Q.R.)



I.Q.R. = Interquartile Range

AVERAGE SCREEN ZONE DEPTH OF MONITORING WELLS:

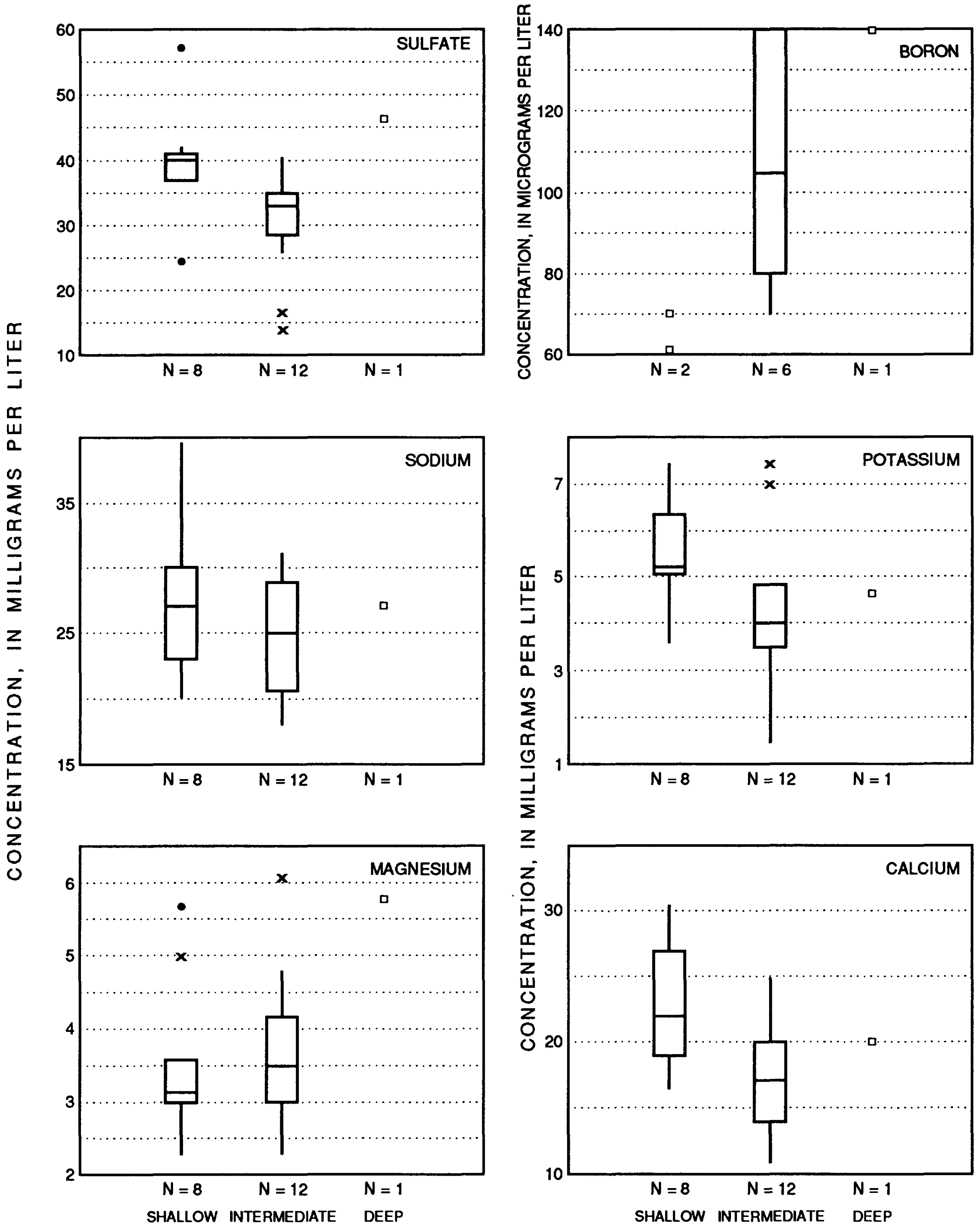
SHALLOW--0-10 feet below water table

INTERMEDIATE--50-65 feet below water table

DEEP--86 feet below water table

□ DENOTES DATA POINT FROM SINGLE MONITORING WELL

Appendix II. —Box Plots showing concentration ranges of selected constituents in ambient ground water; grouped by depth below water table (continued).



Appendix II.—Box Plots showing concentration ranges of selected constituents in ambient ground water; grouped by depth below water table (continued).